The efficacy of the load-velocity profile to predict one repetition maximum

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A thesis submitted in partial fulfilment of the requirements of Sheffield Hallam University for the degree of Doctor of Philosophy

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Candidate declaration

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2. None of the material contained in the thesis has been used in any other submission for an academic award.

3. I am aware of and understand the University's policy on plagiarism and certify that this thesis is my own work. The use of all published or other sources of material consulted have been properly and fully acknowledged.

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Thesis abstract

Autoregulation is the process of acutely manipulating training variables in response to an individual's fluctuations in strength and fatigue and is vital for optimising programming. Load-velocity profiles (LVPs) have been proposed as effective flexible programming strategies to optimise resistance training load (kg), often through the daily estimation of one repetition maximum (1RM). This PhD, therefore, adopted a pragmatic, mixed methods research design and followed an applied research model (ARMSS) to devise a series of studies to ascertain a novel, efficient, and valid approach to LVP-based 1RM prediction.

Prior to choosing an autoregulatory method, strength and conditioning (S&C) practitioners must first determine an appropriate non-flexible programming strategy. A systematic review of literature revealed percentages of 1RM (% 1RM) as the superior method for increasing maximal strength (study one). After thematic analyses (study two) revealed barriers such as inaccurate 1RM predictions, time-costly protocols, and "iPad coaching" to the implementation of LVPs within practice; common velocity-based technology used by coaches; and the combination of ballistic and non-ballistic exercise when profiling, a new LVP method addressing these factors was devised in a key training, but under-researched exercise, the free-weight back squat.

The new approach to LVP-based 1RM prediction developed from this thesis utilised the Gymaware linear-position transducer given its superior reliability and validity (study three); individualised profiling due to stronger load-velocity relationships and large between-participant variability observed (study four); ballistic (jump squat) exercise after larger mechanical output was revealed in 0-60% 1RM when compared to non-ballistic (back squat) (study five); a submaximal point of extrapolation (80% 1RM mean velocity) due to poor within-participant reliability of loads > 85% 1RM (study four); quadratic modelling (study four); and as few as four incremental loads. Results revealed this combination to be an effective method for estimating 1RM and autoregulating daily load for S&C coaches.

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Publications and conference presentations

Peer reviewed publications arising from this PhD

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Thompson, S. W., Lake, J., Rogerson, D., Ruddock, A., & Barnes, A. (2022). Kinetics and kinematics of the free-weight back squat and loaded squat jump. *Journal of Strength and Conditioning Research,* ahead of print. doi: 10.1519/JSC.0000000000004186

Thompson, S. W., Rogerson, D., Ruddock, A., Greig, L., Dorrell, H., & Barnes, A. (2021). A novel approach to 1RM prediction using the load-velocity profile. *Sports, 9*(7), 88-99. doi: 10.3390/sports9070088

Thompson, S. W., Rogerson, D., Ruddock, A., Banyard, H., & Barnes, A. (2021). Pooled versus individualized load–velocity profiling in the free-weight back squat and power clean. *International Journal of Sports Physiology and Performance, 16*(6), 825-833. doi: 10.1123/ijspp.2020-0534

Thompson, S. W., Rogerson, D., Dorrell, H., Ruddock, A., & Barnes, A. (2020). The reliability and validity of current technologies for measuring barbell velocity in the free-weight back squat and power clean. *Sports*, *8*(7), 94-113. doi: 10.3390/sports8070094

Thompson, S. W., Rogerson, D., Ruddock, A., & Barnes, A. (2020). The effectiveness of two methods of prescribing load on maximal strength development: a systematic review. *Sports Medicine*, *50*(5), 919-938. doi: 10.1007/s40279-019-01241-3

Peer reviewed publications related to this PhD

Banyard, H., Tufano, J., Degado, J., **Thompson, S. W**., & Nosaka, K. (2019). Comparison of the Effects of velocity-based training methods and traditional 1rm-percent-based training prescription on acute kinetic and kinematic variables. *International Journal of Sports Physiology and Performance, 14*(2), 246-255. doi: 10.1123/ijspp.2018-0147

Conference presentations related to this PhD

Techmanski, B., Kissick, C., Comfort, P., Banyard, H., **Thompson, S. W**., & Suchomel, T. J. (2021). The reliability of and relationships between three velocity-based training devices during the hang high pull. *NSCA National Conference,* Florida, USA.

Kissick, C., Techmanski, B., Comfort, P., Banyard, H., **Thompson, S. W**., & Suchomel, T. J. (2021). The reliability of and relationships between three velocity-based training devices during the hang clean pull. *NSCA National Conference,* Florida, USA.

Thompson, S. W. (2020). Velocity-based training: From the lab to the weight room (50 min breakout lecture). *NSCA National Conference,* Las Vegas, USA. (event cancelled due to Covid-19).

Thompson, S. W., Rogerson, D., Ruddock, A., Banyard, H., & Barnes, A. (2019). Pooled versus individualized load–velocity profiling in the free-weight back squat and power clean. *NSCA National Conference,* Washington DC, USA.

Thompson, S. W., Rogerson, D., Ruddock, A., Banyard, H., & Barnes, A. (2019). The reliability of the load-velocity profile in the power clean. *UKSCA National Conference,* Milton Keynes, UK.

Seminar presentations related to this PhD

Thompson, S. W. (2019). The load-velocity relationship: Important considerations and applications. *Velocity-based Training Symposium*, Sheffield Hallam University, UK

Thompson, S. W. (2019). Velocity-based training. *UKSCA Regional Seminar*, Sheffield Hallam University, UK

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List of abbreviations

Δ – change in

η_p^2 – partial eta squared

% 1RM – percentages of 1RM

% diff – percentage difference

1RM – one repetition maximum

2D – two-dimensional

3D – three-dimensional

a – acceleration

$a_{average}$ – average acceleration

ACh – Acetylcholine

ADP – Adenosine diphosphate

AMRAP – as many repetitions as possible

ANOVA – analysis of variance

APRE – adjusted progressive resistance exercise

ARMSS – Applied research model for sport sciences

ATP – Adenosine triphosphate

BCE – Before the Common Era

BM – body mass

Ca – Calcium

CE – Common Era

CI – confidence intervals

CoM – centre of mass

CR10 – Category ratio scale

CV – coefficient of variation

d – Cohen's *d* effect size

DAPRE – daily adjusted progressive resistance exercise

dt – time derivative

DUP – daily undulating periodisation

dv – velocity derivative

f – Cohen's *f* effect size

F – Force

F_{app} – Force applied by an individual

F_{ext} – External force

F_{load} – Resistive force of the load

F_{net} – Net force

FNLP – flexible non-linear programming

$Force_{max}$ – theoretical maximum force

Fx – medial-lateral force

Fy – anterior-posterior force

Fz – vertical force

g – Hedges *g* effect size

GAS – General adaptation syndrome

GRADE – Grading of Recommendation, Assessment, Development, and Evaluation

Hz – Hertz (sampling rate)

ICC – intraclass correlation coefficient

IMU – inertial measurement units

IPF – International Powerlifting Federation

IWF – International Weightlifting Federation

k_1 – degree of curvature

k_2 – point of transition

kg – kilogram

$kg.bm^{-1}$ – kilograms per body mass

LOA – Limits of agreement

LPR – Least products regression

LPT – linear position transducers

LVP – load-velocity profile

m – mass

m.s – meters per second

MD – mean difference

MeSH – Medical Subject Headings

mm – millimetre

ms – millisecond

MVT – minimal velocity threshold

Na – Sodium

NSCA – National Strength and Conditioning Association

OMNI-Res – OMNI-resistance exercise scale

p – alpha level

p – momentum

P – Power

PCr – phosphocreatine

Pi – Phosphate

PRISMA - Preferred Reporting Items for Systematic Reviews and Meta-Analyses statement

r – correlation coefficient

R^2 – explained variance

RFD – rate of force development

RIR – repetitions in reserve

RM – repetition maximum

RPE – ratings of perceived exertion

RTF – repetitions to failure

s – displacement

S&C – strength and conditioning

SD – standard deviation

SDD – smallest detectable difference

SEE – standard error of the estimate

SEM – standard error of measurement

SI - Systéme International d'Unite's

SMD – standardised mean difference

SRB – set-repetition best

t – time

TE – typical error

TEE – typical error or the estimate

v – velocity

V_{1RM} – velocity at 1RM

$v_{average}$ – average velocity

VBT – velocity-based training

W – mechanical work

Chapter 1.0: Introduction

1.1 Introduction

Resistance training is integral for increasing force and velocity, two underpinning physical qualities of human movement. As sporting tasks are often restricted by time (e.g., sprinting), producing large magnitudes of force in short durations (e.g., rate of force development (RFD) or impulse) is critical for sports performance (Turner et al., 2020, 2021). Periodising training across the force-velocity curve targets the physiological mechanisms essential for maximising RFD and impulse (Haff & Nimphius, 2012; Suchomel et al., 2018). Effective long- and short-term planning of acute programming variables such as training volume, intensity, rest, frequency, and exercise choice can all contribute to programming success (Bird et al., 2005; Kraemer & Ratamess, 2004; Sheppard & Triplett, 2016). Training intensity, or external resistance training load, is critical when targeting adaptations specific to the force-velocity curve, particularly when maximising force production (Bird et al., 2005). As such, several strategies for prescribing and manipulating load within a training block are used by strength and conditioning (S&C) coaches (Banyard et al., 2019; Helms et al., 2016; Mann et al., 2010; Suchomel et al., 2021; Zourdos et al., 2016).

The prescription of external load, which in this context can be defined as mass (kgs) lifted, is traditionally administered via a two-part process: 1) determination of an individual's maximum strength using a one repetition maximum (1RM) or equivalent repetition maximum (RM) assessment; 2) prescription of load through percentages of 1RM (% 1RM) or RM targets. Limiting exposure to muscular failure is important for maximising strength adaptations, potentially placing % 1RM as the more appropriate method (Carroll, Bazyler, et al., 2019; Carroll, Bernards, et al., 2019). Nevertheless, prescribing load using % 1RM has its limitations when used in a multi-factorial and nuanced sporting environment with frequent and prolonged competitive schedules.

Controlling the impact of extraneous variables within professional sport can be challenging, with strength improvements, residual fatigue, sleep, nutrition, stress, nutritional status, and competition all affecting an individual's 1RM (Bartholomew et al., 2008; Cribb et al., 2007; Greig et al., 2020; Lopes Dos Santos et al., 2020; Moore & Fry, 2007; Ratamess et al., 2003). Managing these regular fluctuations in maximum strength can be challenging but are necessary to optimise prescriptions and limit injury-risk through improper loading. Mid-intervention 1RM assessments could be integrated into training blocks but can be time-consuming, create neuromuscular fatigue, and interrupt training cycle progressions. Therefore, alternative methods are required to manage these fluctuations in maximum strength through autoregulation.

Autoregulation is the process of manipulating training variables in accordance with an individual's response to training or non-training stressors and can be used to adjust load prescriptions and account for fluctuations in strength (Greig et al., 2020; Shattock & Tee, 2020). Autoregulatory methods are often dictated by time, access to equipment, and suitability to training environment. Ratings of perceived exertion (RPE), repetitions in reserve (RIR), flexible non-linear programming (FNLP), or repetitions-to-failure protocols (RTF) are all examples of autoregulation, however, often require extended lifting experience, contain intra-individual variability, or create neuromuscular fatigue, potentially impacting progression through a training cycle (Graham & Cleather, 2021; Hackett et al., 2012; Helms et al., 2016; Helms, Byrnes, et al., 2018; Mann et al., 2010; Mayhew et al., 2002, 2008; McNamara & Stearne, 2010; Morán-Navarro et al., 2017; Reynolds et al., 2006).

An alternative method for autoregulating load involves the application of technology to track and analyse velocity, typically referred to as velocity-based training (VBT) (Weakley, Mann, et al., 2020). Technological advancements have enabled the development of portable, reliable, and user-friendly devices such as linear-position transducers (LPTs), inertial measurement units (IMUs), and smartphone applications (Weakley et al., 2021), which has made live tracking, feedback, and analysis of velocity more accessible for S&C coaches. Velocity can be utilised to identify an individual's neuromuscular status based on the strong inverse relationship between load (% 1RM or kg) and velocity (r and $R^2 > 0.9$) (Banyard et al., 2018; Benavides-Ubric et al., 2020; García-Ramos, Ulloa-Díaz, et al., 2019; Muñoz-López et al., 2017; Pestana-Melero et al., 2018). The validity, reliability, and consistency of this relationship impacts how load is adjusted and optimised through the applications of load-velocity profiling.

Load-velocity profiles (LVPs) are incremental protocols that, when modelled mathematically (e.g., linear regression), produce equations to estimate load or velocity and can be used to adjust load prescriptions or set training targets (Balsalobre-Fernández & Torres-Ronda, 2021; McBurnie et al., 2019). The interaction between load and velocity appears stable over time (e.g., 6-10 weeks) and across the load spectrum (e.g., 20-90% 1RM), even following significant strength improvements (Banyard et al., 2020; González-Badillo & Sánchez-Medina, 2010; Hernández-Belmonte et al., 2020; Pérez-Castilla & García-Ramos, 2020). Changes in an individual's acute velocity output during key training exercises such as the back squat or bench press, therefore, can be used to optimise load when compared to baseline LVP data.

Optimising load prescriptions from load-velocity data can be achieved using two methods: cross-referencing performed velocities against baseline LVPs, and adjusting load based on arbitrary values (e.g., ± 5% 1RM following fluctuation of 0.06 $m.s^{-1}$) (Banyard et al., 2020; Orange, Metcalfe, Robinson, et al., 2020); or through sessional or set-by-set re-calculation of an individual's 1RM using LVP-based predictive equations (Dorrell, Moore, et al., 2020; Moore & Dorrell, 2020). Whilst the former is effective, it can generalise load adjustments and limit the individualisation of prescriptions, however, re-calculating 1RM on a sessional basis could account for the magnitude of load adjustments required for an individual.

Predicting 1RM from load-velocity data has been shown to be a reliable and valid (e.g., low coefficient of variation (CV), high intraclass correlation coefficient (ICC), small systematic bias) method for autoregulating load within S&C (García-Ramos, Barboza-González, et al., 2019; García-Ramos, Haff, Pestaña-Melero, et al., 2018; Janicijevic et al., 2021; Pérez-Castilla, Jerez-Mayorga, et al., 2020a; Pestana-Melero et al., 2018; Sayers et al., 2018). Importantly, this research is almost exclusively in upper-body and smith-machine-based exercises, limiting application to other key training movements. Therefore, understanding the efficacy of 1RM predictions in integral components of athletic programmes such as free-weight, lower body exercises (e.g., back squat, deadlift, and power clean) is vital for S&C coaches wanting to optimise load prescription using LVP data.

The paucity of research investigating lower-body, free-weight exercise presents less favourable results, with large systematic bias and standard error of the estimates (SEEs) evident from 1RM prediction models (Banyard, Nosaka, & Haff, 2017; Lake et al., 2017; Ruf et al., 2018). The discrepancy between upper- and lower-body 1RM prediction data could be due to poor reliability of the velocity at 1RM (V_{1RM}) during free-weight movements, the statistical models applied to load-velocity data, differences in shape of the profiles, or configurational limitations, with upper-body exercise protected due to more constrained movement patterns and the inclusion of fewer joints (Banyard et al., 2018; Banyard, Nosaka, & Haff, 2017; Chéry & Ruf, 2019; Janicijevic et al., 2021; Lopes et al., 2022; Pestana-Melero et al., 2018; Ruf et al., 2018). Developing a better understanding of the most effective method for estimating 1RM in athletes will provide coaches with beneficial autoregulatory strategies that can be implemented throughout a periodised plan.

Practically, LVPs can be time consuming, difficult to administer with large squads or groups, and remove the coach from their main role – coaching (Garcia-Ramos & Jaric, 2018). The two-point method has been developed as a time efficient alternative to multi-point LVPs, presenting high levels of reliability and validity in predicting 1RM (García-Ramos, Barboza-González, et al., 2019; García-Ramos, Haff, Pestaña-Melero, et al., 2018; Garcia-Ramos & Jaric, 2018; Janicijevic et al., 2021; Pérez-Castilla, Suzovic, et al., 2021). Again however, this research has been conducted exclusively in upper-body – typically smith-machine-based – exercises.

Autoregulation can assist with optimising training prescriptions in multi-faceted sports with long competitive phases. Being able to individualise and objectify load manipulation could permit S&C coaches to quantify neuromuscular readiness, physiological status, and strength fluctuations across the course of an intervention to facilitate optimised performance. LVP-based 1RM predictions might be the most effective way to achieve this, however, understanding the efficacy of such methods is limited in key training exercises. Similarly, simpler and more time efficient protocols are required to ensure coaches can adjust load on a sessional basis without elongating or stagnating training.

1.2 Doctoral philosophy

Scientific research is underpinned by philosophical reasoning which is governed by ontological (the study of being and the nature of reality) and epistemological (how knowledge is acquired) positions (Allmark & Machaczek, 2018). Research paradigms (i.e., an accepted model organising a philosophical position) are typically prescriptive in nature, often reasserting already established theories at the exclusion of others and potentially constraining intellectual curiosity and creativity (Kuhn, 1962). Scientific research, however, should be flexible, amenable, and fallible, answering specific questions using the most appropriate tools and strategies, whilst being hypothesis-driven, precise and accurate in measurement, and adhering to Systéme International d'Unite's (SI) (Winter & Fowler, 2009).

This doctoral programme, therefore, has combined a pragmatic philosophical approach (Creswell & Plano Clark, 2017; Feilzer, 2010) with a systematic way of working (the scientific method) (Ruddock et al., 2019), all the while being underpinned by an applied research model designed for sport sciences (ARMSS) (Bishop, 2008). This combination allowed for the development of practical solutions to "real world" problems (pragmatism) whilst ensuring the logical progression of research and providing integrated findings that are based on cumulative knowledge (ARMSS) (Bishop, 2008; Creswell & Plano Clark, 2017; Feilzer, 2010).

Pragmatists view an existential reality: a world with various layers, nuances, ambiguities, and possibilities (Dewey, 1925). They also suggest that research should aim to serve utility for the reader, not to represent a truth or reality, something that is engrained in reflexive practice (Morgan, 2007). This acceptance of divergent epistemological and ontological viewpoints allows for the flexibility in methodological approaches required to answer complex research questions that address the descriptive, causal, experiential, and perceptual. Approaching the doctorate in this fashion permitted iterative and progressive research in an applied and robust manner, ensuring each study built on the last to culminate in answering a practical question that would inform and progress practice.

Other philosophical stances such as realism – the existence of only one truth; empiricism – the belief knowledge comes only from sensory experience; or relativism – the view that reality is inseparable from human perception, interpretation, and is experienced within the mind often oppose the paradigmatic (scientific) assumptions of objective truth and empirical knowledge quantitative researchers typically possess (Allmark & Machaczek, 2018; Feilzer, 2010; Ladyman, 2002; Okasha, 2016). In fact, true nature of science (e.g., Poppler's theory of falsification) exists to consistently challenge theories, principles, and ideologies in an attempt to advance knowledge and it's organic evolution (Allmark & Machaczek, 2018).

This PhD has utilised a pragmatic philosophical approach to combine objective quantitative analysis with the contextual and subjective inquiry based on experiences and interpretations of qualitative research (Creswell & Plano Clark, 2017; Feilzer, 2010). In doing so, nuanced research problems were addressed using pluralistic approaches (Allmark and Machaczek, 2018) to place the S&C practitioner as the central focus. Combining this mixed method approach with an applied framework ensured each research study was progressive, logical, and informed practice.

This doctoral programme adopted an ARMSS, as proposed by Bishop (2008), to promote the logical progression of research and provide integrated findings that are based on cumulative knowledge. By doing so, a research framework that fostered a series of applied, practitioner-led, and robust studies was developed that included three stages: description, experimentation, and implementation. These stages can then be broken down further in to eight interacting levels (Bishop, 2008) (table 1). Although these stages are presented as a linear, multiphase model by Bishop (2008), the author suggests using the model flexibly to acknowledge the iterative, bidirectional nature of scientific discovery. Therefore, this thesis has adapted the phases in a pragmatic fashion to answer the relevant questions pertinent to the overall aim of the PhD.

Qualitative methods seldom frequent sports science research outside of psychological and behavioural investigations. Nevertheless, the initial stages of Bishop's model includes "defining the problem" and "descriptive research" (Bishop, 2008), which not only utilises the researchers knowledge and understanding of the line of inquiry, but also seeks to utilise that of expert practitioners, coaches, and athletes (Harper & McCunn, 2017). It is thought that this approach can help to identify barriers to research, offer practical relevance to investigations, improve practical representativeness, and help to bridge the gap between research and the applied field (Drust & Green, 2013; Harper & McCunn, 2017; Thompson, 2020). Furthermore, researchers have suggested including qualitative designs within earlier studies of a doctoral programme (Harper & McCunn, 2017).

The pragmatic approach of this PhD enabled the evolution of research questions and hypotheses without the need to reflect the boundaries (and limitations) of one paradigm. Lines of inquiry have evolved based on systematic literature searches, reflexive analysis of elite coach's perceptions, reliability and validity of technologies, systems, and protocols, and efficacy studies evaluating the effectiveness of novel strategies (table 1). This approach has ensured that the research has evolved organically, adjusting to new and emergent findings from the literature, advancements in technology, and in consultation with applied practitioners. It was essential that the philosophical underpinning and methodological approaches adopted permitted an organic and iterative cycle of implementation and reflection, to ensure clear interlinkage and evolvement of the programme of study as it developed (figure 1).

The outcomes of research explored the knowledge, experiences, and perceptions of applied practitioners to inform the progression of a programme of research that designs and evaluates load-velocity profiling using novel statistical techniques. The overarching aim of this PhD, therefore, is to identify, design, and evaluate the effectiveness of load-velocity profiling for the autoregulation of training intensity (i.e., 1RM prediction) via quantitative and qualitative methods.

Table 1. Applied Research Model for Sport Sciences (Bishop, 2008) applied to the doctoral programme of study.

Stage of ARMSS	Evidence from (Bishop, 2008)	PhD Study	Content
1) Defining the problem	It is at this stage that researchers need to ensure that they have an excellent understanding of the underlying science that relates to the identified research problem. Reviews or meta-analyses should also be undertaken to determine the state of the knowledge for the particular problem identified by the researcher and sport-science practitioners.	Systematic review	This study initially aimed to investigate the efficacy of four commonly used load prescriptive methods in practice; % 1RM, RM targets, RPE, and VBT. It was deemed important to understand the landscape of load prescriptive research at the inception of this doctoral programme to identify gaps in the literature.
	The first step of this model is for sport-science researchers to identify the types of real-world problems and issues that coaches and athletes face. In this respect, athletes, coaches, and sport-science staff should help to illuminate and prioritise broad re- search questions that need to be answered. During this stage, it is also important to learn about the sport and to talk to athletes, coaches and officials about issues related to individual and team performances.	Semi-structured interviews and thematic analysis	This study was conducted to better understand the perceptions of elite-level S&C practitioners on VBT and try to understand how they utilise it in practice. By identifying this, it would help to determine appropriate avenues of research to ensure application suited the applied world.
2) Descriptive research	Stage 2 of ARMSS may also include methodological studies, as descriptive research will only contribute if sufficiently valid and reliable methodologies are developed to collect data.	Reliability and validity of VBT technologies	This study was implemented to identify the most valid and reliable VBT technology which would then be utilised in the remainder of the PhD. Additionally, it was deemed appropriate to investigate a variety of commonly available devices (e.g., LPTs vs. IMUs vs. smart device applications) across a wide price range (e.g., £9.99 to £2000) to provide consumer advice for S&C coaches.

3) Predictors of Performance (regression studies)	Once descriptive studies (stage 2) have been per-formed, which provide coaches and sport scientists with an indication of where to look for solutions, stage 3 then involves research to better understand factors that are likely to affect performance. Typically, this would be accomplished by investigating relationships between predictor variables and actual sports performance	Load-velocity profiling of key strength exercise(s)	By investigating the relationship between load (% 1RM) and velocity, identifying an effective and reliable method for conducting a profile, and determining meaningful changes of velocity at specific loads, assumptions could be made into the predicted effectiveness of VBT as a prescriptive method (or as an autoregulatory method that could reliably predict 1RM and utilised as a complimentary tool to traditional prescriptive methods).
5) Determinants of key performance predictors	The word 'intervention' here is used in its broadest sense and may refer to training, nutritional guidelines, technique alteration, feedback methods, etc. Re- search that seeks to determine the causal mechanisms responsible for changes in the chosen predictor variables may also form part of this stage.	Ballistic vs. non-ballistic comparisons	Methodological flaws were evident regarding the construction of a LVP and thus stage 4 of the ARMSS model was missed to determine the mechanical appropriateness of utilising non-ballistic exercise across a large spectrum of loads (0-60% 1RM). Understanding the kinetics and kinematics of non-ballistic exercise vs. ballistic helped to recommend technical alterations to the LVP protocol to improve the efficacy and validity of the profile when assessing and predicting load-velocity and maximum strength characteristics.
6) Intervention studies (efficacy trials)	Efficacy trials can be defined as a test of whether an intervention has a substantial positive or negative effect on actual sports performance when delivered under optimum/ideal conditions. Efficacy trials are characterized by strong control in that a standardized intervention is delivered in a uniform and tightly controlled fashion to a specific,	Identification of a novel LVP-based 1RM prediction model	One of the original aims of the PhD was to compare % 1RM with VBT prescriptive methods to identify the efficacy of such methods. However, the global pandemic prevented the possibility of carrying out such research, and thus, the research aims of the thesis and remaining studies were amended. Instead, the final study investigated the efficacy (and validity) of a novel LVP-based 1RM prediction model that combined elements of the previous five

	often narrowly defined, homogenous, motivated population.	research projects (see figure 1), culminating in an efficient and practically applied method for autoregulating sessional load.

1.3 Thesis aims and objectives

Following the approach described above, the overarching aim of this thesis was to identify, design, and evaluate a novel method for predicting 1RM from load-velocity profiling. Specifically, to develop a time-efficient, valid, and reliable protocol that enables S&C coaches to effectively autoregulate sessional load prescription and optimise training recommendations across a variety of S&C settings. To address these aims, the following research objectives were developed:

1. To evaluate the current literature base surrounding load prescription and the effectiveness of a variety of methods. Specifically, to determine the quality of research to date with regards to VBT (ARMSS stage 1).
2. To explore and describe the application and perceptions of VBT and velocity-based technology within different elite S&C contexts (ARMSS stage 1).
3. To determine the most valid and reliable VBT technology commonly used by S&C coaches (ARMSS stage 2).
4. To determine between-participant variability, within-participant reliability, and the most appropriate statistical model for LVP data when performed in free-weight, lower body exercises (ARMSS stage 3).
5. To compare the mechanical differences between lower-body, free-weight ballistic and non-ballistic exercise when calculated across mean concentric and propulsive metrics (ARMSS stage 5).
6. To identify a novel method of 1RM prediction utilising LVPs to address procedural, statistical, and logistical issues identified in the previous studies and the current literature base (ARMSS stage 6).

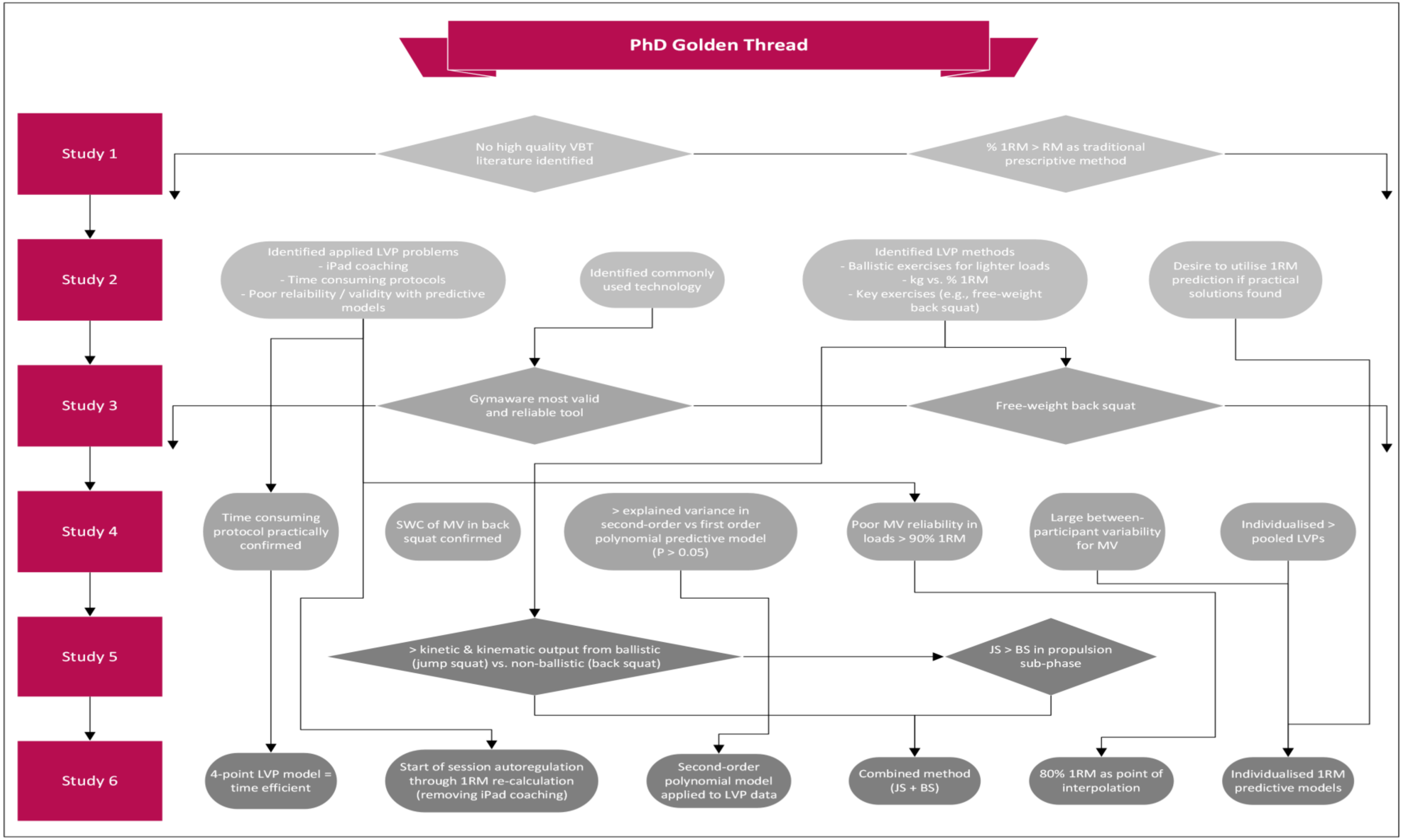

Figure 1. Schematic detailing the golden thread of the thesis and interlinkage between studies.

Chapter 2.0: Literature Review

2.1 Resistance training

Resistance training, interchangeably known as strength or weight training, is the act of completing movement- or stationary-based tasks against external loads during fixed or free-movement patterns and is well established as an effective exercise method for developing muscular fitness (i.e., generating muscular force) (Bird et al., 2005; Kraemer & Ratamess, 2004). Feats of strength are documented throughout history, dating as far back as 1000 Before the Common Era (BCE) with Li Ji and the Book of Rites; 776 BCE and the inception of the Olympic Games; Milo of Crotona and his famous carrying of the bull in 550 BCE; and Plato, who advocated different forms of exercises and rest in 400 BCE (Kraemer et al., 2017; Stojiljković et al., 2013; Stone et al., 2021). Medicine and resistance training progressed, with scholars such as Galen (129-216 Common Era (CE)), Philostratus (170-247 CE), and Leonardo Da Vinci (1452-1510 CE) all describing forms of resistance training relevant to injury, accounts of gymnastics preparation for Olympic competitions, and depicted through illustration (Stone et al., 2021).

Our understanding and knowledge of resistance training strategies progressed markedly during the 19th and 20th centuries. During this time, practitioners, researchers, and scholars such as Archibald McClaren (1819-1884) who discussed the role of growth and maturation and long-term development; Boris Kotov (1916) that introduced the concept of periodisation; Hans Selye (1907-1982) who published the general adaptation syndrome (GAS); the USSR and Eastern Bloc training methods (1930's-1960's) that were implemented in preparation for the Olympic games; Thomas DeLorme (1950's) who developed his widely-publicised progressive resistance training model; and Len Matveyev (1950's-1970's), Yuri Verkoshansky (1960's-1970's) and Vladimer Issurin (1980's) that all promoted forms of periodisation, plyometrics, and special strength training (Kraemer et al., 2017; Stojiljković et al., 2013; Stone et al., 2021).

A common factor in resistance training across ages is the combination of long-term, chronic planning (or periodisation) with short-term, acute programming (Cunanan et al., 2018). Periodisation is the macro-management of training, whereby periods of time are assigned to physiological adaptations that are strategically aligned towards competition (Cunanan et al., 2018; Stone et al., 2021). These phases, or 'training blocks', provide coaches with an outline for preparing specific physical characteristics required for competitive success (Cunanan et al., 2018; Stone et al., 2021).

Programming is the micro-management of training phases that make up periodisation (Cunanan et al., 2018). Acute programme variables such as external lifting load (intensity e.g., kg), volume (sets and reps), exercise (choice and order), frequency (sessions per week) and rest periods are manipulated across training phases to target specific physiological adaptations, limit unwanted fatigue, and optimise sport performance (Bird et al., 2005; Kraemer & Ratamess, 2004; Suchomel et al., 2018). The strategic adjustment of these variables during training improves (Harris et al., 2000; Tricoli et al., 2005) physiological mechanisms such as motor unit recruitment and synchronisation (Duchateau et al., 2006; McBride et al., 2003; Suchomel et al., 2018), mechanical output such as force production and RFD (Aagaard et al., 2002a; Andersen et al., 2010; Suchomel et al., 2016), and performance qualities such as sprinting, jumping, and change of direction (Comfort et al., 2012; Cormie et al., 2010; Hammami et al., 2019; Harris et al., 2008; Suchomel et al., 2016). Consequently, the interaction between load and volume when programming can optimise neuromuscular adaptations and are likely the main contributing factors to longer-term adaptations and performance improvement.

Carefully planned strength training can optimise an athlete's preparedness, which is a nuanced interaction between fitness and fatigue following bouts of physical stress (e.g., one-factor and two-factor models), and is vital for improving sprinting, jumping, and change of direction, all of which contribute to competitive success (Chiu & Barnes, 2003; Comfort et al., 2012; Cormie et al., 2010; Hammami et al., 2019; Harris et al., 2008; Kraemer & Ratamess, 2004). Whilst programme configuration is nuanced by sport, athlete, and competitive calendar, fundamental principles such as specificity of training, individualisation, progressive overload, and variation are all essential for physical preparedness (DeWeese et al., 2015a; Turner, 2011). Additionally, the cycling of heavy, multi-joint, non-ballistic exercises (e.g., back squat, bench press, deadlift at > 80% 1RM) with lighter (e.g.,) multi-joint, explosive or ballistic exercises (e.g., jump squat, bench-throw, trap-bar jumps at 0-60% 1RM) will aid the development of more impulsive and 'powerful' athletes when programmed and periodised effectively (Cormie et al., 2011b; Suchomel et al., 2018; Turner et al., 2021).

2.2 Physiological considerations for resistance training

Adaptations to resistance training (e.g., increases in strength) are underpinned by physiology. Consequently, when configuring programme variables, the desired physiological adaptations should dictate a coach's decisions. A detailed understanding of the physiological mechanisms that contribute to the various facets of training and performance will ensure focused interventions are implemented. Practitioners often develop 'specific' programmes that only considers time-motion demands of a sport (e.g., movement patterns) as opposed to the specific physiological demands, potentially limiting athletic preparedness.

2.2.1 Motor unit recruitment

When attempting to perform any physical action (e.g., lift a weight), the intent to do so stimulates the motor cortex to discharge an electrical impulse, exciting the corticospinal pathway (Kraemer & Looney, 2012; Tallent et al., 2021). This electrical stimulus is transmitted through an axon terminal of the motor neuron to a neuromuscular junction (Deschenes, Covault, et al., 1994; Deschenes, Maresh, et al., 1994). The summation of electrical signals generates an action potential, triggering the release of the neurotransmitter Acetylcholine (ACh) and stimulating muscle activation in accordance with the "all or nothing" principle (Celichowski & Krutki, 2018; Enoka & Duchateau, 2018; D. Jones, 2004a; Scalettar, 2006).

Motor neurons and muscle fibres (motor units) are recruited hierarchically in accordance with their size i.e., size principle, and contain identical metabolic and shortening properties (e.g., fast vs. slow twitch – the tetanic response to an electrical stimulus, high vs. low fatigue and force) and are typically recruited as a "pool" in response to the demands of a task (Celichowski & Krutki, 2018; Duchateau & Enoka, 2011; Henneman, 1957; D. Jones, 2004c; Maffiuletti et al., 2016; Suchomel et al., 2018). Recruitment of fast twitch, type II (a and x) motor units are essential for large magnitudes of force or fast velocity actions such as sprinting and jumping, with specific training modalities such as resistance exercise and plyometrics being fundamental for maximising these adaptations (Suchomel et al., 2018).

Resistance training is an effective strategy for increasing motor unit recruitment which can be achieved via the augmentation of motor unit recruitment and corticospinal activity (Folland & Williams, 2007). Very heavy (> 90% 1RM) and supramaximal (> 100% 1RM) resistance training can increase corticospinal excitation and reduce cortical inhibition (e.g., short-interval intracortical inhibition) (Carroll et al., 2009; Hendy & Kidgell, 2013; Weier et al., 2012), potentially via enhancements in afferent feedback from spinal reflexes (e.g., V-wave and H-reflex amplitudes) (Aagaard et al., 2002b; Sale et al., 1983), however the impact of this on increases in strength is inconclusive (Chow et al., 2021). Similarly, strength training can increase muscle activation via the recruitment of additional, higher threshold motor units (Balshaw et al., 2017; Folland & Williams, 2007). These physiological adaptations can all contribute to peak force generating capability.

An increase in higher threshold, motor unit recruitment is a fundamental adaptation from strength training, however, type II motor units fatigue quickly, meaning prolonged force production must be facilitated via other mechanisms such as rate coding. The frequency motor neurons discharge action potentials across the neuromuscular junction can enhance and prolong force production by 300-1500% (Enoka, 1995; Suchomel et al., 2018) by increasing consecutive motor unit discharges (5 ms between discharges, known as doublet discharges) (Van Cutsem et al., 1998). Additionally, synchronised activation of motor units can enhance force production, potentially improving RFD (Semmler, 2002).

Increases in neuromuscular recruitment, in addition to improvements in inter- and intra-muscular coordination and greater reflex potentiation, can all contribute to improved force capability (Balshaw et al., 2016, 2017; Buckthorpe et al., 2015; Crewther et al., 2006; Folland & Williams, 2007; Hakkinen, 1989; Tillin et al., 2012). Strength training induced adaptations via neural mechanisms can also be enhanced by the effective and strategic planning of rest and recovery through a reduced exposure to mechanical failure (Davies et al., 2016; Sundstrup et al., 2012). Whilst targeting one neural mechanism is unrealistic, prescribing varied, systematic, and individualised training cycles will ensure all are met accordingly.

2.2.2 Muscle activation

During muscle activation, action potentials cross the synaptic cleft at the neuromuscular junction via ACh and bind to the postjunctional region of the sarcolemma (Kraemer & Looney, 2012). This interaction triggers T-tubular depolarisation, releases Sodium (Na^+) and stimulates additional action potentials (Arner & Malmqvist, 1998; Fitts, 2008) which then disrupt adenosine triphosphate (ATP) pumps in the sarcoplasmic reticulum and initiate the release of Calcium (Ca++) into the sarcoplasm (cell) (Davis et al., 2018; D. Jones, 2004b). Ca++ binds with troponin to cause a conformational change in the actin structure, releasing tropomyosin and stimulating actin and myosin to create cross-bridge connections (Davis et al., 2018; Enoka & Duchateau, 2018; D. Jones, 2004d).

Adenosine diphosphate (ADP) is bound to myosin at rest but is released when actin and myosin interact and the “power stroke” occurs. A phosphate molecule (Pi) is released and the myosin head rotates whilst attaching to actin, pulling it towards the centre of the sarcomere (Arner & Malmqvist, 1998; Kraemer & Looney, 2012). Hydrolysis causes this process to repeat by converting ATP into ADP + Pi via the ATPase enzyme (Arner & Malmqvist, 1998; D. Jones, 2004b). Force production is therefore dictated by the repetitive nature (i.e., cycling) of this process, which is in turn, determined by the task.

Resistance training can improve strength through adaptations such as increases in functional cross-sectional area of muscle fibres (hypertrophy), facilitating an increased number of fibres in parallel within the fascicle (Schoenfeld et al., 2014, 2015, 2017). Preferential hypertrophy of type II fibres is more common with heavy resistance training (> 70% 1RM), however, type I fibre increases have also been reported (Campos et al., 2002; Folland & Williams, 2007; Hakkinen et al., 1981). Myofibrillar growth, the addition of sarcomeres within the myofibril, can also account for increases in hypertrophy (20-25%) (Balshaw et al., 2017; Deschenes & Kraemer, 2002; Mangine et al., 2015). Moreover, mitosis of satellite cells can create new myonuclei, producing additional muscle-specific proteins that increase fibre size (Crameri et al., 2004; Kadi et al., 2004). Fibre-type transition, specifically shifting from IIa to IIx, and increases in pennation angle are other morphological changes that contribute to increases in force production (Aagaard et al., 2001; Adams & Bamman, 2012; Folland & Williams, 2007). Unlike neural adaptations, changes to muscle structure and architecture could benefit from regular exposure to muscular failure, stimulating the regenerative mechanisms within the muscle to repair and replenish muscle proteins (Grgic et al., 2022; Schoenfeld et al., 2021).

2.3 Biomechanics of resistance training

The physiological adaptations induced by strength training are directly linked to mechanical principia. For example, increases in motor unit recruitment or cross-sectional area improve capability of force production (Folland & Williams, 2007). The generation of force underpins all human movement, and is simply an act of pushing or pulling that causes a change in state of motion (Goodwin & Cleather, 2021). Sir Isaac Newton (1643-1727) first described that the motion (constant velocity) of any object, moving or stationary, will only alter if acted upon by a disproportional force (Newton, 1687). An object's resistance to alter its state of motion, known as inertia, is directly proportional to its mass and therefore is only impacted by additional external forces (Lake, Mundy, et al., 2014; Lake, Swinton, et al., 2014; Turner et al., 2020). For example, when jumping, a force greater than body weight (F_{net}) must be applied by the individual to overcome inertia and accelerate the centre of mass, propelling the individual in the direction of the force applied. This relationship, known as Newton's second law of motion (Newton, 1687), can be defined as:

$$\boldsymbol{F_{net} = ma}$$

eq.1

where $\boldsymbol{F_{net}}$ is the sum of all external forces acting upon an object (N), $\boldsymbol{m}$ is the mass of the object (kg) and $\boldsymbol{a}$ is the acceleration of the object (m.s^{-2}). This can be extended to:

$$\boldsymbol{F_{net}} = \sum \boldsymbol{F_{ext}} = \boldsymbol{F_{app}} + \boldsymbol{F_{load}}$$

eq.2

where $\boldsymbol{F_{ext}}$ is equal to $\boldsymbol{F_{net}}$ (N), $\boldsymbol{F_{app}}$ is the force being applied by the athlete (N) and $\boldsymbol{F_{load}}$ is the resistive force of the load. The acceleration of an object is also a derivative of the change in velocity occurring over a specific period:

$$\boldsymbol{a} = (\boldsymbol{v_1} - \boldsymbol{v_2})/(\boldsymbol{t_1} - \boldsymbol{t_2})$$

eq.3

where $\boldsymbol{v_1}$ is the velocity (m.s^{-1}) of the object at the first time point $\boldsymbol{t_1}$(seconds), and $\boldsymbol{v_2}$ is the velocity (m.s^{-1}) of the object at the second time point $\boldsymbol{t_2}$ (seconds). Therefore, Newton's second law of motion can be rearranged to read:

$$\boldsymbol{F_{net}} = \boldsymbol{m} \times (\boldsymbol{v_1} - \boldsymbol{v_2})/(\boldsymbol{t_1} - \boldsymbol{t_2})$$

eq.4

When resistance training, the displacement or velocity of an individual or system (individual plus external load, e.g., barbell) is dictated by the magnitude of F_{net} given mass remains constant (Lake, Swinton, et al., 2014). To understand the mechanics of athletic movements, specifically resistance training, however, Newton's second law can be somewhat limited due to the varying magnitude of F_{net} that occurs across the course of muscular actions (Frost et al., 2010). Therefore, S&C coaches must consider more than just force and acceleration when trying to assess and monitor strength developments, compare athletes, and understand the mechanical demands of activities or sports.

An extension of Newton's second law is the impulse-momentum relationship, a mechanical principium that underpins many sporting actions such as jumping and sprinting (Lake, Swinton, et al., 2014). Momentum can be defined as:

$$\boldsymbol{p} = \boldsymbol{m} \times \boldsymbol{v}$$

eq.5

where $\boldsymbol{p}$ is the momentum of the object (kg • m.s^{-1}). The proportional relationship momentum has with impulse (the magnitude and duration of the net force) can then be described by combining equations four and five, and rearranging to read:

$$\boldsymbol{F_{net}} \times (\boldsymbol{t_1} - \boldsymbol{t_2}) = (\boldsymbol{m} \times \boldsymbol{v_2}) - (\boldsymbol{m} \times \boldsymbol{v_1})$$

eq.6

During resistance training, however, equation six must be integrated with respect to time to reflect the changes in momentum that occur over the entire muscular action:

$$\int_{t_1}^{t_2} \boldsymbol{F_{net}} \times \boldsymbol{dt} = \boldsymbol{m} \times \int_{t_1}^{t_2} \boldsymbol{dv}$$

eq.7

where $\int_{t_1}^{t_2} \boldsymbol{F_{net}} \times \boldsymbol{dt}$ is the integral of the force-time curve (N • sec - impulse) and $\int_{t_1}^{t_2} \boldsymbol{dv}$ is the integral of velocity (m.s^{-1}) between the two time points. Impulse is an important concept because sporting actions are not only restricted by the time to perform an action but also technical or strategic requirements, which determines force production and therefore impulse. Such information is vital for the understanding of athlete's physical capabilities and suitability for specific tasks (Lake, Swinton, et al., 2014; Turner et al., 2020).

Mechanical work is another important concept for S&C coaches to understand as it describes the amount of energy required to produce force or perform particular actions, and can be a useful tool to quantify the demands of specific tasks (Goodwin & Cleather, 2021):

$$\boldsymbol{W} = \boldsymbol{F_{net}} \times \boldsymbol{s}$$

eq.8

Where $\boldsymbol{W}$ is the mechanical work (J) and $\boldsymbol{s}$ is the displacement of the object (m). Work is directly proportional to half of the mass of the object multiplied by its velocity squared (Goodwin & Cleather, 2021):

$$\boldsymbol{F_{net}} \times \boldsymbol{s} = \frac{\boldsymbol{1}}{\boldsymbol{2}}\, \boldsymbol{m}\left(\boldsymbol{v_2^2} - \boldsymbol{v_1^2}\right)$$

eq.9

where $\frac{1}{2}\boldsymbol{mv_2}$ represents the kinetic energy required to perform movements, and therefore is proportional to mechanical work. Like mass, displacement is constrained in resistance exercise due to human anatomy (i.e., limb length). Therefore, greater work done requires more kinetic energy (Turner et al., 2020). The amount of work performed will also impact mechanical power through the interaction between velocity and the duration taken to apply that velocity:

$$\boldsymbol{P} = \frac{(\boldsymbol{F_{net}}\ \boldsymbol{x}\ \boldsymbol{s})}{\boldsymbol{t}}$$

eq.10

where $\boldsymbol{P}$ = power (W). Power is commonly used by practitioners to identify improvements in mean or peak power during strength- or jump-based monitoring tasks, or when referring to training blocks at the end of a training cycle (e.g., "power training") (Turner et al., 2021). Despite this, the assessment of external mechanical power is typically more suited to activities such as cycling where strict mechanical definitions are more easily applied and interpreted to provide a convenient metric by which to describe mechanical output (Knudson, 2009; Winter

& Fowler, 2009). Within S&C, however, power is often utilised during short, dynamic, or impulsive activities such as jumping or sprinting. The direction of force production within these actions is typically important (e.g., vertical vs. horizontal force vectors during sprinting) and given these '*impulsive'* tasks are directly underpinned by the impulse-momentum (e.g., jump height is determined from take-off velocity which is underpinned by net impulse) and work-energy theorems, coaches should have an appreciation of and analyse the appropriate underpinning mechanical qualities (Knudson, 2009; Ruddock & Winter, 2016).

Moving mass quickly is often a simple concept for S&C coaches to understand. Power, which can be rearranged to highlight an important interaction between force and velocity, is therefore a common variable utilised by practitioners:

$$\boldsymbol{P = F_{net}\ x\ v}$$

eq.11

Logic would suggest that an increase in either force or velocity will increase mechanical power (Turner et al., 2020). Furthermore, increases in force or velocity also represents an increase in impulse and momentum given the proportional relationship between the two variables and the fact that mass is constant during resistance training (Turner et al., 2020). For S&C practitioners, therefore, targeting increases in force and velocity through sequenced and well-planned training cycles will ultimately improve an athlete's underpinning physical qualities, creating a simple model for improving performance.

Improvements in sporting performance are often related to increases in velocity (e.g., track sprinting or evading opponents in Rugby). By rearranging equation one, it is evident that several strategies exist to improve velocity:

$$F_{net} = m\frac{v}{t}$$

eq.12

$$V = F_{net}\frac{t}{m}$$

eq.13

Based on this, coaches could target increases in the magnitude or duration of force application, or the individual's or system's mass (Turner et al., 2021). Increasing system mass may be counter-productive or unfeasible as often sports are restricted by weight categories, implementation, or the need to be 'light' and agile (Turner et al., 2021). Similarly, increasing the duration of force application could negatively impact performance given most sporting actions are restricted by time (Maffiuletti et al., 2016) (table 2). Consequently, increasing the magnitude of force production seems to be the most effective strategy to improve an athlete's velocity, indicating the inherent importance of strength training.

Table 2. Ground contact times for common sporting actions adapted from McBurnie & Dos'Santos (2021).

Sporting action	Ground contact time (ms)
Maximal velocity (sprinting	105
Curvilinear sprint	150
Crossover step (change of direction)	150
Side steps (change of direction)	150-250
Acceleration (sprinting)	190
Fast stretch shortening cycle plyometrics (e.g., drop jump)	< 250
Slow stretch shortening cycle plyometrics (e.g., countermovement jump)	> 250
Deceleration	400

ms millisecond

From a training perspective, targeting non-ballistic, strength exercises with heavy loading (> 80% 1RM) will increase force requirements and in turn, power and impulse (Suchomel et al., 2018). It is suggested, however, that cycling through high force- and high velocity-based training phases is more advantageous than high-force alone as this will not only increase force magnitude, but decrease the time it takes to produce that force, i.e., target RFD (Cormie, McCaulley, et al., 2007; Haff & Nimphius, 2012). A potential limiting factor of strength-only training is the inability to stimulate neuromuscular recruitment throughout the full range of motion due to a period of negative acceleration, and therefore negative impulse, at the end of the concentric phase of non-ballistic exercise (Cormie et al., 2011b; Kubo et al., 2018; Newton et al., 1997) (figure 2). Ballistic or "explosive" training naturally avoids this issue through projection of the barbell or system.

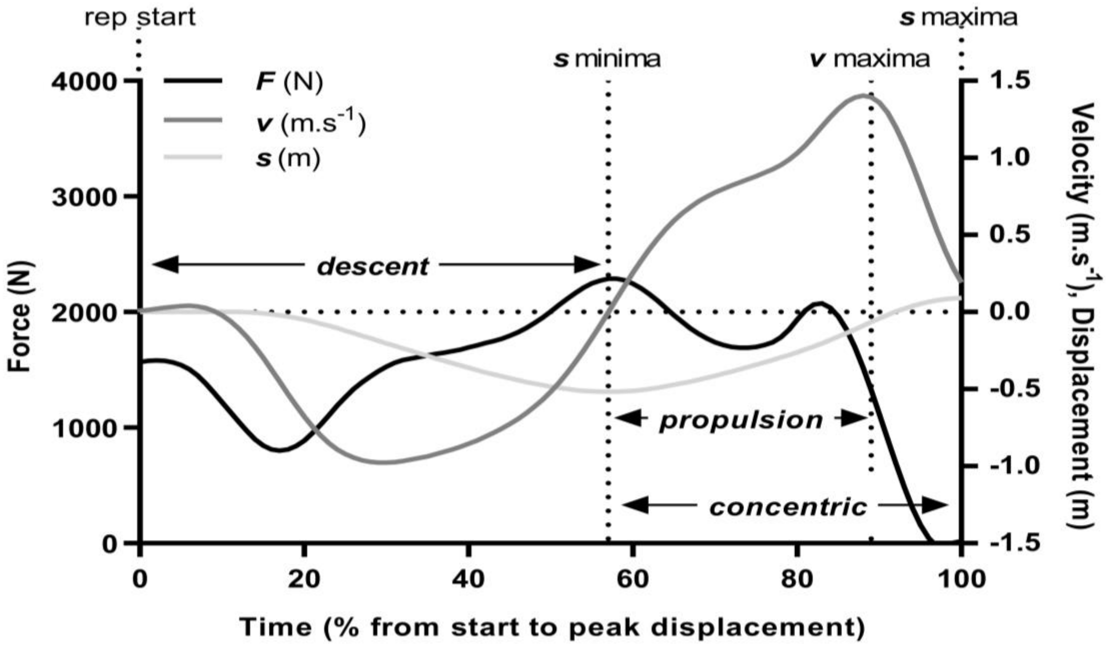

Figure 2. Key phases of a non-ballistic exercise (back squat) depicting the descent phase (onset of movement to displacement minima), propulsion sub-phase (displacement minima to velocity maxima – period of positive acceleration), and concentric phase (displacement minima to displacement maxima). The difference between the propulsion and concentric phase, therefore, is referred to as the braking phase (velocity maxima to displacement maxima – period of negative acceleration). *F* = Force; *v* = velocity; *s* = displacement.

Combining non-ballistic (e.g., back squat) and ballistic (e.g., jump squat) training has been shown as an effective method for improving power, RFD, and impulse (Cormie et al., 2010; Cormie, McCaulley, et al., 2007; Harris et al., 2000). Heavy, non-ballistic training stimulates the recruitment of fast-twitch muscle fibres as per the size principle (Bompa & Carrera, 2005). More explosive, ballistic exercise subsequently targets the firing frequency of the newly recruited type IIa and IIx fibres, improving the rate of force production (Bompa & Carrera, 2005). This suggests, that physiologically, strength training acts as the vehicle for eliciting changes required to develop an athlete's RFD, impulse and power.

When using kinetic and kinematic data to identify physical competencies, athleticism, and improvements following training blocks, coaches should select metrics that provide a clear picture of output (variables that provide immediate and clear feedback to an athlete such as velocity or power), drivers (variables that underpin neuromuscular function such as force), and strategy (variables to determine the strategy an individual employs to complete a task such as duration or displacement). For example, when analysing changes in impulse, coaches must consider the magnitude of force (driver) and the time it takes to apply that force (strategy) to fully understand whether the increase in output has been derived from improvements in neuromuscular function or simply a change in strategy. By clarifying how improvement in mechanical output occur, practitioners can make informed programming decisions to improve specific facets of an athlete's sporting performance.

2.4 Force-velocity relationship

The interaction between force and velocity has important implications for S&C practitioners. As previously described, cycling through high-force and high-velocity training blocks can be effective for improving neuromuscular function (Cormie, McCaulley, et al., 2007; Haff & Nimphius, 2012). The force-velocity relationship can therefore be used as an amenable performance diagnostic or programming tool for coaches to utilise.

2.4.1 Theoretical underpinning

First described by A.V. Hill in 1938, the relationship between force and velocity has been extensively researched over the past century (Bassett, 2002; Hill, 1938). Hill's fascination with heat production in muscle and its impact on mechanical and chemical changes led to central physiological discoveries, including the role of ATP and phosphocreatine (PCr) in muscle action and the description of aerobic and anaerobic metabolism, with which he was awarded the coveted Nobel Prize in 1922 (Bassett, 2002; Hill & Lupton, 1922, 1923; Hill & Meyerhof, 1923; Hill, 1922).

Arguably Hill's most famous discovery, the two-compartment model, demonstrates the series-elastic (lengthening) and 'contractile' (shortening) properties of active muscle and their distinct relationships with force (figure 3) (Hill, 1938). Building on earlier work that revealed greater heat production during concentric vs. isometric actions (Bassett, 2002; Fenn & Marsh, 1935; Fenn, 1923, 1924), Hill observed a proportional vs. continuous rise in temperature during shortening and stationary muscle lengths, respectively. This proportional rise permitted a constant measurement of velocity through increases in rate of temperature and prompted Hill to develop a mathematical equation helping to explain these muscle mechanics:

$$(\boldsymbol{force} + \boldsymbol{a})(\boldsymbol{velocity} + \boldsymbol{b}) = (\boldsymbol{force_{max}} + \boldsymbol{a})\boldsymbol{b}$$

eq.14

where $\boldsymbol{a}$ and $\boldsymbol{b}$ are constants representing changes in heat respective to changes in force and velocity. This equation has helped scientists describe the inverse, rectangular hyperbolic relationship between force and velocity, distinguish slow-twitch vs. fast-twitch muscles and determine peak power from force-power curves (Bassett, 2002; Cormie et al., 2011a). The finite amount of time available for cross-bridge cycling to occur has been theorised as the primary explanation for this relationship. As shortening velocity increases, the time available for cross-bridges to form reduces, limiting force production (Alcazar et al., 2019; Cormie et al., 2011a; Gulch, 1994).

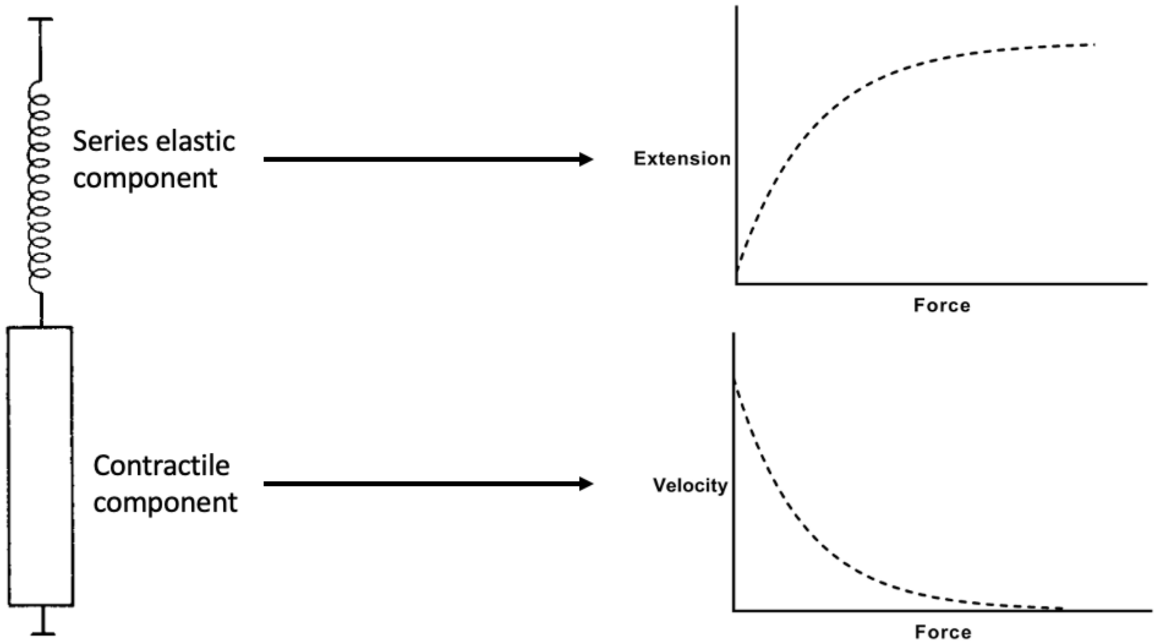

Figure 3. Hill's 2-compartment model of contracting muscle, showing the "series elastic" and contractile components. The force-velocity curve defines the properties of the contractile component, whereas the force-extension curve defines the properties of the series elastic component. Reproduced from Bassett (2002).

The discoveries by Hill (1938), despite being ground-breaking, have since been challenged. Firstly, Hill proposed the ratio of a/force$_{max}$ indicated the curvature of the force-velocity relationship, and was a fundamental constant of all humans (Hill, 1940). Later studies, however, reported that a/force$_{max}$ could vary at different muscle lengths, temperatures and excitation levels, as well as between individuals (Abbott & Wilkie, 1953; Bigland & Lippold, 1954; Close, 1964; Katz, 1939; Wilkie, 1949). Secondly, it was suggested that the full force-velocity curve deviated away from a single rectangular hyperbola, indicated by large prediction errors of force$_{max}$ (e.g., 20-32% higher than measured isometric force$_{max}$) (Alcazar et al., 2019; Devrome & MacIntosh, 2007; Edman et al., 1976). In fact, it has been proposed that the relationship at moderate to high forces (40% to 100% $force_{max}$) adopted a separate second hyperbola, making the full force-velocity profile double hyperbolic (Alcazar et al., 2019):

$$\boldsymbol{V = \frac{(Force_{max} - Force)b}{Force + a}\left(1 - \frac{1}{1 + e^{-k_1(Force - k_2 Force_{max})}}\right)}$$

eq.15

where the first term expresses the force-velocity relationship at low and moderate forces (< 78% $force_{max}$) based on previous research (Edman, 1988a, 1988b) and $force_{max}$ is the isometric force predicted from Hill's equation; and the second term modifies the force-velocity relationship at high forces (> 78% $force_{max}$), with k_1 and k_2 as constants to determine the degree of curvature and point of transition, respectively. Simply, the first term corresponds to Hill's original equation, with the second being a correction term to reduce velocity at very high forces during single-joint or isolated muscle actions (Alcazar et al., 2019; Edman, 1988b).

Research has highlighted the shape of the force-velocity curve for multi-joint actions (e.g., back squat or bench press) adopts more of a linear profile (Bobbert, 2012; Jaric, 2015; Zivkovic et al., 2017). This is thought to be due to variation in muscle lengths, pennation angles, fibre orientation, and cross-sectional areas (Samozino, Rejc, et al., 2014). Furthermore, the length-tension relationships of the active muscles also vary, stimulating different magnitudes of force and velocity throughout a task which, when summated, have been suggested to create the linear shape (Bobbert, 2012; Jaric, 2015; Samozino, Rejc, et al., 2014).

Despite this suggested linear profile of multi-joint actions, Alcazar et al., (2021) observed curvilinear relationships between 40% and 100% $force_{max}$ in the leg press and bench press exercises, suggesting that multi-joint actions could be better fitted with double hyperbolic models similar to single-joint actions. Potential reasons for this might be due to detachment rate, force decline per cross-bridge does not occur at a linear rate, and that attachment rate is not independent from shortening velocity (Piazzesi et al., 2007; Seow, 2013). Understanding the statistical relationship between force and velocity can therefore have practical implications for practitioners wishing to use the profile as training tool.

2.4.2 Practical applications

Irrespective of the mathematical model applied to force-velocity data, the practical importance of the relationship is clear for S&C practitioners. Force-velocity profiling can be utilised as a diagnostic tool to monitor training (Colyer et al., 2018; Iglesias-Soler et al., 2017; Jiménez-Reyes, Samozino, Brughelli, et al., 2017), individualise training prescription (Jiménez-Reyes, Samozino, Brughelli, et al., 2017; Morin & Samozino, 2016; Simpson et al., 2021) and predict theoretical maxima (e.g., power, velocity, and force) (Jiménez-Reyes, Samozino, Pareja-Blanco, et al., 2017; Junge et al., 2021; Pérez-Castilla & García-Ramos, 2021; Samozino et al., 2008). Moreover, it has been posited that assessing force-velocity characteristics is a more valid representation of an individual's physical capabilities than a single measure of power, jump height, or sprint time, for example (Jiménez-Reyes, Samozino, Pareja-Blanco, et al., 2017; Morin & Samozino, 2016; Samozino et al., 2012).

The aim of training based on force-velocity profiling is to optimise load prescription and when combined with appropriate exercise choice, can enable the athlete to develop the physical qualities that underpin sports performance (e.g., impulse, RFD, and power) (Simpson et al., 2021). Force-velocity data can be used to identify whether an individual is more force or velocity dominant based on the computation of an 'optimal' profile (Samozino et al., 2014; Samozino et al., 2008, 2012) or predict an individual's 1RM through predictive equations

(Picerno et al., 2016; Sandau et al., 2021).

2.5 Technology for measuring force and velocity

The assessment and monitoring of resistance (e.g., pushing, pulling, squatting etc.) or sport (e.g., sprinting, throwing, jumping etc.) specific tasks often require the use of technology (McMaster et al., 2014). The utilisation of devices such as force plates, motion analysis cameras, position transducers, and accelerometers provide practitioners with comprehensive data to profile athletes and effectively influence programming (McMaster et al., 2014). Nevertheless, identifying the most appropriate technology for different environments can be challenging due to data quality (e.g., reliability and validity), cost, useability, and accessibility.

2.5.1 Laboratory-based technology

Laboratory-based technologies are typically considered the "gold standard" and used as the criterion measure for athlete testing and monitoring. For example, analysing ground reaction forces can help to identify mechanical strengths and weaknesses, and provide practitioners with information on how to individualise training, as well as ensure data collection is valid and reliable (Burden, 2019; Newton, 1687; Sewell et al., 2013). By calculating mean, mean net, or peak force, all other variables can be derived through integration (e.g., velocity from acceleration data with respect to time), typically using the trapezoid method (summing the area under a curve (integration) via a series of trapezoids) (Mundy et al., 2016; Owen et al., 2014; Turner et al., 2020). Importantly, when utilising force plate data solely, only kinetic and kinematic data representative of the centre of mass (CoM) can be measured (Mundy et al., 2016). If, however, coaches are interested in barbell metrics, additional technology must be integrated (e.g., camera systems or LPTs), meaning variables are differentiated (i.e., multiplied), which can amplify noise and require additional data manipulation (e.g., filtering or smoothing), potentially introducing additional error (Cormie, Deane, et al., 2007; Cormie, McBride, et al., 2007; Dugan et al., 2004; Mundy et al., 2016; D. Winter, 2009). Additional measurement error could impact testing and monitoring data, influencing athlete evaluations, programming choices, or selection.

Force plates are considered criterion due to their multi-planar (medial-lateral (*Fx*) anterior-posterior (*Fy*) and vertical (*Fz*)) measurements, excellent validity and reliability, and sophisticated technology (e.g., strain-gauge or piezoelectric) (Chockalingam & Healy, 2018; Laza-Cagigas et al., 2019). Important considerations when standardising force plate procedures include vertical force range (≥ six times body weight), sampling frequency (typically 1000 Hz), method of integration (trapezoid or Simpson's rule), determination of body weight (one second of quiet standing), and detecting the initiation of movement (five times standard deviation of body or system weight) (Chavda et al., 2020; Dos'santos et al., 2018; Guppy et al., 2021; Owen et al., 2014). Applying this strategy can reduce error to < 1% whilst improving workflow efficiency through automated thresholds and procedures (Chavda et al., 2020; Owen et al., 2014).

Three-dimensional (3D) motion capture, another sophisticated and "gold standard" method of human measurement, permits in-depth kinematic analysis by determining 3D coordinates of an individual within space (e.g., combining retroreflective markers (ranging from 3 to 30 mm in diameter) and infra-red cameras (typically 6-12)) (Bernardina et al., 2019; Cole, 2019; Ford et al., 2007; Myers et al., 2017). Commonly found in biomechanics laboratories (Papić et al., 2004), its popularity stems from relatively short and automated post processes (Cole, 2019), high 3D reconstruction accuracy (1:10,000) (Bernardina et al., 2019), small measurement error (< 1 mm) (Bernardina et al., 2019; Dorrell et al., 2019; Windolf et al., 2008), and high repeatability (> 0.9 ICC, < 5% CV) (Appleby et al., 2019; Dorrell et al., 2019; Ford et al., 2007). Performance of motion capture systems and quality of data are highly dependent on a sophisticated set-up (e.g., camera configuration, video-digital conversion, calibration, camera resolution etc.) (Eichelberger et al., 2016; Windolf et al., 2008), but can provide practitioners with in-depth analysis of human movement, biomechanical strategies for completing a task (e.g., weightlifting), and kinematic data designed to improve performance and reduce injury risk.

Laboratory-based testing can be utilised within S&C to provide coaches with accurate and reliable data to help inform practice. Nevertheless, the practical restrictions of such approaches might make this more challenging in the field. The high associated costs of force plates and 3D motion cameras can often render their usage unattainable for many sporting organisations. Lengthy set-up and calibration procedures can also make the application of such equipment logistically challenging, particularly when utilising with large squads or groups of athletes. As a result, technology companies are constantly trying to develop new and innovative tools for accurate, cost-effective, and portable field-based data collection.

2.5.2 Field-based technology

2.5.2.1 Linear position transducers

Linear position transducer (LPT) technology is manufactured using stainless steel measuring cables tightly wound around a spool that turns when the cable extends and retracts (Harris et al., 2010). The spool is connected to a sensor (e.g., potentiometer or encoder) which generates an electrical signal proportional to the velocity of the object attached to the cable (Harris et al., 2010). Simply, an LPT measures cable displacement and time, differentiating velocity and acceleration via the finite central difference technique (Hamill et al., 2014;

Weakley et al., 2021):

$$v_{average} = \frac{s^2 - s^1}{t^2 - t^1}$$

eq.16

$$a_{average} = \frac{v^2 - v^1}{t^2 - t^1}$$

eq.17

Once acceleration is calculated, all other variables of interest can be determined based on Newton's second law (Newton, 1687). As previously described, when calculating first order (e.g., velocity) and second order (e.g., acceleration) derivatives, noise will be amplified and therefore additional filtering or smoothing (e.g., moving averages or Butterworth order filters) is required to remove error (Harris et al., 2010). Signal noise could therefore impact training recommendations as practitioners would be using data that is not reflective of an individual's true capacities and unreliable across multiple sessions.

There are many commercially available LPTs (e.g., Gymaware, Tendo, T-Force etc.), all with nuanced configurations, costs, and data quality (Weakley et al., 2021). Gymaware is typically the most researched LPT (Weakley et al., 2021), demonstrating high validity when compared to 3D motion capture or a custom four-LPT rig (ICC: > 0.97 ; correlation coefficient (*r*): > 0.94; CV: < 8.0%; R^2: > 0.85) and high inter and intra-session reliability (ICC: > 0.58-0.91; typical error (TE): 0.6-8.8%; *r*: 0.70-0.99; standardised mean difference (SMD): 0.00-0.56) (Askow et al., 2018; Banyard, Nosaka, Sato, et al., 2017; Beckham et al., 2019; Dorrell et al., 2019; Drinkwater et al., 2007; Lorenzetti et al., 2017; Mitter et al., 2021; Orange, Metcalfe, Marshall, et al., 2020). Other LPT devices also have favourable validity and reliability such as Tendo (validity = CV: 1.0-4.1%; ICC: 0.85-0.99; reliability = CV: 2.0-13.2%; ICC: 0.56-0.98; standardised error of the mean (SEM): 3.1-12.6%), T-Force (validity = bias: -0.01 ± 0.03 $m.s^{-2}$; reliability = CV: 0.44-4.9%; ICC: 0.87-1.00) and Chronojump (validity = bias: -0.03 ± 0.03 $m.s^{-2}$; CV: 2.8-1.6%; ICC: 0.98-1.00; reliability = 0.8-6.4%; ICC = 0.72-1.00). These data suggest LPTs could be utilised by S&C coaches to effectively assess and monitor athletes within a training environment.

The strong validity and reliability of LPTs has prompted researchers to use them as criterion measures (Chéry & Ruf, 2019; Courel-Ibáñez et al., 2019; García-Ramos, Pérez-Castilla, et al., 2018; Garnacho-Castaño et al., 2014; Goldsmith et al., 2019; Martínez-Cava et al., 2020; McGrath et al., 2018; Pérez-Castilla, Piepoli, Delgado-García, et al., 2019; Stock et al., 2011). Whilst this presents simpler data collection than using more complex technology such as 3D motion capture, it is likely to add erroneous data into the dataset. For example, if two LPTs over-estimate a variable (e.g., mean velocity) by 10%, the systematic bias between these two devices would be minimal, but against a true criterion such as 3D motion capture, this error would be apparent, resulting in two very different conclusions. Therefore, it is important for practitioners to consider the research design (e.g., the criterion measure, participant information etc.) when utilising literature to inform decisions on which technology to purchase.

As LPT's are cable-based devices, they are primarily limited to barbell exercises, with some offering the options of waist-belts for body weight jump exercises. Secondly, tether placement is important to maximise reliability and validity of the data (Appleby et al., 2020; Dorrell et al., 2019). Dorrell et al. (2019) found poor agreement between the Gymaware and 3D motion capture when measuring displacement during the deadlift, surmising that the difference observed could have been due to the counteraction between tension and flexion simultaneously placed at the central and proximal parts of the barbell, respectively. Similarly, Appleby et al. (2020) found greater error in barbell displacement as tether placement moved more proximal (mean bias: central = 0.9-1.5%; right = 7.3-11.2%; left = 4.9-7.3%). This was again attributed to potential flex or "whip" in the barbell when lifting heavy loads. Coaches, therefore, must be aware of common issues when using LPTs, particularly during exercises when tether placement cannot be central to the barbell. On the other hand, LPTs provide coaches with a smaller, more cost effective, and portable device to analyse human movement compared to the more traditional lab-based approaches.

2.5.2.2 Inertial measurement units

Inertial measurement units (IMUs) are considered alternatives to LPTs due to their simple set-up, small footprint, portability, and low cost (O'Reilly et al., 2018; O'Reilly et al., 2017b). IMU technology typically combines accelerometery, magnetometry, and gyroscopic sensors to determine motion, 3D coordinates, and orientation (O'Reilly et al., 2018; O'Reilly et al., 2017a). This type of equipment uses Bluetooth technology, machine learning techniques, and sophisticated signal processing methods to provide information to the end-user (Veiga et al., 2017).

There are several commercially available IMUs within the field of S&C (e.g., PUSH, Beast, Bar Sensei, Output Sports), all with varying reliability and validity. PUSH presents mixed validity (ICC: 0.92; CV: 3.4-38.5%; TE: 7.2-14.0%; mean difference (MD): 5.0-14.0%) and reliability (CV: 5.0-19.1%; ICC: 0.27-0.98; *r*: 0.95-0.96) data across several research studies (Balsalobre-Fernández et al., 2016; Banyard et al., 2017; Chéry & Ruf, 2019; Courel-Ibáñez et al., 2019; Lake et al., 2019; McGrath et al., 2018; Orange et al., 2019; Pérez-Castilla et al., 2019; Sato et al., 2015). Poorer data quality, however, can be offered from alternative IMUs such as Bar

Sensei (validity = SEE: 0.03-0.17 $m.s^{-2}$; ICC: 0.30-0.55; reliability = CV: 14.2-43.8%; ICC: 0.17-0.45) and Beast Sensor (validity = SEE: 0.04-0.18 $m.s^{-2}$; reliability = CV: 24.2-54.9%; ICC: 0.27-0.64) (Abbott et al., 2020; Balsalobre-Fernández et al., 2017; Beckham et al., 2019; Mitter et al., 2021; Pérez-Castilla et al., 2019). The conflicting reliability and validity data across IMUs could be a result of algorithm sophistication, device placement (wrist vs. forearm), lower sampling frequencies, or malalignment between device (wearable) and barbell movement path (Abbott et al., 2020; Beckham et al., 2019; Pérez-Castilla, Piepoli, Delgado-García, et al., 2019) Practitioners, therefore, must be cognisant of the reliability and validity of devices prior to purchasing to ensure the data provided is trustworthy and can be utilised confidently to influence programming decisions.

In addition to the benefits of cost, portability, and ease of use, IMU technology is wearable (e.g., on the forearm), offering flexibility regarding the type of exercise and equipment being utilised (e.g., dumbbells), regular software updates, and artificial intelligence and machine learning, permitting the creation of solutions to bespoke problems. Nonetheless, IMUs can suffer from connectivity issues which can often result in erroneous data or missed repetitions. In addition, 'black-box technology' can limit a coach's understanding of specific calculations, filtering systems, and data smoothing techniques (Lake et al., 2019).

2.5.2.3 Smartphone applications

Smartphone applications offer a cheaper and potentially more accessible alternative to LPTs and IMUs for measuring mechanical variables such as velocity. Rapid developments in phone and tablet technology (e.g., camera quality, accelerometery etc.) has enabled the creation of unique applications able to track human movement. Typically, smartphone applications such as MyLift or iLOAD require initial measurements of the distance a barbell will travel for given exercises prior to completing the task, followed by retrospective analyses of video whereby the start and end frames are identified to calculate velocity.

The most common and researched smartphone application is the MyLift app (formerly PowerLift) (Weakley et al., 2021) and has demonstrated good validity (CV: 7.0-11.7%; ICC: 0.93-1.00; *r*: 0.94; SEE: 0.03-0.05 $m.s^{-2}$) and reliability (CV: 5.02-10.4%; ICC: 0.97-0.99) (Balsalobre-Fernández et al., 2017; Balsalobre-Fernández, Marchante, et al., 2018; Courel-Ibáñez et al., 2019; Martínez-Cava et al., 2020). The low cost (e.g., £9.99), accessibility, and data quality make applications an attractive alternative for practitioners. A major drawback, however, is the inability to provide live feedback due to the retrospective nature of the calculations, limiting the opportunity to enhance acute performance through augmented feedback and motivation.

Technology is an integral tool to aid S&C coaches with athlete performance diagnostics and prescription as it is possible to gain reliable and valid data immediately for analysis and live feedback. Field-based technological choices are often dictated by factors such as reliability and validity, budget, portability, user-interface, portal availability, and ease of use. Whilst laboratory-based technology is considered the gold-standard, the high associated costs and limited portability can negatively impact their accessibility and practical representativeness due to laboratory-based settings. Coaches, therefore, might compromise on data quality for more portable, lower-cost, and user-friendly technology such as LPTs or IMUs.

2.6 Load prescription

The interaction between programming and periodisation is vital to optimise physiological adaptations (Cunanan et al., 2018). Acute programming can organise the delineated stages of training designed to meet specific goals of periodisation (Cunanan et al., 2018). Optimising the prescription of load – traditionally defined as an RM target or as a % 1RM – can help to regulate accumulative fatigue and facilitate the desired physiological adaptations through exposure to appropriate stimuli, contributing to the effective physical preparation of athletes (Bird et al., 2005; Iversen et al., 2021). With many load optimisation strategies available to S&C coaches, selecting the most appropriate one to ensure prescriptive accuracy is important during phases of specific preparation and competition.

2.6.1 Periodisation

Periodisation is a systematic method of manipulating fitness and recovery based on pre-determined goals, designed to progressively improve the potential for competitive success and minimise injury risk (Stone et al., 2021). Periodisation combines micro (e.g., one week) and meso (e.g., four to six weeks) training cycles of general and specific training to create a macro (e.g., > 3 months) plan (DeWeese et al., 2015a, 2015b; Turner, 2011). The systematic strategy of periodisation manages physiological adaptations, often generating superior physical (e.g., strength and hypertrophy) and performance (e.g., jumping and sprinting) improvements when compared to non-periodised interventions (Cunanan et al., 2018; Issurin, 2008; Pliauga et al., 2018; Prestes et al., 2009; Rhea, Phillips, et al., 2003; Stone et al., 2021). Periodisation is therefore considered an integral part of the training process, providing a theoretical framework with which programming can occur (Williams et al., 2017).

'Traditional' or 'Linear' periodisation is based on the GAS first conceptualised by Hans Selye in 1936. GAS depicts an organisms three-stage response to stress (alarm, resistance, and exhaustion phases), but has more recently been applied to the response to training stressors (Cunanan et al., 2018; Selye, 1936). Linear periodisation is based on the simultaneous training of physical qualities combined with simple reductions in repetitions (or volume) over time that is proportional to increases in intensity (load) (Stone et al., 2021). This simplistic overview of training has been criticised, however, suggesting adaptations more likely occur non-linearly, with oscillations in load being more pertinent to the supercompensation theory (Stone et al., 2021; Viru, 2002; Yakovlev, 1975).

The seemingly simplistic model of traditional periodisation has its limitations. The single "peak" in performance often does not marry with modern competition schedules, with most sports typically competing more frequently or across longer periods (e.g., 3+ weeks) (DeWeese et al., 2015a). This is exaggerated in team and court sports, whose competitive schedules can last the majority of the calendar year (Stone et al., 2021). Additionally, increasing the volume of multiple training variables can create residual central and peripheral fatigue, requiring increased recovery time and potentially reducing the effectiveness of training (e.g., interference effect) (DeWeese et al., 2015a). As a result, coaches and researchers have developed alternative methods of periodisation to account for these drawbacks.

Single-factor block periodisation has been proposed as a suitable alternative to the traditional model (Verkhoshansky, 1979, 1988) as it permits the development of a single or few closely related training variables in blocks of 'concentrated loading', typically lasting 6-12 weeks (DeWeese et al., 2015b; Issurin, 2008; Issurin, 2016; Stone et al., 2021). Utilising the "long-term lagging training effect", initial declines in physical performance from the stress-response to training, followed by subsequent enhancements (e.g., supercompensation) is generated through phasic variations in volume and load (Issurin, 2008; Issurin, 2016). The magnitude of decline in physical performance, however, can sometimes be hard to differentiate from overreaching and overtraining (Issurin, 2008). Additionally, one full single-factor block periodised cycle was designed to last 22-26 weeks, permitting just two ‘peaks’ within a calendar year, and thus not being too far removed from traditional methods. As a result, multi-targeted block periodisation was developed to utilise smaller blocks of concentrated loading (DeWeese et al., 2015a, 2015b; Issurin, 2008). Exploiting phase potentiation, this approach contains three repetitive phases: accumulation (general development of global adaptations), transmutation (specific development of sporting qualities), and realisation (taper and recovery for competition) (DeWeese et al., 2015b; Issurin, 2008). Lasting approximately two months, these cyclical blocks allow for much more flexibility in the number of peaks within a training season. As with all periodised approaches, however, detecting acute fluctuations in strength and fatigue can be challenging during multi-targeted block methods.

Periodisation facilitates the medium and long-term planning of training but has been conceptually questioned in recent years (Buckner et al., 2017, 2020; Kiely, 2018; Mattocks et al., 2016). It has been suggested that the strict “rules” of periodisation might not reflect the complex intersectionality of sport, training, and the individual (Buckner et al., 2017; Kiely, 2018; Mattocks et al., 2016). Specifically, stress and other non-training factors can affect an individual’s ability to produce consistent high performance and could therefore present the risk of overtraining and injury through improper prescriptions (Kiely, 2010, 2012, 2018). Irrespective of these criticisms, long-term planning through systematic and progressive practices is an essential component of effective S&C. Perhaps, failings to achieve initial goals, injury, and non-functional overreacting or overtraining are the result of improper micro-management of training variables (programming) as opposed to macro-management of training phases (periodisation).

2.6.2 Programming

Programming can be defined as the micro-management of the delineated stages of periodisation (Cunanan et al., 2018; Stone et al., 2021). Specifically, programming involves the organisation of acute training variables (e.g., volume, load, rest, exercise, exercise order, and frequency) across the course of a training phase or block (Cunanan et al., 2018; Stone et al., 2021). The distribution of these variables will be dictated by the periodisation model, phase of training, training history, sport, and level of competition (DeWeese et al., 2015a). Effective programming can combat fatigue and reduce the risk of reversibility, unwanted psychological stress, and risk of injury (DeWeese et al., 2015a). The acute planning of training variables, therefore, must adhere to training principles, including individualisation, variation, specificity, and progressive overload (Turner, 2011).

As previously mentioned, effective load prescription is vital to optimise physiological adaptations and performance (Bird et al., 2005). The most common and popular method for prescribing load is using % 1RM and typically contains a two-stage process: 1) baseline incremental 1RM protocol to determine an individual's maximum strength; and 2), prescribe submaximal 1RM percentages corresponding to a desired physiological adaptation (e.g., 90% 1RM to increase motor unit recruitment, rate coding, and intra- and intermuscular coordination) (Folland & Williams, 2007; Suchomel et al., 2018, 2021).

The 1RM is a reliable method for assessing maximum strength in different exercises and demographics (e.g., professional, youth, older adults etc.) (McMaster et al., 2014). CVs < 5.0%, ICCs > 0.9, smallest detectable differences < 6.0 %, and SMDs < 0.2 have been reported across experienced and inexperienced men and women in exercises such as back squat, power clean, bench press, deadlift, and leg press (Benton et al., 2013; Comfort & Mcmahon, 2015; Ruf et al., 2018; Washif et al., 2021). It is also a more practical assessment of strength compared to alternatives such as isometric and isokinetic testing due to the simplicity of post-test prescriptions, the dynamic nature of sport, and the isolated actions of such protocols.

Despite the reliability of the 1RM assessment, prescribing session or weekly load as a percentage of this number can be problematic, particularly in sports with regular fixtures, lots of travel, or other training priorities. An individual's 1RM fluctuates regularly and can be affected by changes in physiological or psychological status (Bartholomew et al., 2008; Moore & Fry, 2007). Moreover, maximum strength can fluctuate as a result of fatigue, sleep, stress, training phase, and nutrition (Cribb et al., 2007; Enoka & Duchateau, 2008; Lopes Dos Santos et al., 2020; Reilly & Piercy, 1994) (figure 4). Strength adaptations can also occur mid-intervention, reducing the efficacy of subsequent prescriptions from baseline 1RMs.

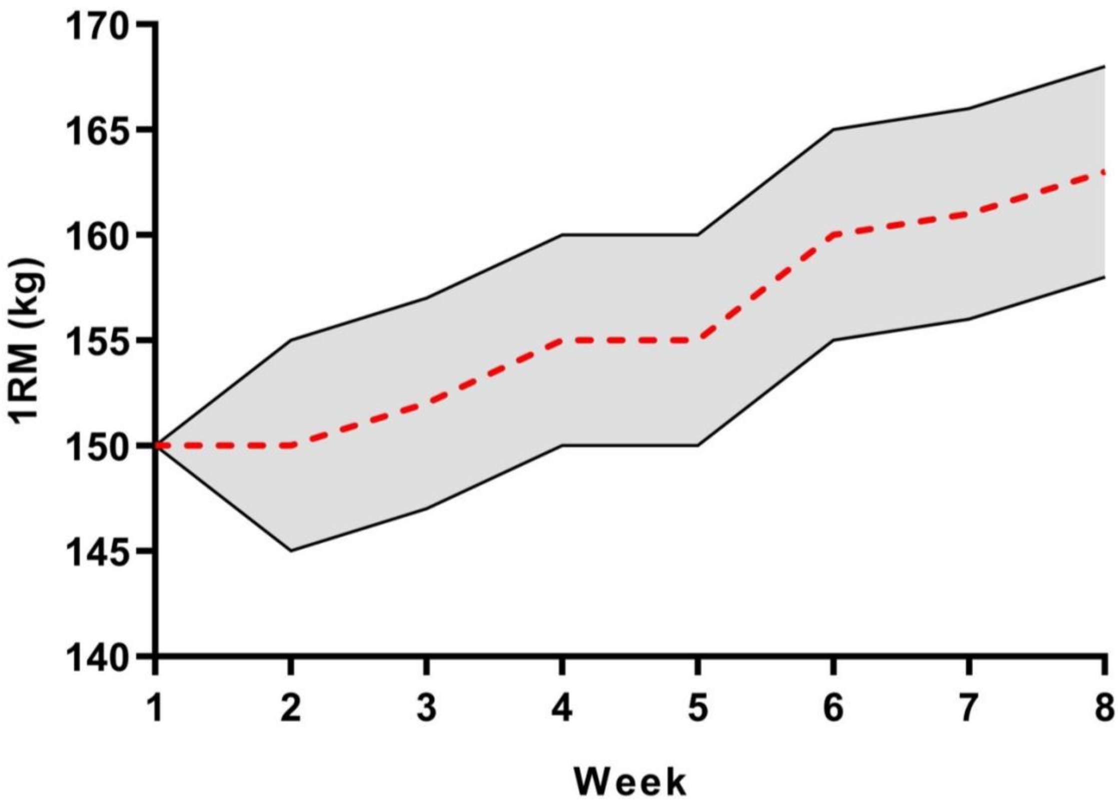

Figure 4. Theoretical example of the weekly fluctuations that could occur across the course of a training intervention. (---) indicates the planned increase in 1RM, with the shaded area indicating the theoretical range 1RM could fluctuate because of confounding variables.

When prescribing load via % 1RM, repetition targets must also be prescribed, with common load-repetition continuums being developed to assist S&C practitioners (Sheppard & Triplett, 2016). Nevertheless, the load-repetition continuum can be highly individual, creating challenges when manipulating volume-load across the course of a training block (Suchomel et al., 2021). For example, significantly more repetitions ($p < 0.05$) were performed in weightlifting vs. endurance athletes in the leg press at 70% (17.9 vs. 39.9), 80% (11.8 vs. 19.8), and 90% (7.0 vs. 10.8) 1RM, in addition to wide ranges of repetitions reported in the bench press at 70% (11-20), 80% (5-15), and 90% (2-7) 1RM (Julio et al., 2012; Richens & Cleather, 2014). Additionally, exercise type, age, sex, and training status have all been reported to affect the number of repetitions performed by individuals (Hoeger et al., 1990; Shimano et al., 2006). The interindividual demands of training must, therefore, steer and shape programming to optimise training and physiological adaptations.

RM targets or zones are often used by practitioners as alternatives to % 1RM. Proponents of this method argue it accounts for some of the challenges faced when using % 1RM given the athlete self-selects loads that achieve particular repetition ranges which can increase prescriptive flexibility and account for an individual's physiological status and inter-individuality of repetition ranges (Campos et al., 2002; Carroll, Bernards, et al., 2019; Suchomel et al., 2021). Nevertheless, a key shortcoming of this approach is the requirement to train to failure when meeting the repetition target (Painter et al., 2012). Indeed, irrespective of the load, training sessions become maximal, risking neuromuscular fatigue and impairing responses to recovery management, potentially culminating in non-functional overreaching or overtraining (Bell et al., 2020; Peterson et al., 2005). It is important that practitioners understand and account for the shortcomings of prescriptive strategies appropriately to maximise the efficacy of programming, perhaps seeking additional methods to account for these restrictions.

2.7 Autoregulation

Autoregulation is the process of acutely manipulating training variables (e.g., load, volume, frequency etc.) to coincide with an individual's response to training or non-training stressors (Greig et al., 2020). A training system originally credited to Dr. Thomas DeLorme in the 1940's (DeLorme, 1945), and later developed by Kenneth Knight in the 1970's (Knight, 1979), autoregulation attempts to account for the accumulation of fatigue whilst reducing the impact of training residuals by individualising prescriptions on a session-to-session or week-to-week basis (Greig et al., 2020; Mann et al., 2010). Practitioners can utilise subjective or objective strategies when autoregulating, manipulating training in response to the individual's physiological status via a system that seeks to reduce the chance of human error (Greig et al., 2020; Helms et al., 2020).

2.7.1 Subjective strategies (ratings of perceived exertion)

Rating of perceived exertion (RPE) is a simple method of autoregulation. Originally created by Gunnar Borg in the 1970s for endurance exercise (Borg, 1970, 1982), RPE is the subjective evaluation of perceived effort to complete a task and was designed as a complimentary tool to other objective physiological measures (Suchomel et al., 2021). RPE consists of a 6-20 weighted scale that corresponds specifically to heart rate and is the most commonly used, however, additional versions have been created to simplify the scale (e.g., CR10 1-10 scale) (Borg, 1982). Despite being intended for longer-duration exercise, RPE has more recently been applied to resistance training (Helms et al., 2016).

The OMNI-Resistance Exercise Scale (OMNI-Res) is a pictorial interfaced anchored version of the Borg CR10 scale and designed specifically for resistance training (Faulkner & Eston, 2008).

Practically, coaches could prescribe self-selected loads based on the OMNI-Res Sliding Zone System (i.e., 3 for muscular endurance, 6 for hypertrophy and 9 for maximal strength), followed by an RPE (e.g., 8), to determine the number of repetitions and proximity to failure (10 being volitional failure) (Helms et al., 2016; Lagally et al., 2009). RPE scales such as the OMNI-Res have demonstrated a linear relationship between ratings of exertion and load (i.e., as load increases, so does RPE), small between-session differences in loads lifted at the same RPE (ES < 0.21), and agreement between the scale and load selection (% 1RM) using the Sliding Zone System (e.g., RPE 3 = 50-56% 1RM, RPE 6 = 69-74% 1RM, RPE 9 = 88-90% 1RM) (Lagally et al., 2009; Lagally & Amorose, 2007; Pincivero et al., 2002). Nevertheless, despite acceptable concurrent and construct validity (r = 0.79-0.97) and good reliability (ICC = 0.69-0.95) (Lagally et al., 2009; Lagally & Robertson, 2006; R. Robertson et al., 2003), RPE is not without limitations. Several studies have reported sub-maximal ratings of perceived exertion when using 1-10 scales despite training to failure across multiple loads (Hackett et al., 2012; Pritchett et al., 2009; Shimano et al., 2006). In fact, participants were able to predict the number of repetitions remaining more accurately than rate their perception of effort, prompting the creation of the repetitions in reserve (RIR) scale (Hackett et al., 2012; Zourdos et al., 2016).

Perception of exertion was originally defined as the “the feeling of how heavy, strenuous and laborious exercise is” (Borg, 1962), but later extended to “the subjective intensity of effort, strain, discomfort, and/or fatigue that is experienced during physical exercise” (Noble & Robertson, 1995). These broad definitions leave ratings of exertion open to several nuanced feelings (e.g., force, strain, fatigue, discomfort, motivation), each being interpreted differently be athletes (Pageaux, 2016). Additionally, from a neurophysiological perspective, peripheral afferent feedback such as increases in muscle acidosis or metabolites and central corollary discharge related to central motor command and activity have all been suggested as sensory mechanisms to rating perceived exertion (Amann et al., 2010; De Morree & Marcora, 2012; Marcora, 2009; Pageaux, 2016), all of which can be influenced by psychological and sociological factors (Noble & Robertson, 1995). The complexity of defining perception of effort and the variety of mechanistic influences on RPE could be reasons for its varied validity.

RIR is a reversed 1-10 weighted scale that estimates the perceived number of repetitions that could be performed before volitional failure (e.g., 0 = volitional failure, 9 = 1 repetition remaining etc.) (figure 5). (Greig et al., 2020; Helms et al., 2016). The RIR scale is a valid tool for predicting the proximity to failure in lower body exercise (e.g., front squat: RIR 1 = 0.09-0.19, RIR 4 = 0.71-0.86; hex-bar deadlift: RIR 1 = 0.21-0.25, RIR 4 = 1.00-1.09 – reported as difference between actual repetitions performed and predicted repetitions from RIR) (Odgers et al., 2021). RIR is also reliable for determining loads that correspond to a 1 RIR at different repetition schemes in the deadlift and bench press across two sessions (ICC = 0.95-0.99, CV = 2.7-6.2%) (Lovegrove et al., 2021). This data provides practitioners with a subjective method for autoregulating load and volume (Helms, Cross, et al., 2018; Lovegrove et al., 2021). Moreover, the cost-effective, and quick and easy application could make scales such as RIR highly popular with S&C coaches.

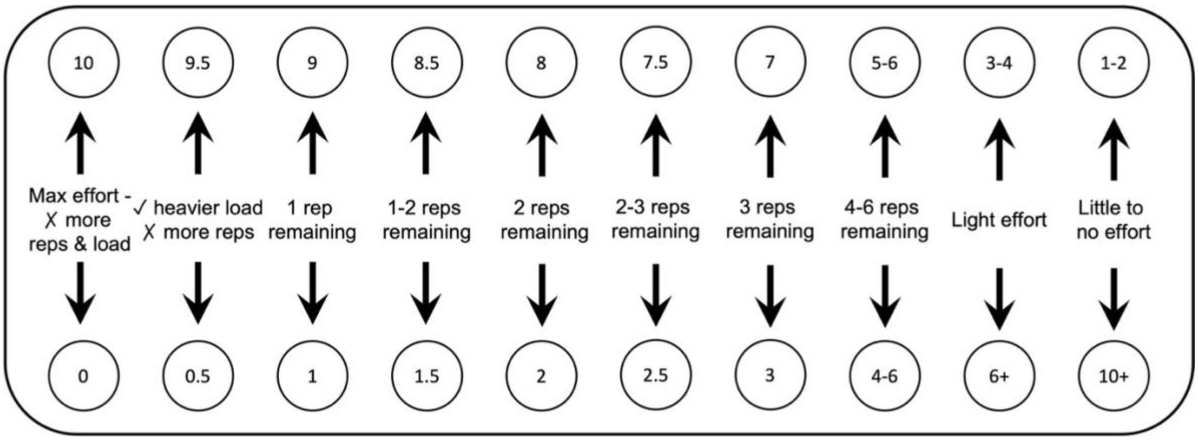

Figure 5. Rating of perceived exertion (RPE - top) vs. repetitions in reserve (RIR - bottom) scales adapted from (Greig et al., 2020).

RIR can facilitate greater strength improvements than 8-week daily undulating or 12-week (3 x 4-week mesocycles) fixed loading blocks when volumes, exercises, and relative intensities were all matched (Graham & Cleather, 2021; Helms, Byrnes, et al., 2018). Larger increases in bench press and squat (front and back) 1RMs have been observed when comparing RIR to % 1RM, both significantly (*P* = 0.004-0.006: η_p^2 = 0.23-0.26) (Graham & Cleather, 2021) and non-significantly (*p* > 0.05) (Helms, Byrnes, et al., 2018). In both studies, the RIR groups lifted a greater mean volume and/or intensity, across the course of the interventions, suggesting autoregulation occurred in line with increasing strength levels, potentially facilitating greater adaptations. The authors, however, identified the challenges with matching intensities across groups and accuracy of selecting loads based on RIR for the autoregulation group and identified future research with more experienced lifters was potentially warranted.

Despite research advocating the use of RIR, some challenges still exist. Lifter experience can affect rating efficacy as 71.4% of experienced and only 23.1% of non-experienced powerlifters reported RPEs of 10 (RIR 0) when performing 1RMs in the bench press (Ormsbee et al., 2019). Similarly, greater inaccuracies were evident the further away from failure RIR or RPE ratings occurred (5 RIR = 5.2 $\pm$ 2.9 repetitions vs. 1 RIR = 2.1 $\pm$ 1.7 repetitions) and when more repetitions were performed within a set (p < 0.05) (Zourdos et al., 2021). Similar neurophysiological issues might also exist when using RIR as when using RPE (Pageaux, 2016). Consequently, as the application of RIR might be limited to experienced lifters or moderate-to-low RIR ratings, it might be pertinent for practitioners to consider combining subjective autoregulatory practices with objective approaches, such as velocity measures or 1RM predictions.

2.7.2 Objective strategies

Adjusting and manipulating training variables such as load can be problematic when using a subjective tool. The very nature of subjectivity lends itself to human error, with individuals needing extensive training experience to fully understand and reliably implement subjective scales (Helms et al., 2020). Alternative objective strategies exist for coaches, however, and could be used to address some of the issues previously described regarding subjective approaches.

2.7.2.1 Protocols to failure

Adjusting resistance training load (kg) through a recalculation of an individual's maximum strength is a common method of autoregulation (Greig et al., 2020; Helms et al., 2020; McBurnie et al., 2019). The 1RM assessment can place stress on the neuromuscular system, and thus frequent administration might be undesirable in applied contexts due to increases in neuromuscular fatigue and impact on performance. Therefore, practitioners could use repetitions to failure (RTF) or as many repetitions as possible (AMRAP) protocols using submaximal loads to regularly recalculate an individual's 1RM based on simple predictive equations (Desgorces et al., 2010; Reynolds et al., 2006; Shimano et al., 2006).

Adjusted progressive resistance exercise (APRE) – an extension of the original progressive resistance exercise (PRE) (DeLorme et al., 1950) and updated daily adjusted progressive resistance exercise (DAPRE) (Knight, 1979, 1985) – is a method by which repetition maximums are utilised to adjust load based on an individual's physiological status (Mann et al., 2010). Like the sliding zone system of the OMNI-res scale, APRE adopts three separate protocols, dictated by desired training goals or physiological adaptations (Siff, 2000). When utilising APRE, 10RMs, 6RMs, or 3RMs are prescribed, initially performing 50% and 75% of the projected load for this target, followed by 100% in the third set. The number of repetitions performed in this third set dictates the load adjustment for the fourth and final set (Mann et al., 2010) (table 3). Whilst the efficacy of this method is under-investigated, when compared to traditional linear loading, larger increases in back squat, bench press, and hang clean maximum strength, in addition to bench press endurance performance, have been observed (Mann, 2011; Mann et al., 2010; Weber, 2015). Importantly, these protocols use a generalised approach to load adjustment and therefore might require trial and error over time to optimise the process.

Table 3. The applied protocol for adjusted progressive resistance exercise (APRE) (Mann et al., 2010).

Set	APRE 10	APRE 6	APRE 3
1	12 repetitions @ 50% 10 RM	10 repetitions @ 50% 6 RM	6 repetitions @ 50% 3 RM
2	10 repetitions @ 75% 10 RM	6 repetitions @ 75% 6 RM	3 repetitions @ 75% 3 RM
3	Repetitions to failure @ 10 RM	Repetitions to failure @ 6 RM	Repetitions to failure @ 6 RM
4	Repetitions to failure @ adjusted load	Repetitions to failure @ adjusted load	Repetitions to failure @ adjusted load

APRE 10		APRE 6		APRE 3	
3rd set reps	**Load adjustment**	**3rd set reps**	**Load adjustment**	**3rd set reps**	**Load adjustment**
4-6	↓ 2.5-5 kg	0-2	↓ 2.5-5 kg	1-2	↓ 2.5-5 kg
7-8	↓ 0-2.5 kg	3-4	↓ 0-2.5 kg	3-4	Maintain load
9-11	Maintain load	5-7	Maintain load	5-6	↑ 2.5-5 kg
12-16	↑ 2.5-5 kg	8-12	↑ 2.5-5 kg	7+	↑ 5-10 kg
17+	↑ 5-7.5 kg	13+	↑ 5-7.5 kg		

RM Repetition maximum, *reps* repetitions

A more individualised method of autoregulation is the implementation of predictive equations from RTF protocols, typically created from the inverse linear or exponential relationship between RTF and load (kg) (Desgorces et al., 2010; Macht et al., 2016; Reynolds et al., 2006). Many equations have been investigated in the literature, typically in the bench press exercise, and all with nuanced differences (Cummings & Finn, 1998; Desgorces et al., 2010; Horvat et al., 2003; Mayhew et al., 1992, 2002, 2008; Reynolds et al., 2006; Tucker et al., 2006). Importantly, the accuracy of predictive equations can vary largely, with reported CVs of up to 54.1% (Macht et al., 2016; Mayhew et al., 2002, 2008; Reynolds et al., 2006). This wide range of predictive validity and limited research across key lower body exercises questions the use of such equations due to the potential impact on their ability to optimise training prescriptions.

The use of RTF predictive equations or APRE could offer coaches a simple, cost-effective method to autoregulate load, however, the requirement to train to volitional failure could be of concern for practitioners. Training to failure can increase the time-course to recovery, as well as muscle damage, peripheral and central fatigue, potentially impacting readiness to train during subsequent training sessions (Davies et al., 2016; Morán-Navarro et al., 2017; Sundstrup et al., 2012). Additionally, the required RTF protocols to achieve valid predictions could limit their effectiveness. Lower repetition ranges and heavier loads (e.g., 3RMs) provide more accurate predictive equations than lighter loads, potentially facilitating a similar neuromuscular stress to a direct 1RM assessment (Mayhew et al., 2008; Reynolds et al., 2006). Practitioners must therefore consider these risks if implementing such strategies within their training practices.

2.7.2.2 Flexible programming

Criticisms of periodisation regarding its amenability has prompted the development of flexible programming to bridge between initial planning and autoregulation (Greig et al., 2020; Suchomel et al., 2021). First developed by Fleck & Kraemer (2007), FNLP follows the guidelines of daily undulating periodisation (DUP) and provides structured sessions across a training block that undulate in volume and intensity, but sequencing of those sessions is determined by the athlete based on measures of performance, perceived ability to perform, or factors such as motivation (Colquhoun et al., 2017; Fleck & Kraemer, 2007; Greig et al., 2020; McNamara & Stearne, 2010). The limited research on FNL provides mixed conclusions. Beginner college students significantly improved their leg press 1RM when following a 12-week FNLP programme compared to fixed DUP (p = 0.015) (McNamara & Stearne, 2010), whereas DUP was superior to FNLP for improving strength in competitive powerlifters, with a larger MSD for total strength increases (d = 0.58 vs. 0.42) (Colquhoun et al., 2017). Perhaps sample demographics (powerlifters vs. college students) across these two studies could account for the discrepancy in findings, with DUP being flexible enough to adjust load and monitor fatigue in a sport such as powerlifting (Colquhoun et al., 2017) where resistance training is the only modality used and the impact of extraneous variables (e.g., on-field training or regular competitions) can be controlled for.

FNLP relies on the athlete autonomously determining their fatigue status to dictate the sequence of sessions. This might not be appropriate for all sports, potentially where weekly competitions take place and certain sessions (e.g., maximal strength) might need to be completed on a specific day (e.g., match day -3) (Wing, 2018). A more prescriptive method, set-repetition best (SRB) for example, could be an appropriate alternative. Originally proposed by Stone & O'Bryant (1987) and further described by DeWeese et al. (2015b), SRB relies on percentages of maximum loads performed for set x repetition combinations that are based on desired intensities (e.g., very heavy or heavy etc.) for a given day (Carroll, Bernards, et al., 2019). Relative intensity zones of 5% can also be provided for additional autoregulation (Suchomel et al., 2021). Additionally, continuums can be developed based on set-repetition combinations (e.g., 3 x 2) that guides the reduction in load for alternative set-repetition combinations (e.g., 3 x 3 = < 5%, 3 x 5 = < 15%, 3 x 10 = < 25% etc.) (Stone & O'Bryant, 1987; Suchomel et al., 2021). The SRB method essentially operates from an individual's RM for a given repetition scheme, however, accounts for the concern of constantly training to failure by utilising a relative intensity.

The literature investigating SRB is limited, however, two studies by Carroll and colleagues (Carroll, Bazyler, et al., 2019; K. Carroll, Bernards, et al., 2019) demonstrated the superiority of the SRB method when compared with RM targets across 10-week programmes. The SRB group significantly improved their unweighted and 20 kg squat and countermovement jump heights, isometric peak force, and squat jump peak power (between-groups effects, *g* = 0.64-1.25). The SRB group also significantly improved their vastus lateralis cross-sectional area, muscle thickness and key myofibrillar proteins (e.g., myosin heavy chain 2a) in comparison to the RM group (between-groups effects, *g* = 0.31-1.03). The authors attributed the superiority of the SRB method to the reduction in overall training volume, variation in loading (e.g., light vs. heavy days), and the lower associated training stress (Carroll, Bazyler, et al., 2019; Carroll, Bernards, et al., 2019).

Flexible programming can provide an objective bridge between periodisation and autoregulation, promoting autonomy within athletes, and improving goal setting through the application of historical data (Suchomel et al., 2021). Nonetheless, it does require the athlete-coach dynamic to be well-established, with knowledge and understanding of specific set-repetition maximums. Additionally, the subjective rating required to determine one's physiological status might lead to erroneous prescriptions. Therefore, more objective approaches such as velocity could be an effective alternative due to the fully quantifiable nature of the data.

2.8 Velocity-based training

Velocity-based training (VBT) is a contemporary training modality encompassing many strategies designed to individualise and optimise programming, prescription, testing, and monitoring and is most effective when utilised alongside pre-established traditional methods such as % 1RM (Suchomel et al., 2021; Weakley, Mann, et al., 2020). These complimentary approaches include performance diagnostics (load-velocity profiling), autoregulation, volume control (velocity loss), load prescription (velocity-based zones and targets), and external feedback (figure 6) (Banyard et al., 2018, 2019, 2020; Dorrell et al., 2020; García-Ramos, Barboza-González, et al., 2019; Janicijevic et al., 2021; Jiménez-Alonso et al., 2020; Orange, Metcalfe, Robinson, et al., 2020; Pareja-Blanco, Alcazar, et al., 2020; Weakley, McLaren, et al., 2020; Weakley, Ramirez-Lopez, et al., 2020; Weakley, Wilson, et al., 2020; Weakley et al., 2019).

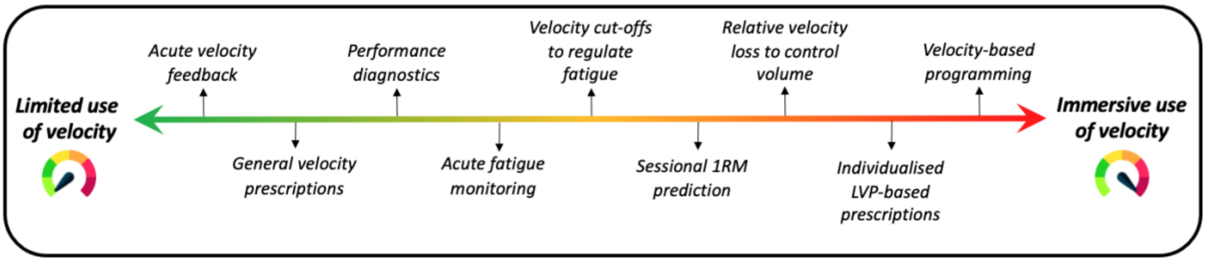

Figure 6. Continuum of velocity-based training (VBT) applications. Adapted from (Weakley, Mann, et al., 2020).

Matching the velocity metric to the desired goal or task is essential when utilising VBT (García-Ramos, Pestaña-Melero, Pérez-Castilla, et al., 2018). Mean velocity (the average velocity across the concentric phase), peak velocity (maximum instantaneous velocity measured during the concentric phase), and mean propulsive velocity (average velocity across the propulsion phase, often defined when acceleration is > 9.81 $m.s^{-2}$) have all been used (Banyard et al., 2018).

Peak velocity is suited to ballistic-type exercises (e.g., jump squat and bench-throw) due to their high-velocity nature. Quantifying the ability to accelerate the CoM could provide useful information regarding physical capacities (Weakley, Mann, et al., 2020). Additionally, take-off or release velocity is directly related to jump height or throw distance per the impulse-momentum relationship (González-Badillo & Marques, 2010; Jiménez-Reyes et al., 2016). Similarly, in weightlifting derivatives, the peak velocity achieved during the second-pull is considered an important metric when evaluating the physical capabilities of weightlifters (Stone et al., 2006).

Mean and mean propulsive velocity are synonymous with heavy, non-ballistic-type exercises (e.g., back squat and bench press) as this requires a constant acceleration to change the state of inertia (e.g., sticking regions) and complete the lift (Cronin et al., 2003; Frost et al., 2010; Lander et al., 1985). Mean propulsive velocity only considers the phase of positive acceleration, arguably providing a truer reflection of an individual's neuromuscular capabilities (Cormie, McBride, et al., 2007; García-Ramos, Pestaña-Melero, Pérez-Castilla, et al., 2018; Muñoz-López et al., 2017). Mean velocity, however, could be more closely related to athletic performance, given most actions occur over a given duration as opposed to being instantaneous and typically include periods of deceleration (e.g., change of direction) (Jidovtseff et al., 2011; McBurnie et al., 2019).

The reliability of the different velocities must also be considered when selecting the most appropriate one. Smaller CVs (1.9-3.2% vs. 2.1-5.2%) and stronger ICCs (0.91-0.95 vs. 0.77-0.95) have been observed for peak vs. mean velocity in loaded jumps (17-75 kg) (Pérez-Castilla, Jiménez-Reyes, et al., 2021). Conversely, García-Ramos et al., (2018) reported superior reliability for mean velocity (SEE = 3.8-4.8%; R^2 = 0.99; CV = 4.1-4.9%) when performing the bench press throw compared to peak (SEE = 5.4-5.8%; R^2 = 0.97; CV = 3.5-3.9%) and mean propulsive (SEE = 4.9-5.6%; R^2 = 0.98; CV = 5.1-6.0%) velocities. Comparable reliability and validity data have been reported between mean, mean propulsive, and peak velocities (Banyard et al., 2018; Benavides-Ubric et al., 2020; Hernández-Belmonte et al., 2020; Morán-Navarro et al., 2021), suggesting that either one could be used based on training goals, sporting demands, personal preference, or athlete feedback.

2.8.1 Velocity and feedback

Augmented feedback, the process of providing an external source of information, is a vital strategy to enhance acute and chronic mechanical output, and underpins the basic principles of VBT (Nagata et al., 2020; Randell et al., 2011b, 2011a). The objective feedback provided by VBT technology can help to inform training prescriptions or motivate athletes, driving intent within a session (Randell et al., 2011a; Weakley, Wilson, Till, Read, Scantlebury, et al., 2019).

Augmented feedback is commonly understood in two ways: knowledge of results and knowledge of performance (Nagata et al., 2020). Knowledge of performance typically refers to the kinetics or movement patterns of a task, whereas knowledge of results refers to the objective data or outcome (e.g., velocity output) (Kompf, 2016; Nagata et al., 2020). Within knowledge of results, visual or verbal feedback could be provided in the form of specific kinematic targets (e.g., 0.8 $m.s^{-1}$ verbally or visually) or simple encouragement (e.g., verbalising “let’s go” or “keep pushing”) (Weakley, Wilson, et al., 2020). Providing kinematic feedback verbally can help to maintain higher mean velocities across ten repetitions of back squat compared to visual kinematic or verbal encouragement (MSD = 0.86 vs. 0.77 vs. 0.74 when compared to the control, respectively) (Weakley, Wilson, et al., 2020). Additionally, providing athletes with a velocity target can generate higher velocities compared to encouraging movement “as fast as possible” (0.84 vs. 0.82, $p < 0.001$) (Hirsch & Frost, 2021).

The time at which feedback is provided can also affect performance (Pérez-Castilla, Jiménez-Alonso, et al., 2020). With the portability and intuitive nature of VBT devices, providing terminal feedback after each repetition, or set averages, are both possible. When compared to a non-feedback control condition, feedback following each repetition produced higher velocities compared to mid- or post set (1.9-5.3% vs. 1.3-3.6% vs. 0.7-4.3%, respectively)

(Pérez-Castilla, Jiménez-Alonso, et al., 2020). Similarly, larger effect sizes have been reported when comparing terminal audible feedback at the end of reach repetition to visual feedback across a four-week loaded jump squat intervention (MSD = 0.11-1.60) (Nagata et al., 2020). Despite the nuances of providing velocity feedback, it is evident that any type of feedback will result in improved acute and chronic performance (Hirsch & Frost, 2021; Nagata et al., 2020; Pérez-Castilla, Jiménez-Alonso, et al., 2020; Randell et al., 2011a; Weakley, Wilson, et al., 2020; Weakley, Wilson, Till, Read, Scantlebury, et al., 2019). VBT, therefore, can be an effective strategy to ensure maximal effort and intent is provided during every session, harnessing long-term performance improvements.

2.8.1 Load-velocity relationship

The load-velocity and force-velocity relationships are analogous and underpinned by the same physiological and mechanical principles, i.e., as load increases, velocity decreases, and vice versa (Weakley, Mann, et al., 2020). When performing exercises that start and end with zero acceleration (e.g., isotonic or constant velocity movements), mean net force must also equal zero, resulting in mean force equating to system weight as force and acceleration are directly proportional (see equation 1) (Frost et al., 2010). Therefore, when performing traditional compound isotonic exercises (e.g., back squat, bench press, deadlift), mean force and load can be interchangeable, permitting the creation of comparable profiles. Given VBT technology (e.g., LPT, IMU) is typically cheaper, more accessible, and employs quicker and simpler processes than more complex devices such as force-plates, administering load-velocity profiling could be more practically advantageous than force-velocity profiling given the extraction of more useable data (e.g., % 1RM vs. velocity) to assist with programming and prescription in addition to providing robust overviews of force-velocity characteristics.

2.8.1.1 Load-velocity profiling

Many LVP protocols, statistical approaches, and applications are available to S&C practitioners. LVPs are incremental protocols (similar to 1RMs) that measure concentric movement velocity (typically barbell) and is then plotted against absolute (kg) or relative (% 1RM) load (figure 7) (McBurnie et al., 2019). The load-velocity relationship quantifies the neuromuscular response to load and can be used as a mechanical evaluation of strength, fatigue, and programme success (González-Badillo & Sánchez-Medina, 2010; Sánchez-Medina et al., 2014).

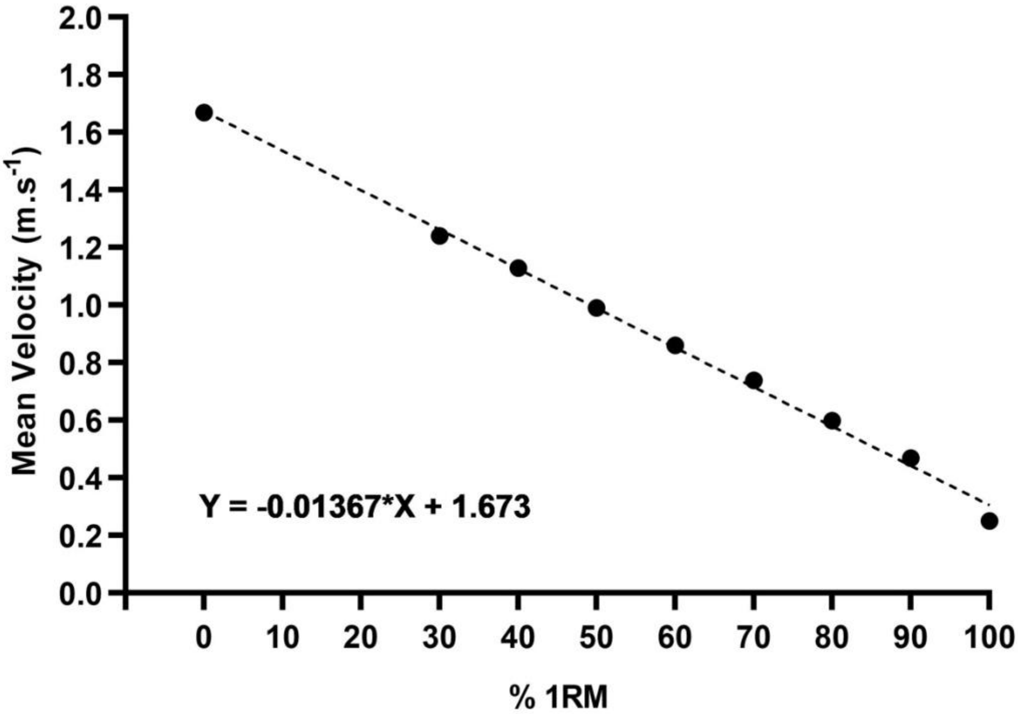

Figure 7. Example load-velocity profile.

The main goals of load-velocity profiling is to acutely evaluate intensity of effort and readiness to train through terminal repetition feedback, and chronically identify strength and power improvements through pre-post intervention diagnostics (González-Badillo & Sánchez-Medina, 2010; McBurnie et al., 2019). By utilising mathematical modelling (e.g., linear regression), predictive equations are developed to estimate velocity or load. Furthermore, measuring the specific velocity of a working load (e.g., 80% 1RM), relative effort, levels of fatigue, and acute fluctuations in strength can be identified (Weakley, Mann, et al., 2020). Load-velocity profiling has been researched in many exercises, including back squat (Banyard et al., 2018; Martínez-Cava et al., 2019; Sánchez-Medina et al., 2017), front squat (Spitz et al., 2019), deadlift (Benavides-Ubric et al., 2020; Morán-Navarro et al., 2021; Ruf et al., 2018), bench press (García-Ramos, Pestana-Melero, et al., 2018; Pareja-Blanco et al., 2020; Sánchez-Medina et al., 2014), pull-up (Muñoz-López et al., 2017), bench pull (García-Ramos et al., 2019; Sánchez-Medina et al., 2014), military press (Balsalobre-Fernández, García-Ramos, et al., 2018), power clean (Haff et al., 2020; Naclerio & Larumbe-Zabala, 2018), bench press throw (García-Ramos, Pestaña-Melero, Pérez-Castilla, et al., 2018), loaded squat jump (Pérez-Castilla, Jiménez-Reyes, et al., 2021) and loaded jump squat (Pérez-Castilla, Jiménez-Reyes, et al., 2021), demonstrating its popularity and appropriateness to S&C practitioners.

The strength of the interaction between load and velocity is practically perfect, with r and R^2 values of > 0.9 often reported, irrespective of exercise (Benavides-Ubric et al., 2020; Conceição et al., 2016; García-Ramos, Pestana-Melero, Pérez-Castilla, et al., 2018; García-Ramos, Suzovic, et al., 2021; García-Ramos, Ulloa-Díaz, et al., 2019; Muñoz-López et al., 2017; Sánchez-Medina et al., 2017; Spitz et al., 2019). Similarly, strong inter- and intra-day reliability has been observed across multiple exercises, with ICCs of 0.79-0.97, CVs of 1.4-10.0% and SEMs of 0.02-0.07 $m.s^{-1}$ (Banyard et al., 2018; Chéry & Ruf, 2019; García-Ramos, Haff, Padial, et al., 2018; García-Ramos, Ulloa-Díaz, et al., 2019; Pestana-Melero et al., 2018). Load-velocity profiling can therefore be harnessed by S&C coaches as a complimentary testing, monitoring, and prescriptive tool for utilisation with key training exercises.

Minimal velocity threshold (MVT) or V_{1RM} represents an individual's maximum strength capabilities and is a key component of profiling (McBurnie et al., 2019). The V_{1RM} can be used to identify if true 1RMs occur during testing and training, as a reference point to measure proximity from failure against, and as the point of extrapolation when predicting maximal or submaximal loads from LVP data (Banyard, Nosaka, & Haff, 2017; Chéry & Ruf, 2019; Ruf et al., 2018). Despite its practical uses, the V_{1RM} is typically unreliable, with CVs of 22.5% and ICCs of 0.19 being reported, questioning its appropriateness within the predictive model and whether it full aligns to submaximal velocities (figure 8) (Banyard et al., 2018; Chéry & Ruf, 2019; García-Ramos, Ulloa-Díaz, et al., 2019; Pestana-Melero et al., 2018; Ruf et al., 2018). Reasoning for poorer reliability at heavier loads is unclear, however, movement variability (Kristiansen et al., 2019) and the influence of the stretch-shortening cycle (Banyard, Nosaka, & Haff, 2017) have been postulated as potential reasons.

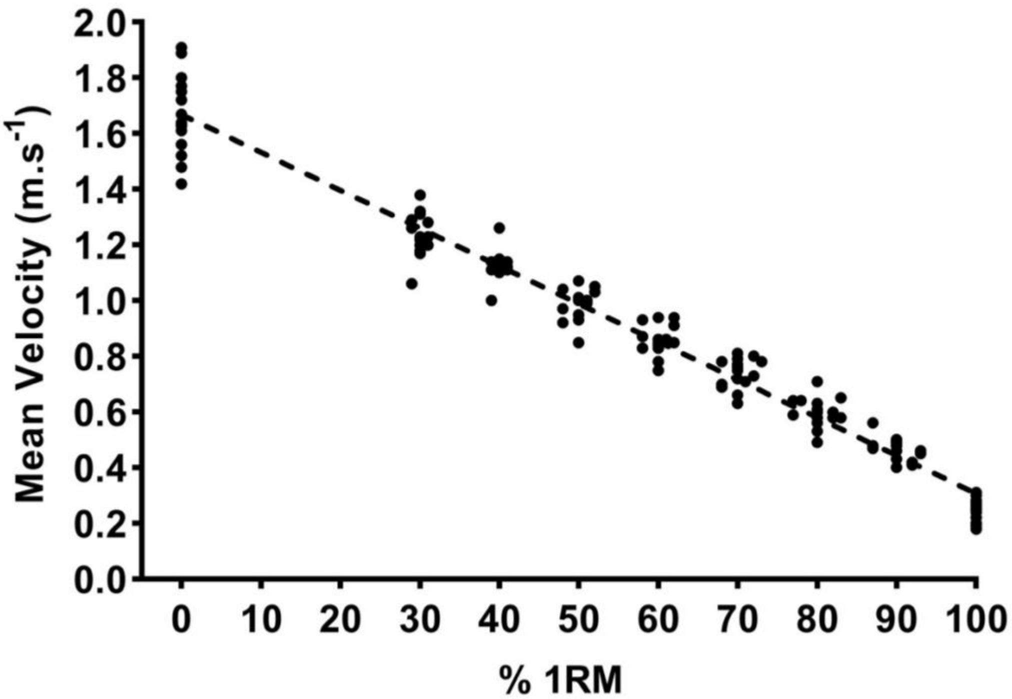

Figure 8. Example load-velocity profile data in the free-weight back squat displaying the misalignment of the velocity at 1RM (V_{1RM}) with submaximal data.

Which mathematical model to apply to load-velocity data should also be a consideration for

S&C coaches. Some researchers have proposed the relationship to be truly linear (Haff et al., 2020; Janicijevic et al., 2021; Pestana-Melero et al., 2018), therefore applying linear regression, or first order polynomial models to the data:

$$\boldsymbol{y = ax + b}$$

eq.18

where $\boldsymbol{y}$ is the outcome variable, $\boldsymbol{x}$ is the predictor variable, $\boldsymbol{a}$ is the y-intercept and $\boldsymbol{b}$ is the slope of the line. Others have proposed the relationship to be curvilinear, however, (González-Badillo & Sánchez-Medina, 2010; Lopes et al., 2022; Martínez-Cava, Morán-Navarro, Sánchez-Medina, et al., 2019; Sánchez-Medina et al., 2017), fitting quadratic or second-order polynomial models:

$$\boldsymbol{y = ax^2 + bx + c}$$

eq.19

where the interaction between $\boldsymbol{a}$ and $\boldsymbol{b}$ represents the shape of the line and $\boldsymbol{c}$ represents the y-intercept. Researchers have evaluated the strength of load-velocity data when applying first and second-order polynomials, reporting comparable variance in exercises such as the bench press (R^2: 0.99 vs. 0.99), back squat (R^2: 0.89-0.99 vs. 0.89-0.99), and prone bench pull (R^2: 0.93-0.95 vs. 0.94-0.97) (Banyard et al., 2018; García-Ramos, Ulloa-Díaz, et al., 2019; Pestana-Melero et al., 2018). Differentiating between the two models could therefore be dictated by specifics of the profile such as exercise, number of data points, or equipment (free-weight vs. smith-machine).

Load-velocity research typically employs common protocols that can limit the practical representation of the data. Firstly, many studies administer LVPs using a fixed-path smith-machine rack, which is designed to limit any anterior-posterior and medial-lateral movement

(Cotterman et al., 2005). Whilst smith-machines are legitimate pieces of equipment, they are uncommon in practice, limiting transferability of the data. Research suggests that mechanical outputs such as peak velocity, maximum load lifted, and electromyographical muscle activity differ when performing smith-machine exercises compared to free-weight and therefore cross-comparisons can be misleading (Cotterman et al., 2005; Pérez-Castilla, McMahon, et al., 2020; Schwanbeck et al., 2009).

Secondly, implementing a pause between eccentric and concentric portions of an exercise reportedly improves the reliability of velocity data (Pallarés et al., 2014), and is common in load-velocity research. Unless performing concentric-only phases of training or paused exercise variations, however, the transferability of this research is again, limited. Coaches will typically programme isotonic actions that utilise eccentric-concentric coupling and the stretch-shortening cycle, and therefore, methods employed in research should look to reflect this.

Finally, research has shown that force-velocity characteristics are underestimated in light-to-moderate loads during non-ballistic exercises due to the period of negative acceleration at the end of the concentric phase during non-ballistic exercise (Cormie et al., 2011b; Cormie, Mccaulley, et al., 2007; Newton et al., 1996). Load-velocity profiling, however, is typically performed in non-ballistic exercises starting with loads as light as 20% 1RM, which can contain approximately 50-70% negative acceleration, potentially influencing velocity output (table 4) (Newton et al., 1996; Sanchez-Medina et al., 2010). Ballistic exercises remove this period of negative acceleration, and therefore, it could be suggested that to provide a valid reflection of an individual's load-velocity characteristics, light-to-moderate loads during LVPs should be performed using ballistic equivalents (e.g., jump squat, bench-throw, trap-bar jumps etc.).

Table 4. Percentages of the propulsion phase with respect to the full concentric phase for common resistance exercises.

Load (% 1RM)	Propulsion Phase (%)					
	Bench Press[4]	Bench Press[5]	Bench Press[2]	Prone Bench Pull[5]	Shoulder Press[1]	Deadlift[3]
30	76	76	73	85		
35	79	79	76	86		
40	81	81	79	87	84	81
45	83	83	81	88	87	82
50	86	85	84	89	89	84
55	88	88	86	89	91	86
60	91	90	88	90	93	88
65	93	92	90	91	94	91
70	95	94	92	92	96	93
75	98	97	94	93	97	96
80	100	99	95	94	98	99
85	100	100	97	95	99	100
90	100	100	98	96	100	100
95	100	100	99	97	100	100
100	100	100	100	98	100	100

[1]Hernández-Belmonte et al., 2020; [2]Martínez-Cava et al., 2019; [3]Morán-Navarro et al., 2021; [4]Sanchez-Medina et al., 2010; [5]Sánchez-Medina et al., 2014
1RM = 1 repetition maximum

The load-velocity profile underpins VBT. It is an integral component that influences the accuracy of its application. The stability of velocity at % 1RM is an essential criterion for efficacious applications of LVPs. Whilst the impact force-velocity alterations have on the load-velocity profile is under-investigated, mean velocity appears stable (i.e., no change in velocity at specific 1RM percentages), irrespective of increases in overall strength (figure 9) (Banyard et al., 2020; Davies et al., 2020; González-Badillo & Sánchez-Medina, 2010; Hernández-Belmonte et al., 2020; Pérez-Castilla & García-Ramos, 2020). The stability of velocity across the LVP, therefore, provides coaches with a useful tool for regular and non-invasive evaluations of strength, readiness, and fatigue, as well as providing training targets. Furthermore, by planning and implementing an effective protocol that suits the intended environment, further use such as load autoregulation and programming can be highly beneficial to S&C practitioners.

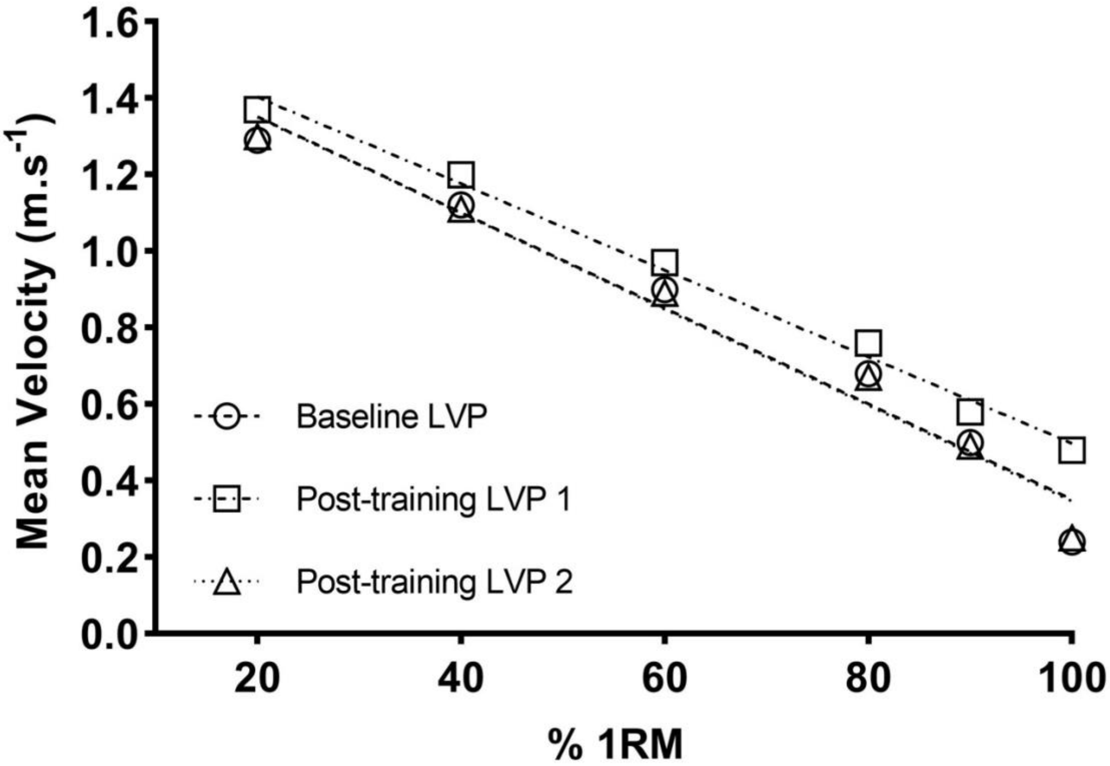

Figure 9. Example data taken from (Banyard et al., 2020) illustrating the stability of the load-velocity profile. Baseline LVP was collected prior to a 6-week training intervention. Post-training LVP 1 was taken post-intervention using the same absolute loads as the baseline profile. Post-training LVP 2 was then performed using the newly acquired 1RM and subsequent submaximal loads. Baseline and LVP 2 were performed using the same relative load (% 1RM) and different absolute loads (kg).

2.8.2 Velocity-based autoregulation

VBT can be used as an objective strategy for autoregulating load (Greig et al., 2020). The flexibility of velocity-based methods means a continuum of approaches are available to coaches depending on their applied environment (figure 10). These approaches include simple velocity tracking based on historical data, utilising pre-determined velocity-based zones, and various load-velocity profiling methods.

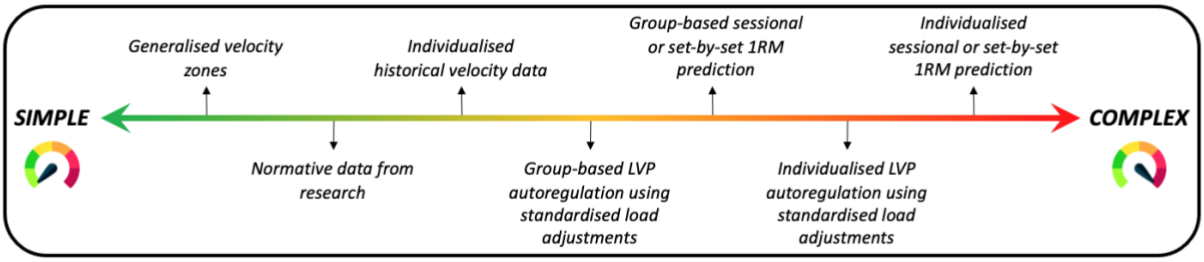

Figure 10. Continuum of velocity-based autoregulatory strategies.

2.8.2.1 Simple velocity-based methods

When working with large groups of athletes, S&C coaches often require simple and time-efficient autoregulatory strategies (Garcia-Ramos & Jaric, 2018). The use of wide-scale, generalised zones (figure 11) is common practice to guide load manipulation, however, this approach limits the individualisation and exercise-specific nature of load-velocity data (Banyard et al., 2018). Simple tracking of historical velocity-data for various working loads and set-repetition schemes could provide a more athlete-centred method for adjusting prescriptions, however, this could ignore fluctuations in fatigue and strength and rely on similar physiological statuses being present when repeating prescriptions. Whilst these velocity-based methods provide simple ways to adjust load, there is no literature to date investigating their efficacy and thus, implementation might be limited.

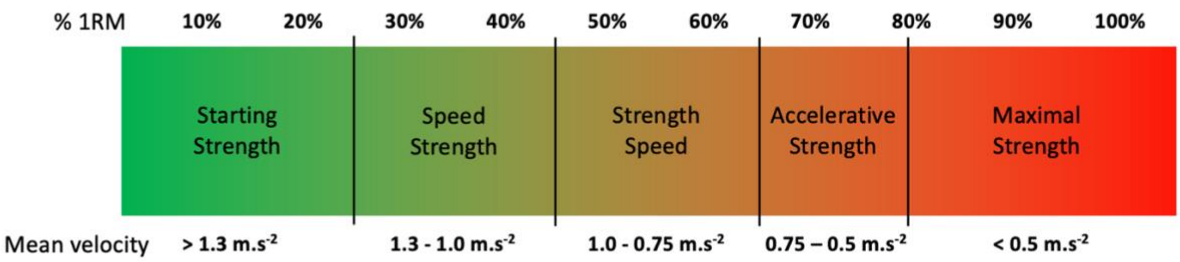

Figure 11. Generalised velocity-based zones in relation to specific strength qualities and percentages one repetition maximum (1RM).

2.8.2.2 Load-velocity profiling and autoregulation

Load-velocity profiling could provide S&C coaches with an effective method to adjust and manipulate daily prescriptions and optimise load. As previously described, collecting load-velocity data and applying a mathematical model creates a predictive equation that can be utilised to determine daily working loads (Banyard et al., 2020). This approach relies on the strong and stable inverse relationship between load (kg or % 1RM) and velocity. Research has indicated that velocity remains similar across the load-spectrum, irrespective of changes to maximum strength, suggesting that LVP-based autoregulation could be an objective, sensitive, and reactive method for practitioners to utilise (Davies et al., 2020; González-Badillo & Sánchez-Medina, 2010; Pérez-Castilla & García-Ramos, 2020). Typically, autoregulation via load-velocity data consists of a three-stage process involving either a sessional re-prediction of 1RM or standardised load adjustments based on fluctuations in velocity (figure 12).

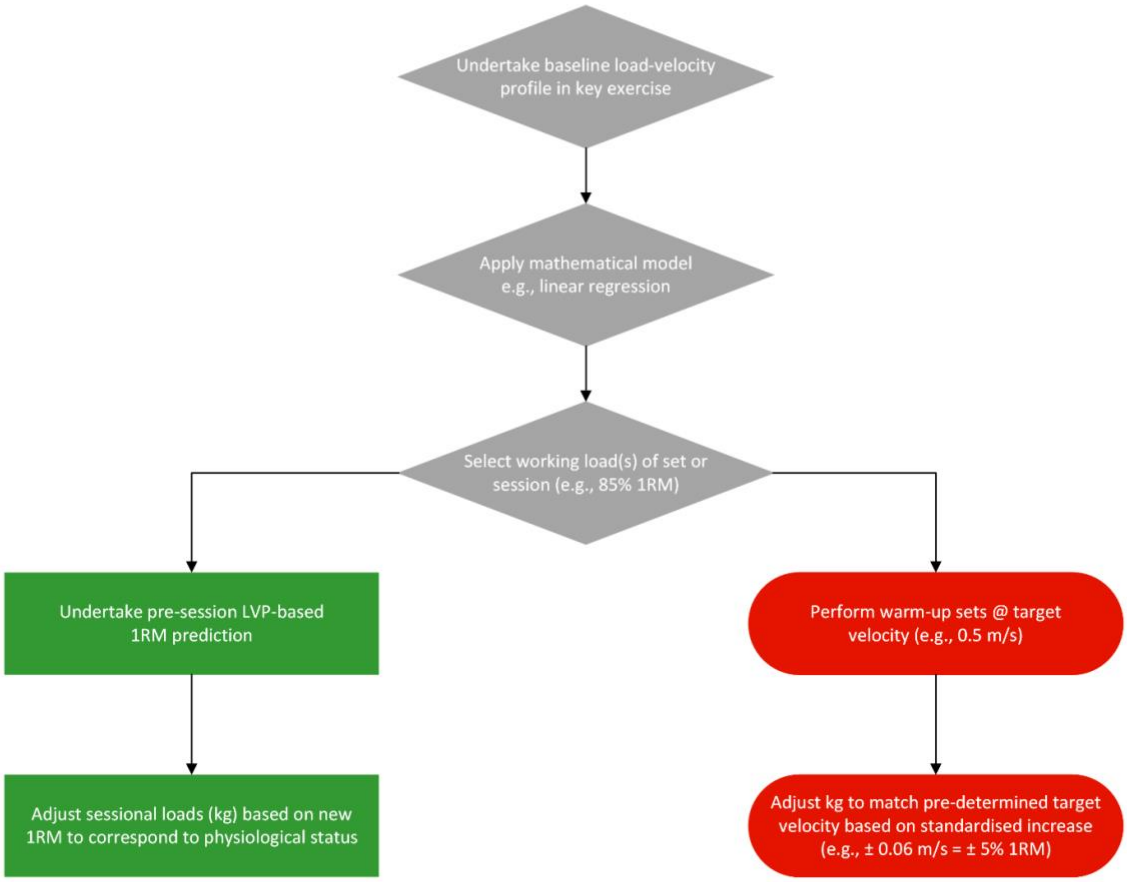

Figure 12. A flow diagram detailing the step-by-step process for utilising load-velocity profiles to autoregulate sessional loads.

It was originally hypothesised that the predictive equations developed from load-velocity data could be utilised across multiple athletes, irrespective of relative strength or demographic (Conceição et al., 2016; González-Badillo & Sánchez-Medina, 2010; Sánchez-Medina et al., 2017). Such equations have since been compared to individualised data, with one emerging as being valid for predicting 1RM (Loturco et al., 2021) in the prone bench-pull (García-Ramos, Barboza-González, et al., 2019) and another (González-Badillo & Sánchez-Medina, 2010) not valid in the bench press (García-Ramos, Haff, Pestaña-Melero, et al., 2018). Despite the conflicting conclusions regarding generalised equations, the time effective nature of implementing them could be attractive to practitioners. Nonetheless, load-velocity data is seemingly individual with between-participant variability reportedly greater than within-participant variability across several exercises (Balsalobre-Fernández, García-Ramos, et al., 2018; Banyard et al., 2018; García-Ramos, Haff, Padial, et al., 2018; García-Ramos, Ulloa-Díaz, et al., 2019; Pestana-Melero et al., 2018; Ruf et al., 2018). Additionally, each LVP performed is unique to the exercise (table 5), technique employed, and sex of the athlete (Fahs et al., 2019; García-Ramos, Pestana-Melero, Pérez-Castilla, et al., 2018; Torrejón et al., 2019). Finally, the systematic differences between devices limits the implementation of generalised data across multiple applied settings (Fernandes et al., 2021; García-Ramos, Pérez-Castilla, et al., 2018). Therefore, if wanting to utilise generalised predictive equations, it is imperative that the environment closely matches that of the methodology from which the equation is taken.

Table 5. Normative load-velocity profile data for common upper and lower body resistance exercises.

Load (% 1RM)	Mean Velocity (m.s^{-1})								
	Bench Press[3]	**Bench Press[9]**	**Bench Press[4]**	**Shoulder Press[6]**	**Prone Bench Pull[5]**	**Bent Over Row[7]**	**Back Squat[2]**	**Deadlift[1]**	**Deadlift[8]**
30	1.40	1.20	1.10		1.33	1.42			
35	1.31	1.13	1.03		1.26		0.88		
40	1.22	1.05	0.96	1.15	1.20	1.28		1.02	1.01
45	1.14	0.98	0.90	1.07	1.14		0.84	0.97	0.96
50	1.05	0.91	0.83	0.98	1.08	1.22		0.91	0.90
55	0.96	0.83	0.76	0.90	1.02		0.77	0.85	0.84
60	0.87	0.76	0.69	0.82	0.95	1.08		0.80	0.78
65	0.79	0.68	0.62	0.74	0.89		0.66	0.74	0.72
70	0.70	0.61	0.55	0.66	0.83	0.97		0.68	0.66
75	0.61	0.54	0.49	0.58	0.77		0.60	0.62	0.59
80	0.52	0.46	0.42	0.50	0.70	0.83		0.57	0.52
85	0.44	0.39	0.35	0.43	0.64		0.47	0.51	0.45
90	0.35	0.31	0.28	0.35	0.58	0.74		0.45	0.39
95	0.26	0.24	0.21	0.27	0.52		0.35	0.39	0.32
100	0.18	0.16	0.14	0.19	0.46	0.63	0.26	0.33	0.25

[1]Benavides-Ubric et al., 2020; [2]Fahs et al., 2019; [3]García-Ramos, Pestana-Melero, Pérez-Castilla, et al., 2018; [4]García-Ramos, Suzovic, et al., 2021; [5]García-Ramos, Ulloa-Díaz, et al., 2019; [6]Hernández-Belmonte et al., 2020; [7]Loturco et al., 2021; [8]Morán-Navarro et al., 2021; [9]Pérez-Castilla, Jerez-Mayorga, et al., 2020
1RM = 1 repetition maximum

As alluded prior, smith-machines frequent LVP literature, with high levels of validity and reliability observed when predicting 1RM (García-Ramos, Suzovic, et al., 2021; Janicijevic et al., 2021; Jidovtseff et al., 2011; Sánchez-Medina et al., 2014, 2017). Conversely, when performed with free-weight exercises, the validity and reliability of 1RM prediction is reduced. For example, 1RM predictions based on the free-weight back squat and deadlift rendered systematic biases of 16.3-30.9 kg, SEEs of 10.6-17.2 kg, CVs of 3.3-12.8%, typical error of estimate (TEE) of 9.1-13.7 kg and MSDs of -1.24-1.04 (Banyard, Nosaka, & Haff, 2017; Lake et al., 2017; Ruf et al., 2018). Considerable individual variation in the error of the prediction methods were also present (e.g., -5.5-47.6%) (Banyard, Nosaka, & Haff, 2017; Ruf et al., 2018). This poorer data representing free-weight-based LVP predictive models questions the efficacy of such an approach.

The poor validity data presented above could be a result of several methodological limitations. Lake et al. (2017) represented the MVT from the velocity of the final repetition from a set to failure, despite reporting significant differences compared to the actual velocity recorded at 1RM (MPV = 0.28-0.32 $m.s^{-1}$ vs. 0.16 $m.s^{-1}$; MV = 0.32-0.34 $m.s^{-1}$ vs. 0.17 $m.s^{-1}$). Banyard, Nosaka, & Haff (2017) and Ruf et al. (2018) attributed the poor validity of their predictive models to high variability and poor reliability of V_{1RM}. When utilising a 1RM predictive model from LVP data, the point of extrapolation (i.e., V_{1RM}) must represent the point of prediction (i.e., 1RM). Therefore, if this point presents large statistical error (e.g., CVs of 15.7-22.5%) (Banyard, Nosaka, & Haff, 2017; Ruf et al., 2018), this will likely be reflected in the validity of the predictive model.

The statistical equation applied to LVP data might also affect the validity of predictive modelling. Despite first and second-order polynomials producing comparable R^2 values

(Banyard et al., 2018; Pestana-Melero et al., 2018), the overall validity and reliability of the equation could be affected as a result of the residual error between actual and predicted coefficients. Research investigating the effect of the regression model on 1RM prediction is limited. First-order polynomials were a better predictor of 1RM compared to second-order polynomials (p = 0.13) in the touch-and-go (mean difference = 2.5 kg vs 3.2 kg; r = 0.98 vs. 0.98; SEE = 3.2 kg vs. 4.0 kg) and paused (mean difference = 2.7 kg vs. 3.7 kg; r = 0.98 vs. 0.97; SEE = 3.1kg vs 4.6kg) bench press (Janicijevic et al., 2021). Similarly, linear regression produced higher absolute reliability compared to its quadratic counterpart in the bench press (CV = 4.4-4.7% vs. 4.6-5.0%) (Pestana-Melero et al., 2018). Again, this research employed smith-machines, limiting its application to free-weight exercises and many applied settings. The only comparison to date in a free-weight exercise was again in an upper-body task, showing linear modelling in the light to moderate loads (20-85% 1RM) (CV: linear = 2.6-4.5%; quadratic 2.7-5.0%), but quadratic in the heavier loads (90-100%) to be the most reliable (CV: linear = 5.2-7.6%; quadratic 4.7-5.1%) (García-Ramos, Ulloa-Díaz, et al., 2019).

Free-weight, lower-body exercises such as the back squat are integral exercises of most training programmes, however, research investigating 1RM predictions from LVP data is very limited, particularly utilising second-order polynomials. Lopes et al. (2022), however, did observe a high degree of accuracy in the hexagonal-bar deadlift when utilising linear regression to predict 1RM (201.5 kg vs. 201.4kg) (p = 0.9; r = 0.93; TE = 5.11 kg; CV = 2.5%), conflicting with previous research in lower-body, free-weight exercises (Banyard, Nosaka, & Haff, 2017; Lake et al., 2017; Ruf et al., 2018). As this previous literature applied linear modelling and reported poor predictive efficacy, the statistical model applied to LVP data could be deemed important, with lower-body exercises presenting more of curvilinear relationship between load and velocity (figure 13).

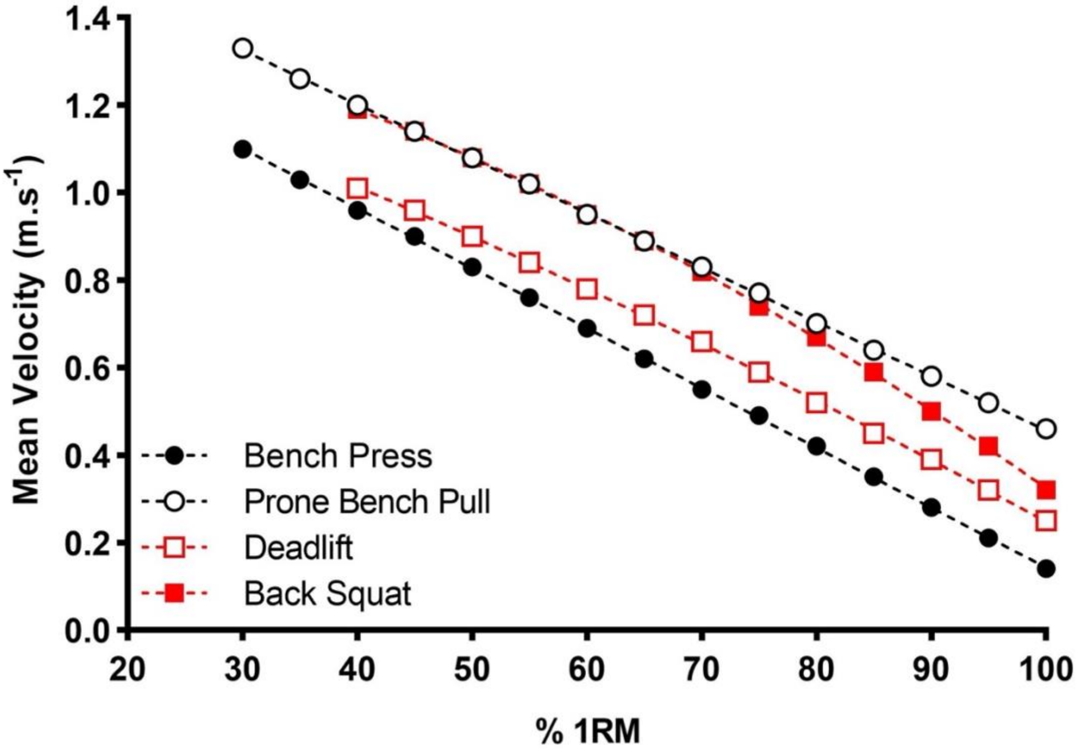

Figure 13. Comparison of upper (black) and lower (red) body exercises with first- (black) and second-order (red) polynomial models applied, respectively. Data taken from García-Ramos, Suzovic, et al., 2021; García-Ramos, Ulloa-Díaz, et al., 2019; Morán-Navarro et al., 2021; Sánchez-Medina et al., 2017).

Traditionally, load-velocity protocols were developed to include multiple incremental loads, ranging from 20-100% 1RM and increasing in 5-10% increments (Conceição et al., 2016; González-Badillo & Sánchez-Medina, 2010; Sánchez-Medina et al., 2014; Sánchez-Medina et al., 2017). Conducting these protocols, however, can be time consuming, particularly with large squads. An alternative method, the two-point method, has been proposed as a time efficient and simpler protocol for collecting load-velocity data. Simply, the two-point method utilises two appropriately spaced loads or velocities (e.g., 20 and 70% 1RM) to model an individual's load-velocity characteristics (figure 14) (Garcia-Ramos & Jaric, 2018).

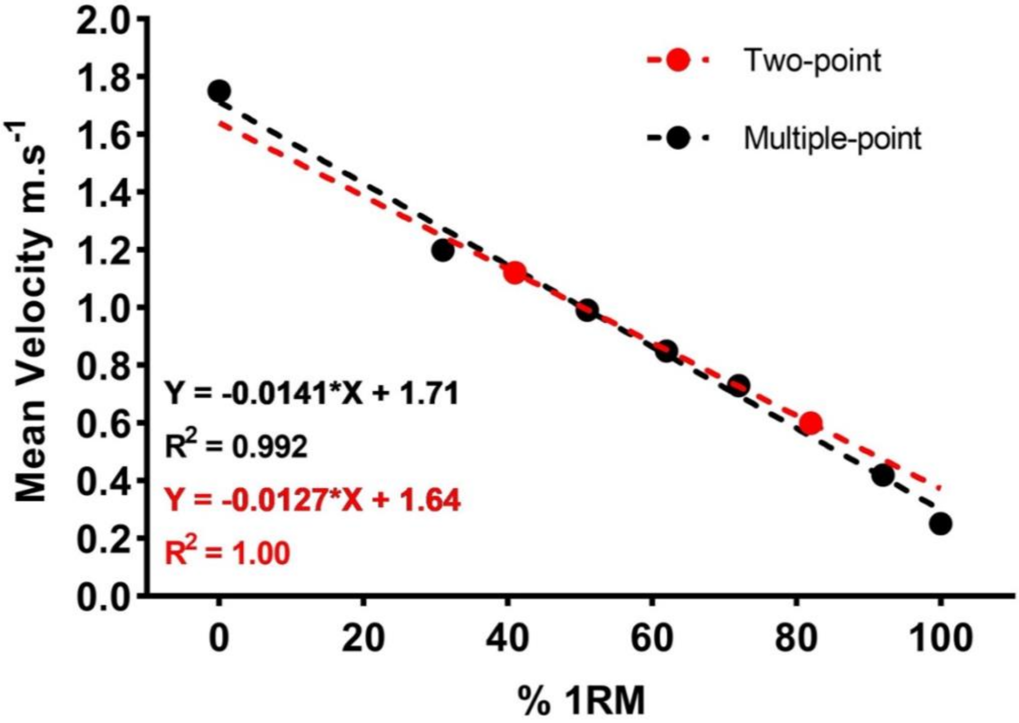

Figure 14. Comparison of the multiple point vs. two-point load-velocity profiles.

It has been hypothesised that because multi-joint force- and load-velocity profiles are almost perfectly linear (e.g., R^2 typically > 0.95), the number and magnitude of the experimental points (i.e., number and mass of loads tested) should not affect the reliability and validity of the predictive model (Jaric, 2016). When utilised to predict load, the two-point method produced high reliability and validity in the bench press, prone bench-pull, and seated row exercises (García-Ramos, Barboza-González, et al., 2019; García-Ramos, Haff, Pestaña-Melero, et al., 2018; Pérez-Castilla, Suzovic, et al., 2021). For example, García-Ramos, Haff, et al., (2018) found mean differences of 0.6-3.6 kg and test-retest CVs of 3.1-5.1% when predicting bench press 1RM from the two-point method compared to a direct assessment, potentially providing a solution for coaches wanting to predict maximum strength in a regular basis.

Importantly, the two-point method has never been investigated to predict load within lower-body exercises. It has, however, produced less favourable reliability data when used to predict force-velocity parameters (i.e., maximum force, velocity and power, and the force-velocity slope) in the loaded squat (CV = 3.4-173.9%) and countermovement (CV = 4.3-103.8%) jumps (García-Ramos, Pérez-Castilla, et al., 2021). This data, again, suggests that perhaps load-velocity relationships in lower body exercises are more curvilinear, compromising a method that relies on linearity of data. Additionally, research has suggested that the most valid and reliable protocol for the two-point method is using two distant loads (e.g., 0 and 75% 1RM) (García-Ramos, Pérez-Castilla, et al., 2021; Garcia-Ramos & Jaric, 2018). Practitioners might question the practicalities of such a protocol, as moving from 0% to 75% 1RM with no intermediate loads could risk injury and reduce practicality. Further, if intermediate loads are collected to reduce the magnitude of this step, this protocol would become obsolete.

Using LVP data to predict sessional 1RM to autoregulate load appears statistically viable for S&C coaches. Individually profiling athletes is the most reliable and valid way to estimate maximum strength, however, the practicalities and logistics can be challenging. Similarly, free-weight, lower-body literature is limited, with evidence to suggest the models applied to smith-machine and upper-body exercises cannot be applied in the same way. Finally, whilst attempts have been made to simplify load-velocity profiling, this, again, might not be appropriate for the curvilinear nature of lower-body data. Therefore, further research is required to find a valid and reliable model, that is also practical, time-efficient, and simple to administer.

2.8.2 Efficacy of the load-velocity profiling method

There is extensive literature assessing the validity and reliability of autoregulation via load-velocity profiling, however, research assessing the efficacy of load-manipulation is limited. A recent meta-analysis appraising VBT-related autoregulatory training studies against traditional methods (e.g., % 1RM or RIR) included only four relevant studies, with the quality of the research rated as very low in accordance with the Grading of Recommendation, Assessment, Development, and Evaluation (GRADE) assessment tool (Guyatt et al., 2008; Orange et al., 2021). Despite this, these studies still provide an initial assessment of the effectiveness of VBT-related autoregulation and is an important addition to the field of research.

Most research comparing VBT training methodologies against traditional percent-based prescriptions (% 1RM) have utilised general or individualised LVPs to autoregulate load inter- or intra-session (Banyard et al., 2020; Dorrell, Smith, et al., 2020; Jiménez-Reyes et al., 2021; Orange, Metcalfe, Robinson, et al., 2020). Dorrell et al., (2020) compared group-based LVP zones against % 1RM load prescription during a 6-week wave-loading strength intervention. Set-by-set loads were adjusted in the LVP group using average group velocities relating to % 1RM intensities, with the zones created by the error associated across the full LVP. Group x time interactions were detected for bench press and vertical jump (p = 0.004-0.018), with the LVP group significantly increasing 1RM (8.2% vs. 4.0%; MSD = 0.61 vs. 0.24) and jump height (5% vs. 1%; MSD = 0.23 vs. 0.06) compared to the % 1RM group. Furthermore, the LVP group produced superior back squat and deadlift 1RMs post-intervention than the % 1RM group (9.3% vs. 7.9%; MSD = 0.59 vs. 0.44, 6.5% vs 3.1%; MSD = 0.38 vs 0.22, respectively).

Similar results have been reported by Orange, Metcalfe, Robinson, et al. (2020) and Banyard et al. (2020), with nuanced methodologies employed. Orange, Metcalfe, Robinson, et al. (2020) implemented a 7-week in-season mesocycle utilising 1 x 60% and 1 x 80% 1RM session per week and Banyard et al. (2020) programmed a 6-week, 3 sessions x week using a weekly reversed linear loading strategy that increased over time (e.g., week 1: 68%, 64%, 59% 1RM, week 2: 72%, 68%, 64% 1RM), both of which were volume matched. Both VBT groups improved their back squat 1RM (5.8-11.3%; MSD = 0.38-0.89), however, the % 1RM group's improvements in 1RM were superior (6.6-12.5%; MSD = 0.51-1.41), with an unclear increase favouring the % 1RM groups (MSD = 0.08-0.57). Comparable changes were evident between groups across all performance outcome measures (sprint times, CMJ height) in Orange, Metcalfe, Robinson, et al. (2020), with the VBT group producing superior improvements in CMJ-PV (MSD = 1.81), 5-m sprint (MSD = 1.35), 10-m (MSD = 1.24) and 20-m sprint (MSD = 1.27) and COD (MSD = 0.67-0.97) in Banyard et al. (2020).

The discrepancies between the three studies could be due to several reasons. For example, Dorrell et al., (2020) individualised load manipulation for the VBT group based on the athletes current performance and physiological status, whereas Orange, Metcalfe, Robinson, et al. (2020) and Banyard et al. (2020) standardised load adjustment based on changes of 0.06 $m.s^{-1}$ resulting in $\pm$ 5% 1RM. This more generalised approach might affect the optimisation of sessional loads, potentially resulting in over- or under-estimation of an individual's maximum strength. Similarly, the % 1RM groups lifted at slower velocities throughout the interventions, exposing themselves to heavier relative loads, potentially facilitating greater neuromuscular adaptations.

An important finding across all three studies was the impact autoregulation had on total volume, session RPE, and time under tension. When compared to the % 1RM groups, VBT yielded significantly lower total training volume (5.86%; $p = 0.005$), lower average session RPE (5.1 vs. 6.0; ES = 0.72), and lower time under tension (MSD = 0.49-0.55) across the training programmes (Banyard et al., 2020; Dorrell, Smith, et al., 2020; Orange, Metcalfe, Robinson, et al., 2020). In addition, the VBT groups were able to maintain a faster average velocity across each training session (MSD = 1.25-2.40) (Banyard et al., 2020; Orange, Metcalfe, Robinson, et al., 2020), suggesting VBT is effective in accounting for fatigue, maintaining a higher mechanical output, and facilitating lower overall training volume-load. S&C coaches, therefore, could facilitate similar or superior performance improvements whilst limiting the amount of total volume or work by implementing VBT as an autoregulatory tool, potentially minimising fatigue and maintaining player readiness throughout a competitive period, however, more research is required to evaluate this hypothesis.

Despite the large between-participant variability present in load-velocity data (Balsalobre-Fernández, García-Ramos, et al., 2018; Banyard et al., 2018; Banyard, Nosaka, & Haff, 2017; Ruf et al., 2018), most VBT-related training studies have utilised group or generalised LVPs to dictate load prescription (Dorrell, Smith, et al., 2020; Orange, Metcalfe, Robinson, et al., 2020; Shattock & Tee, 2020). Interestingly, Dorrell, Moore, et al. (2020) compared group- vs. individualised load-velocity profiling across a 6-week intervention utilising similar prescriptions as their initial study (Dorrell, Smith, et al., 2020). This study is the only one to adopt a true method of readjusting 1RM on a set-by-set basis, using a custom-built application (Moore & Dorrell, 2020). No significant group x time interactions were observed for any of the performance assessments (p = 0.06-0.71), however, there was a slightly higher improvements in back squat 1RM (9.7% vs. 7.2%; MSD = 0.47 vs. 0.41), CMJ (6.6% vs. 4.3%; MSD = 0.30 vs. 0.30) and SJ (4.6% vs. 4.3%; MSD = 0.25 vs. 0.17), suggesting that individualising the LVP to adjust load would be beneficial to practitioners seeking to optimise training adaptations.

Only two studies to date have implemented individualised LVPs (Banyard et al., 2020; Dorrell, Moore, et al., 2020), with only one of them individualising the autoregulatory method

(Dorrell, Smith, et al., 2020), meaning there is currently no literature that investigates the effectiveness of an individualised LVP that also individualises load manipulation (e.g., recalculation of 1RM on a set or sessional basis) against traditional prescriptive methods. This omission from the literature could be due to several reasons: 1) 1RM prediction protocols have been shown to be inaccurate and unreliable in lower-body free-weight exercises (Banyard, Nosaka, & Haff, 2017; Lake et al., 2017; Ruf et al., 2018); 2) LVPs can be time-consuming when implementing the multiple-point method; and 3) LVPs can be impractical when dealing with large groups or squads. Thus, a new, time-efficient, and reliable method for predicting 1RM in free-weight lower body exercises is required to provide practitioners with an effective strategy for autoregulating load.

Chapter 3.0: Study 1 - The effectiveness of two methods of prescribing load on maximal strength development: A systematic review

3.1 Study rationale

This PhD thesis follows an applied research model that organises a series of research studies designed to better integrate and direct research to sporting performance (Bishop, 2008). The initial stages of this model suggests a comprehensive review of relevant literature should be undertaken, enabling researchers to identify and define “a problem” and develop research hypotheses through descriptive research (Bishop, 2008). The first study in this doctoral programme is a systematic review investigating the efficacy of two common methods of load prescription, % 1RM and RM targets. The systematic review was chosen as the most appropriate method to synthesis and summarise this literature as it follows a logical and methodical framework, permits a more stringent search strategy and inclusion criteria, and can provide statistical comparisons across methods vs. more narrative review formats. This review originally set out to compare four different methods for prescribing load (% 1RM, RM targets, RIR, and VBT), however, due to the paucity of high-quality literature, only % 1RM and RM targets were included.

The main aim of this study was to compare these prescriptive methods to identify the most effective for increasing maximum strength (1RM). Both % 1RM and RM can be classified as non-flexible prescriptive methods and were identified as two comparators for VBT during the initial stages of the PhD. Additionally, combining flexible programming strategies with an effective non-flexible approach is essential for effective S&C planning and prescription. A shift in thesis aims, therefore, meant this comparison would be integral in determining the most appropriate prescriptive strategy to compliment VBT-based autoregulation.

3.2 Abstract

Background: Optimal prescription of resistance training load (kg) is essential for the development of maximal strength. Two methods are commonly used in practice with no clear consensus as to the most effective for improving maximal strength.

Objective: The primary aim of this review was to compare the effectiveness of % 1RM and RM targets as load prescription methods for the development of maximal strength.

Method: Electronic database searches of MEDLINE, SPORTDiscus, Scopus, and CINAHL Complete were conducted in accordance with PRISMA guidelines. Studies were eligible for inclusion if a direct measure of maximal strength was used, a non-training control group was the comparator, the training intervention was > 4 weeks in duration and was replicable, and participants were defined as healthy and between the ages of 18-40. Methodological quality of the studies was evaluated using a modified Downs and Black checklist. Percentage change (%) and 95% confidence intervals (CI) for all strength-based training groups were calculated. Statistical significance ($p < 0.05$) was reported from each study.

Results: Twenty-two studies comprising a total of 761 participants (585 males and 176 females) were found to meet the inclusion criteria. Twelve studies were returned for % 1RM, with 10 for RM. All studies showed statistically significant improvements in maximal strength in the training groups (31.3% ± 21.9%; 95% CI: 33.1% to 29.5%). The mean quality rating for all studies was 17.7 ± 2.3. Four studies achieved a good methodological rating, with the remainder classified as moderate.

Conclusions: Both % 1RM and RM are effective tools for improving maximal strength. % 1RM appears to be a better prescriptive method than RM potentially due to a more sophisticated management of residual fatigue, however, large heterogeneity was present within this data.

Lower body and multi-joint exercises appear to elicit greater increases in maximal strength. Greater consensus is required in defining optimal training prescriptions, associated physiological adaptations, and training status.

Key Points:

1. Prescribing load via % 1RM appears to be a better method for improving maximal strength than RM targets due to a more comprehensive management of residual fatigue.
2. Multi-joint, compound, lower body exercises elicited a greater improvement in maximal strength than single-joint, isolated, and upper body exercises.
3. Large heterogeneity in training prescriptions, training status, and physiological assessment methods were evident in the literature, with a clear need for greater consensus on the most effective way to improve maximal strength in various demographics.

3.3 Introduction

Resistance training is important for athletic development and is underpinned by 50+ years of peer-reviewed evidence (Kraemer & Ratamess, 2004; Suchomel et al., 2018; Williams et al., 2017). Resistance training is vital in enhancing maximal strength, speed, agility, RFD, hypertrophy, muscular endurance, motor control, balance, and coordination (Bird et al., 2005; Kraemer & Ratamess, 2004; Suchomel et al., 2016, 2018). Maximal strength can be defined as one's ability to exert maximal force against an external resistance and requires a maximal voluntary contraction (Siff, 2008; Williams et al., 2017), and is associated with many of the aforementioned physical qualities (Suchomel et al., 2016). Optimising the prescription of resistance training is therefore an important consideration for S&C coaches.

Effective resistance training prescription manipulates variables such as training volume and frequency, exercise selection and order, movement velocity, rest periods, and load (Fleck & Kraemer, 2014; Sheppard & Triplett, 2016). Manipulating these variables elicits specific physiological adaptations such as increases in neural recruitment, rate coding, intramuscular coordination, or muscle cross-sectional area (Folland & Williams, 2007; Peterson et al., 2004; Rhea, Alvar, et al., 2003). These physiological adaptations have been linked with prescription methods used to elicit improvements in maximal strength, specifically the manipulation of training volume and load (Peterson et al., 2004; Ralston et al., 2017; Rhea, Alvar, et al., 2003).

Optimising load prescription is essential for the effective development of maximal strength (Bird et al., 2005; Kraemer et al., 1988; Peterson et al., 2004). Load can be prescribed using a two-part method: 1) undertaking a dynamic maximal strength test (1RM); and 2), prescribing submaximal loads based upon the initial 1RM (e.g. 85% of 1RM) (% 1RM) or a specific RM target (e.g. 5RM) (Fleck & Kraemer, 2014; Sheppard & Triplett, 2016). Both these methods of load prescription are common in practice and research, however, the most effective in developing maximal strength is still yet to bet determined.

Training programmes based on the % 1RM load prescription method use submaximal percentages based off the maximal load an individual can lift (1RM) (Fry, 2004; Tan, 1999). Proponents of this method suggest it is more favourable than using RM targets when implementing an undulated approach to training due to the ability to prescribe light and heavy days across a week, control for different proximities to failure and provide a more objective programming strategy for individuals (DeWeese et al., 2015a; Painter et al., 2012). Conversely, providing individuals with RM targets allows for a more autoregulatory approach in which the RM target dictates the load (Tan, 1999). Supporters of this method suggest that due to daily fluctuations in strength based upon a number of factors such as sleep, residual fatigue and nutritional status, RM targets can provide a more flexible programming strategy than % 1RM and reduce the number of required direct or indirect strength assessments (Fry, 2004; Suchomel et al., 2021; Tan, 1999). Nonetheless, using RM targets, similar to that of more novel methods such as RIR — the quantification of training intensity by assigning the number of repetitions still able to perform immediately following a working set in accordance with a 1-10 scale of effort (e.g. 1 = 1 repetition, 0 = 0 repetitions etc.) — require the individual to subjectively adjust loads, potentially resulting in inaccurate or inappropriate prescriptions (Helms et al., 2016; Suchomel et al., 2021; Zourdos et al., 2016).

Comparative charts and tables have previously been designed in order to provide an interchangeable approach between % 1RM and RM targets (Sheppard & Triplett, 2016). Conversely, research has highlighted that the repetition-load continuum can vary dependent on the population (trained vs. untrained or strength vs. endurance, for example) (Brzycki, 1993; Desgorces et al., 2010; Richens & Cleather, 2014; Shimano et al., 2006). Descorges et al. (2010) highlighted differences in the number of repetitions performed when comparing four different types of athletes (handball vs. powerlifters vs. swimmers vs. rowers). The more strength-based athletes performed significantly lower repetitions across multiple percentages of 1RM compared to the endurance-based athletes. Repetition maximum targets and RTF have also been previously used to predict 1RM (Desgorces et al., 2010; García-Ramos, Barboza-González, et al., 2019; Mayhew et al., 2008). Mayhew et al. (2008) investigated 14 different predictive equations and observed differences of -24.0 to 27.1% in some equations when compared to the direct assessment in bench press. Similarly, Garcia-Ramos et al. (2019) compared two predictive equations when lifting to failure in the prone bench-pull, with the largest differences being -3.6 ± 5.4 kg. The various RM targets associated with different %

1RM values demonstrates that pre-defined repetition-load continuums may not be appropriate, and the two methods of prescribing training load are not interchangeable, and therefore, their effectiveness needs to be assessed against one another.

To date, only one study has directly compared the two aforementioned methods of load prescription (Carroll, Bernards, et al., 2019). 15 healthy male participants were split in to two training groups (relative intensity vs. RM targets) and were asked to complete a volume-equated and exercise-matched 10-week block-periodised resistance training intervention (3 x days per week). The RM group worked to a maximum in each training session (the final set performed must be a true RM) whereas the relative intensity group worked to percentages of the maximum set/repetition combinations. This relative intensity method allowed for the perturbations in strength levels to still be accounted for, whilst still working to individual percentages of 1RM. Carroll et al. (2019) observed greater improvements in vertical jump performance, RFD, and maximal strength (peak force) during an isometric mid-thigh pull assessment in the relative intensity group compared to the RM group. These differences were attributed to a greater training stress in the RM group due to the consistent training to failure prescribed each week. Despite encouraging results in the favour of % 1RM prescriptions, more investigation is required to determine the efficacy of each method and provide more robust recommendations as to which is the best method to adopt in practice.

The purpose of this review is to assist practitioners' understanding of methods used to prescribe load. There are several prescriptive approaches available to S&C coaches, however, no study has reviewed the most effective tool for developing maximal strength. Therefore, the aim of this systematic review is to compare the effectiveness of % 1RM vs. RM targets as a means of improving maximal strength. A secondary aim of the review was to investigate the quality of research in this area, to develop recommendations for S&C practitioners, and researchers in terms of methodological approaches and research designs.

3.4 Methods

This review has been written in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses statement) guidelines (Moher et al., 2009).

3.4.1 Literature search

Literature searches were originally performed on 11th October 2017 and then updated on 30th August 2018, 14th March 2019 and 13th September 2019 using the electronic search engines SPORTDiscus, MEDLINE, Scopus and CINAHL Complete. Searches were performed using titles, abstracts, and keywords, and utilised Medical Subject Headings (MeSH), indexing terms and Boolean operators (AND/OR/NOT). Terms were grouped into themes relating to resistance training, prescriptive methods, and age/demographic. For example, for SPORTDiscus, the following search terms were used; ‘resistance exer* or resistance train* or resistance strength* or resistance load*’, ‘musc* strength or strength train*’, ‘musc* power or power train*’, ‘rate of force development or RFD’, ‘weight lift* or weight train*’, ‘olympic lift*’ AND ‘1RM or rep* max*’, ‘rep* to fatigue or RTF or predict* equation or AMRAP’ NOT ‘senior or elder* or old’, 'supplement*', 'obes* or overweight or blood flow restrict*', 'Injur*'. All searches were conducted by the lead author (ST) and developed in consultation with an information scientist. The search strategy was piloted and refined prior to being implemented.

Search results were collated using EndNote software (Thomson Reuters, New York) with duplicates removed automatically (EndNote) and manually (ST). The remaining titles and abstracts were screened for relevance by the lead author. Of those that were deemed potentially relevant, full texts were obtained and independently assessed for eligibility by the lead author, with a random sample (10%) independently assessed by two of the research team (DR, AB). The included studies were then independently assessed by a second author (AR). If the inclusion of a study could not be agreed upon, a third author facilitated a discussion to reach a consensus. Reference lists of each study were manually searched to identify potentially relevant studies (ST).

3.4.2 Inclusion and exclusion criteria

Studies were deemed eligible if they met the following criteria:

- A direct, practical measure of strength was employed (1RM)
- A non-resistance training, control group was used as a comparator
- The control group continued normal daily activities without additional exercise that would influence strength
- The training intervention was progressive
- The methods section contained sufficient information for the training intervention to be fully replicable
- The training intervention was strength based, isotonic exercise lasting for a minimum of 4 weeks
- No form of concurrent training was prescribed (plyometric and/or endurance)
- Participants were aged 18-40
- Full texts were available in English and were original, peer-reviewed and primary research.

Studies were not excluded based on the sex of the participants or previous training history. This review did not control for volume matching. It was thought with the focus being prescribing load, only including studies that also matched training volumes would reduce the inclusivity of the search. In the event a study used multiple groups and only some conditions met the inclusion criteria, only the relevant data was extracted.

3.4.3 Data extraction process

Study characteristics including sample size (n), age (years), body mass (kg), stature (cm), sex, training history, duration of the intervention, training frequency, description of the intervention (exercises, sets, repetitions, rest and load), direct assessment of strength, and method of programme progression were extracted for the eligible studies. The means and standard deviation (*SD*) for the primary outcome measure (change in absolute strength (kg)) were obtained and relative changes (percentage difference (% diff)) calculated with 95% CIs. All strength data was reported in absolute values (kg) unless unavailable, in which case relative ($kg.bm^{-1}$) values were reported. Data extraction of all articles was independently assessed for accuracy (AR). When relevant data were not reported, authors were contacted. If authors failed to provide the necessary data, pixel analysis was used to extract appropriate values (DigitizeIt) (ST). Reviewers were not blinded at any stage of the validation process.

3.4.4 Methodological quality assessment

Methodological quality was assessed using the Downs and Black quality assessment tool (Downs & Black, 1998) (appendix A), as modified by Davies et.al. (2016). This quality assessment tool was deemed more appropriate than other tools (Cochrane and PEDro, for example) due to its greater suitability to a non-clinical intervention (Davies et al., 2017; Grgic, Schoenfeld, Davies, et al., 2018; Grgic, Schoenfeld, Skrepnik, et al., 2018; Schoenfeld et al., 2017). A detailed description of each criterion can be found elsewhere (Downs & Black, 1998). Briefly, of the 29 points available, 20+ was deemed as a 'good' methodology, 11-19 moderate and < 11 as poor quality. This process was independently assessed by two authors (ST/AR). Any disputes were settled through discussion with a third author (DR).

3.5 Results

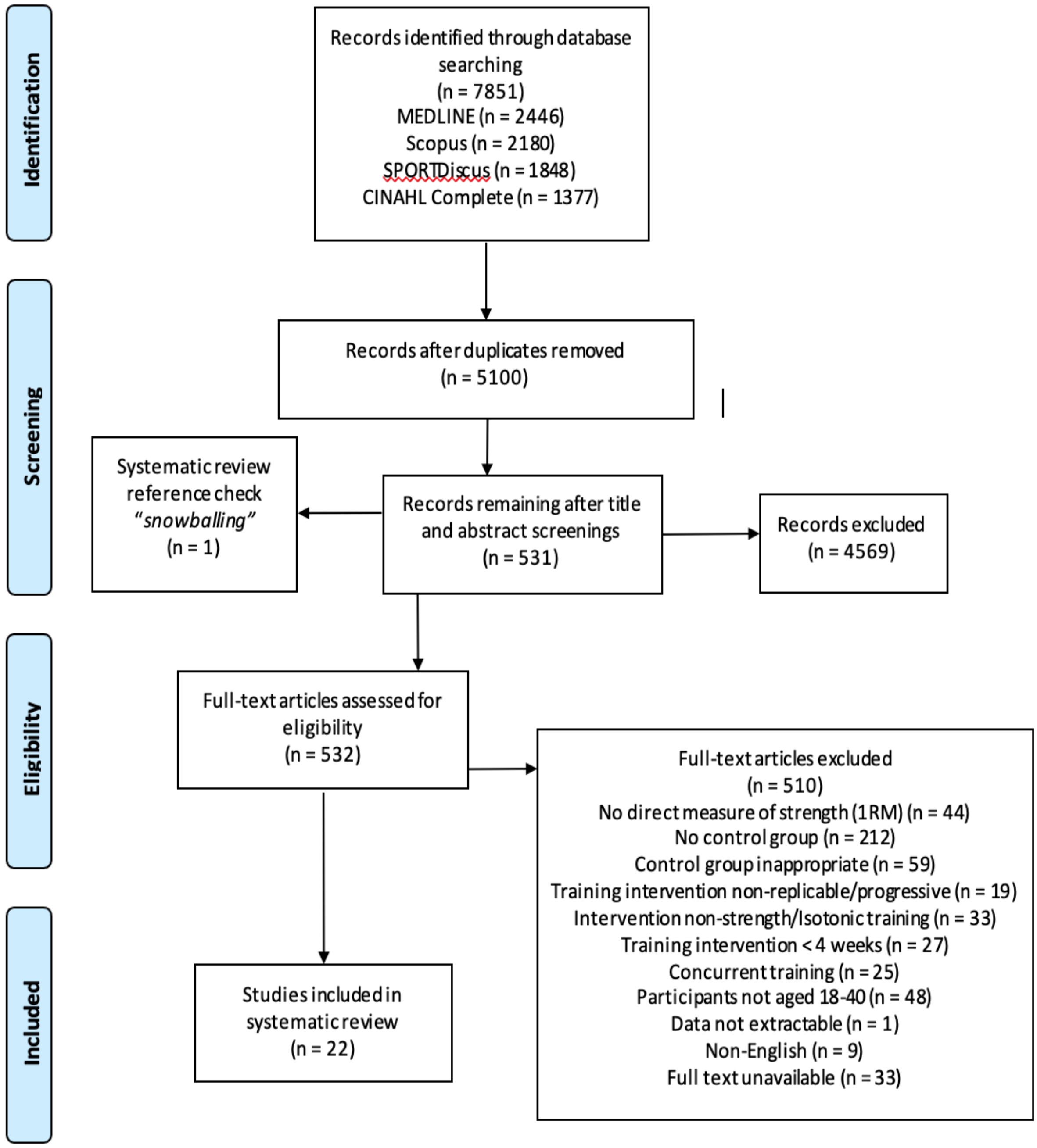

Figure 15. PRISMA flow diagram.
Snowballing = Studies included for eligibility assessment from other, relevant systematic reviews.

Table 6. Study characteristics.

Study	Participants (*n*)	Groups (+ participant numbers (*n*))	Sex (*n*)	Age (years ± SD)	Body mass (kg ± SD)	Stature (cm ± SD)	Resistance training experience	Participant characterisation
Weiss et al. (1988)	56	RT (28) C (28)	M (28) F (28)	20.8 ± 1.8	NR	NR	NRT < 3 months	Healthy
Braith et al. (1993)	58	RT (47) C (11)	M (33) F (25)	24.0 ± 4.0 25.0 ± 5.0	70.1 ± 9.0 74.3 ± 14.5	174.0 ± 6.3 172.6 ± 6.6	NRT < 1 year	Untrained
Moss et al. (1997)	31	RT - G90 (9) RT - G35 (11) RT - G15 (10)	M	22.7 ± 3.4 24.0 ± 3.4 22.9 ± 2.8	75.8 ± 5.6 83.2 ± 8.8 78.1 ± 10.4	179.0 ± 6.8 185.7 ± 8.5 182.6 ± 6.7	Well-trained	University students (Non-dominant arm = Control group)
Bell et al. (2000)	21	RT (11) C (10)	M (12) F (9)	22.3 ± 3.3	73.4 ± 11.6	176.0 ± 9.3	NRT	University students
Campos et al. (2002)	31	RT - LR (9) RT - IR (7) RT - HR (7) C (5)	M	21.1 ± 1.5 20.7 ± 2.9 20.4 ± 3.5 31.6 ± 9.8	80.1 ± 8.4 79.5 ± 7.8 70.2 ± 9.5 80.8 ± 23.3	179.8 ± 6.5 179.6 ± 7.4 174.3 ± 8.6 178.1 ± 5.5	NRT < 6 months	Healthy
McBride et al. (2003)	28	RT - S1 (9) RT - M6 (9) C (10)	M (15) F (13)	22.1 ± 3.4 20.0 ± 1.22 22.4 ± 1.89	83.7 ± 29.4 70.7 ± 23.0 70.6 ± 7.8	172.8 ± 10.5 169.4 ± 11.8 171.3 ± 7.2	NRT (< 6 months)	Untrained
Willoughby (2004)	22	RT (12) C (10)	M	20.9 ± 2.76	78.7 ± 6.2	176.5 ± 7.1	NRT < 6 months	Untrained
Tricoli et al. (2005)	14	RT (7) C (7)	M	22.0 ± 1.5	73.4 ± 10.4	179.4 ± 8.8	NRT < 3 months (trained prior)	College students
Rana et al. (2008)	16	RT (9) C (7)	F	20.6 ± 1.9 22.9 ± 2.4	64.1 ± 7.9 72.5 ± 15.0	165.6 ± 4.9 163.6 ± 4.5	NRT	Untrained
Tanimoto et al. (2008)	24	RT (12) C (12)	M	19.5 ± 0.5 19.8 ± 0.7	63.8 ± 4.0 64.2 ± 4.0	174.8 ± 4.3 174.3 ± 7.2	NRT	Healthy
Terzis et al. (2008)	17	RT (11) C (6)	M	22.0 ± 1.0	85.0 ± 4.0	184.0 ± 3.0	NRT < 1 year	P.E students
Hartmann et al. (2009)	40	RT - SPP (13) RT - UP (14) C (13)	M	24.31 ± 3.2 25.14 ± 4.0 24.77 ± 3.1	84.7 ± 11.2 79.4 ± 10.4 74.4 ± 12.1	183.9 ± 7.2 177.6 ± 7.5 180.5 ± 8.1	RT in BP (minimum 1RM of 100 kg)	Sport Science students
Cormie et al. (2010)	16	RT (8) C (8)	M	23.9 ± 4.8	79.8 ± 12.0	180.0 ± 6.4	NRT (Technically proficient in BS)	Healthy
Chtourou et al. (2012)	30	RT - MTG (10) RT - ETG (10) C (10)	M	22.9 ± 1.3	72.0 ± 8.8	180.0 ± 5.0	NRT < 6 months	P.E students
Weier et al. (2012)	12	RT (6) C (6)	M (6) F (6)	20 ± 0.8 22 ± 0.6	NR	NR	NR	University students

Naclerio et al. (2013)	32	RT - LV (6)	M (20)	23.3 ± 1.2	66.4 ± 11.0	169.9 ± 8.4	NRT < 5 years	Team sports athletes
		RT - MV (6)	F (12)	23.3 ± 1.4	71.4 ± 8.5	173.3 ± 7.6		Soccer (20) (M)
		RT - HV (8)		23.9 ± 2.0	69.4 ± 12.5	173.0 ± 9.8		Volleyball (12) (F)
		C (7)		22.1 ± 1.1	71.1 ± 14.2	169.7 ± 6.9		
Aguiar et al. (2015)	18	RT (9)	M	20.9 ± 2.0	73.7 ± 9.4	173.8 ± 6.9	NRT < 6 months	Healthy
		C (9)		20.0 ± 1.8	75.0 ± 8.8	176.4 ± 8.1		
Akagi et al. (2016)	23	RT (13)	M	22.1 ± 1.1	61.4 ± 5.8	170.6 ± 5.8	NRT upper body (< 6 months)	Healthy
		C (10)						
Botton et al. (2016)	43	RT - UG (14)	F	24.8 ± 1.4	60.8 ± 6.4	163.0 ± 6.5	NRT < 3 months	Healthy
		RT - BG (15)		24.3 ± 3.7	57.0 ± 4.8	160.2 ± 5.8		
		C (14)		22.7 ± 2.8	58.0 ± 5.7	163.6 ± 6.2		
Wirth et al. (2016)	120	RT - SQ (43)	M	23.7 ± 2.7	81.6 ± 9.8	181.7 ± 7.5	NR	Students
		RT - LP (40)		23.8 ± 2.3	80.5 ± 8.1	180.1 ± 7.0		
		C (37)		25.1 ± 2.1	78.2 ± 8.5	181.0 ± 5.7		
Jarvis et al. (2017)	21	RT (11)	M (15)	27.5 ± 3.2	72.7 ± 18.0	169.6 ± 10.3	RT > 1 year	Collegiate Athletes
		C (10)	F (6)	27.2 ± 3.4	76.4 ± 11.5	176.2 ± 7.9		
Souza et al. (2018)	33	RT - NP (8)	M	25.6 ± 6.3	79.5 ± 13.0	172.8 ± 6.1	NRT (< 6 months)	College Students
		RT - TP (9)		25.0 ± 7.0	76.0 ± 9.9	175.3 ± 5.7		
		RT - UP (8)		24.4 ± 5.2	74.9 ± 4.2	176.8 ± 5.3		
		C (8)		25.1 ± 3.3	76.8 ± 11.7	173.6 ± 6.8		

Mean ± SD Standard Deviation

1RM 1 repetition maximum, *BG* bilateral training group, *C* control, *cm* centimetres, *BP* bench press, *BS* back squat, *ETG* evening training group, *F* female, *G15* 15% load group, *G35* 35% load group, *G90* 90% load group, *HR* high-repetition group, *HV* high volume, *IR* intermediate-repetition group, *kg* kilograms, *LP* leg press group, *LR* low-repetition group, *LV* low volume, *M* male, *M6* six set training group, *MTG* morning training group, *MV* moderate volume, *n* number, *NP* non-periodised group, *NRT* no resistance training, *NR* not reported, *P.E* Physical Education, *RT* resistance training, *S1* 1 set training group, *SPP* strength-power periodisation, *SQ* squat group, *TP* traditional periodisation group, *UG* unilateral training group, *UP* daily undulating periodised group,

Table 7. Training parameters.

Study	Duration (weeks)	Frequency (session x week)	Exercise(s)	Sets (*n*)	Reps (*n*)	Rest (min)	Load (% 1 RM or RM target)	Load Adjustment
Weiss et al. (1988)	8	3	Seated Plantar flexion	4	9-13	2-3	9-13 RM	> when RM target exceeded
Braith et al. (1993)	18	2-3	Knee Extension	1	7-10	NR	7-10 RM	> 5% when RM target exceeded
Moss et al. (1997)	9	3	Elbow flexion	3-5	10 (G15) 7 (G35) 2 (G90)	NR	G15 (15%) G35 (35%) G90 (90%)	1RM @ 4 weeks
Bell et al. (2000)	12	3	BL Leg Press, UL Knee Flexion, UL Knee Extension, BL Calf Raises	2-6	4-12	NR	72-84%	> approx. 4% every 3 weeks
Campos et al. (2002)	8	2 x week 1-4 3 x week 5-8	Leg Press, Back Squat, Knee Extension	LR (4) IR (3) HR (2)	3-5 9-11 20-28	3 2 1	3-5 RM 9-11 RM 20-28 RM	> when RM target exceeded
McBride et al. (2003)	12	2	Bicep Curl, Leg Press, Chest Flye, Sit Ups, Back Extension	1-6 1-3	6-10 15	2-3	6-10 RM	> when RM target exceeded
Willoughby (2004)	12	3	Leg Press, Knee Extension, Knee Flexion	3	6-8	1.5	85-90%	1RM @ Weeks 3, 6, 9, 12
Tricoli et al. (2005)	8	3	High Pull, Power Clean, Clean and Jerk, Half-Squat	3-6	4-6	NR	4-6 RM	Volume increased after 4 weeks
Rana et al. (2008)	6	2 x week 1 3 x weeks 2-6	Leg Press, Knee Extension, Back Squat	3	6-10	2	80-85%	> when RM target exceeded
Tanimoto et al. (2008)	13	2	Back Squat, Bench Press, Latissimus-dorsi Pull Down, Abdominal bend, Back extension	3 (+ 1 WU set)	8	1	80-90%	1RM @ 7 weeks
Terzis et al. (2008)	14	2 x week 1-2 3 x week 3-14	Leg press (45° inclination), Semi-squat (knees 90°), Bench press, Arm curl, Overhead press, Elbow Extension (pulley), Seated Row, Sit ups, Back Extension	2-3	6-20	NR	8-10 RM 6 RM	Daily > to meet RM target
Hartmann et al. (2009)	14	3	Bench Press	5	3-25	1.5-5	3-5 RM 8-12 RM 20-25 RM	> 2-10 kg when RM target exceeded
Cormie et al. (2010)	10	3	Back Squat	3-7	3-6	3-5	75-90%	1RM @ Week 5
Chtourou et al. (2012)	8	3	Knee Extension, Knee Flexion, Back Squat	3-6	3-6	2-9	60-120%	1RM @ Week 4
Weier et al. (2012)	4	3	Back Squat	6-9	6-8	3	80%	> 2-5% when target exceeded
Naclerio et al. (2013)	6	3	TP 1: Bench Press, Incline Bench Press,	1-3	8	3	75%	NR

			Dumbbell Fly, Upright Row, Lateral Raise, Posterior Lateral Raise, Barbell Bicep Curl Dumbbell Bicep Curl, Machine Bicep Curl TP 2: Smith Machine Parallel Squat, Leg Press, Knee Extension, Latissimus dorsi Pull Down, Seated Row, SA Dumbbell Row, Machine Triceps Extension, Standing Triceps Pushdown, SA Triceps Extension					
Aguiar et al. (2015)	8	2	Knee Extension	3	8-12	1	75%	1RM @ 15-day intervals
Akagi et al. (2016)	6	3	Triceps Extension	5	8	1.5	80%	1RM every 2 weeks
Botton et al. (2016)	8	2	UL Knee Extension BL Knee Extension	2-4	5-15	1-3	12-15 RM 9-12 RM 7-10 RM 5-8 RM	1-5 kg when RM target exceeded
Wirth et al. (2016)	8	2	Back Squat, Leg Press	5	4-10	5	8-10 RM 6-8 RM 4-6 RM	> 2.5-10 kg when RM target exceeded
Jarvis et al. (2017)	8	3	Hip Thrust	5	5	3	85%	> 2.5% when RM target exceeded
Souza et al. (2018)	12	2	Back Squat Knee Extension	2-4	4-12	2-3	4-12 RM	1RM @ weeks 1, 6, 12

1RM 1 repetition maximum, *BL* bilateral, *G15* 15% load group, *G35* 35% load group, *G90* 90% load group, *HR* high-repetition group, *IR* intermediate-repetition group, *kg* kilograms *LR* low-repetition group, *min* minutes, *n* number, *NR* not reported, *reps* repetitions, *RM* repetition maximum, *UL* unilateral, *SA* single arm, *WU* warm up

Table 8. Summary of the changes in maximal strength following an intervention compared to a non-training control.

Study	Groups	Test	Experimental Group(s)			Control Group		
			Pre kg ± *SD*	Post kg ± *SD*	Percentage Change (%)	Pre kg ± *SD*	Post kg ± *SD*	Percentage Change (%)
Weiss et al. (1988)	RT (M)	Seated Plantar	98.5 ± 16.5	113.5 ± 13.3	15.2	91.9 ± 18.6	91.9 ± 19.8	0.0
	RT (F)	Flexion	81.0 ± 23.8	93.4 ± 22.8	15.3	74.4 ± 8.1	74.4 ± 8.1	0.0
Braith et al. (1993)	RT	Knee Extension	85.4 ± 27.9	111.6 ± 33.6	30.7	97.2 ± 29.7	100.6 ± 32.0	3.5
Moss et al. (1997)	RT (G90)	Elbow Flexion	18.8 ± 3.0	21.7 ± 3.3	15.4	19.4 ± 3.1	20.7 ± 2.8	6.9
	RT (G35)		20.0 ± 4.7	22.0 ± 5.1	10.0	21.0 ± 4.0	21.4 ± 4.2	2.1
	RT (G15)		19.0 ± 4.5	20.3 ± 5.0	6.8	19.8 ± 4.8	21.0 ± 4.7	6.0
Bell et al. (2000)	RT	Knee Extension	17.3 ± 2.8	27.3 ± 4.6	57.8	18.2 ± 4.0	20.0 ± 4.0	9.9
		Leg Press	151.4 ± 51.8	249.1 ± 151.0	64.5	165.9 ± 67.1	180.0 ± 36.7	8.5
		Knee Extension	36.8 ± 9.5	48.6 ± 9.5	32.1	38.2 ± 9.2	39.5 ± 8.1	3.4
		Leg Press	260.5 ± 78.1	393.6 ± 75.7	51.1	266.8 ± 104.7	297.3 ± 106.7	11.4
Campos et al. (2002)	RT (LR)	Leg Press	309.1 ± 65.9	497.2 ± 93.1	60.8	284.8 ± 38.1	302.6 ± 40.7	6.3
	RT (IR)		292.4 ± 44.4	396.7 ± 68.8	35.7			
	RT (HR)		298.6 ± 35.0	361.9 ± 37.5	21.2			
	RT (LR)	Leg Extension	96.1 ± 24.2	154.2 ± 33.3	60.4	93.9 ± 22.9	99.6 ± 24.2	6.1
	RT (IR)		97.5 ± 16.0	144.9 ± 28.8	48.6			
	RT (HR)		86.8 ± 19.7	135.6 ± 11.4	56.2			
	RT (LR)	Back Squat	115.2 ± 30.0	246.5 ± 57.0	114.0	116.8 ± 18.2	139.3 ± 23.6	19.3
	RT (IR)		120.34 ± 21.9	213.4 ± 27.7	77.3			
	RT (HR)		111.2 ± 22.0	193.1 ± 20.2	73.7			
McBride et al. (2003)	RT (S1)	Bicep Curl	33.8 ± 12.6	37.1 ± 15.1	9.7			
		Leg Press	242.9 ± 139.6	324.2 ± 166.4	33.5			
	RT (M6)	Bicep Curl	29.6 ± 10.3	35.6 ± 10.8	20.5	30.2 ± 11.2	30.2 ± 11.2	0.0
		Leg Press	191.2 ± 76.8	293.4 ± 126.2	53.5	198.2 ± 52.1	208.4 ± 61.7	5.2
Willoughby (2004)	RT	Leg Press	3.1 ± 4.2	4.5 ± 5.5	41.4	3.3 ± 4.3	3.8 ± 4.8	15.2
Tricoli et al. (2005)	RT	Half Squat	146.3 ± 30.5	210.3 ± 22.3	43.8	149.5 ± 24.6	159.1 ± 22.2	6.4
		Clean & Jerk	57.4 ± 5.8	77.4 ± 11.7	34.8			
Rana et al. (2008)	RT	Leg Press	198.1 ± 27.2	319.0 ± 52.5	61.1	216.0 ± 36.6	228.8 ± 45.8	5.9
		Back Squat	56.7 ± 8.7	83.1 ± 17.4	46.7	60.7 ± 9.1	60.1 ± 31.3	-0.9
		Knee Extension	51.2 ± 10.9	77.1 ± 11.8	50.7	59.5 ± 14.3	62.9 ± 18.0	5.7
Tanimoto et al. (2008)	RT	Vertical Squat	105.1 ± 16.1	136.5 ± 20.4	29.9	113.7 ± 16.3	112.9 ± 17.8	-0.7
		Chest Press	41.3 ± 5.4	55.1 ± 9.1	33.4	46.1 ± 10.0	47.3 ± 11.1	2.6
		Lat Pull-Down	39.6 ± 7.2	55.7 ± 9.0	40.7	47.7 ± 6.9	48.9 ± 7.3	2.5
		Ab Board	59.3 ± 8.8	90.4 ± 13.4	52.5	66.4 ± 7.9	67.1 ± 8.5	1.1
		Back Extension	61.5 ± 10.0	113.0 ± 13.5	83.7	70.0 ± 16.4	72.4 ± 16.2	3.4
Terzis et al. (2008)	RT	Back Squat	101.0 ± 6.0	123.0 ± 6.0	21.8			
		Leg Press	237.0 ± 16.0	297.0 ± 18.0	25.3			

		Bench Press	77.0 ± 4.0	90.0 ± 5.0	16.9			
Hartmann et al. (2009)	RT (SPP)	Bench Press	95.5 ± 20.9	109.4 ± 19.6	14.5	58.5 ± 10.2	59.2 ± 10.5	1.3
	RT (UP)		95.9 ± 17.5	105.4 ± 19.5	9.9			
Cormie et al. (2010)	RT	Back Squat	1.3 ± 0.2	1.6 ± 0.1	28.1	1.4 ± 0.1	1.4 ± 0.1	-1.5
Chtourou et al. (2012)	RT (MTG)	Leg Extension	71.0 ± 9.9	87.5 ± 7.9	23.2			
	(07:00)	Leg Curl	70.0 ± 11.3	85.5 ± 9.0	22.1			
		Back Squat	74.0 ± 12.0	89.5 ± 9.8	21.0			
	RT (MTG)	Leg Extension	73.5 ± 8.5	87.0 ± 8.2	18.4	69.0 ± 9.7	69.5 ± 9.3	0.7
	(17:00)	Leg Curl	73.0 ± 11.1	85.0 ± 7.5	16.4	64.0 ± 9.4	64.0 ± 6.6	0.0
		Back Squat	76.5 ± 11.1	88.5 ± 8.5	15.7	67.5 ± 10.3	67.0 ± 9.5	-0.7
	RT (ETG)	Leg Extension	69.5 ± 8.0	81.5 ± 4.7	17.3			
	(07:00)	Leg Curl	68.5 ± 10.0	81.5 ± 6.7	19.0			
		Back Squat	68.0 ± 11.1	80.5 ± 9.8	18.4			
	RT (ETG)	Leg Extension	72.0 ± 7.5	85.0 ± 4.7	18.1	72.0 ± 9.2	72.0 ± 8.9	0.0
	(17:00)	Leg Curl	71.0 ± 8.8	85.0 ± 6.7	19.7	66.5 ± 10.6	67.0 ± 10.1	0.8
		Back Squat	71.0 ± 10.5	84.5 ± 9.6	19.0	69.0 ± 10.2	69.5 ± 9.8	0.7
Weier et al. (2012)	RT	Back Squat	86.3 ± 13.4	161.6 ± 23.2	87.3	83.1 ± 13.8	85.2 ± 13.9	2.5
Naclerio et al. (2013)	RT (LV)	Bench Press	49.3 ± 19.1	54.4 ± 22.1	10.3			
		Upright Row	40.8 ± 10.7	45.0 ± 13.8	10.3			
		Back Squat	103.0 ± 30.8	107.1 ± 30.6	4.0			
	RT (MV)	Bench Press	65.9 ± 24.5	72.0 ± 28.4	9.3			
		Upright Row	44.2 ± 9.9	49.9 ± 12.9	12.9			
		Back Squat	126.3 ± 29.2	129.8 ± 40.6	2.8			
	RT (HV)	Bench Press	46.7 ± 19.6	54.5 ± 18.2	16.7	44.6 ± 21.0	44.1 ± 21.9	-1.1
		Upright Row	38.9 ± 10.7	45.7 ± 13.5	17.5	35.4 ± 12.2	35.9 ± 11.7	1.4
		Back Squat	102.1 ± 26.7	119.8 ± 33.6	17.3	100.7 ± 45.0	101.3 ± 43.9	0.6
Aguiar et al. (2015)	RT	Knee Extension	107.4 ± 3.9	135.8 ± 5.5	26.4	106.4 ± 2.6	106.9 ± 2.8	0.5
Akagi et al. (2016)	RT	Tricep Extension	8.6 ± 1.3	11.5 ± 1.8	33.7	9.1 ± 2.0	9.4 ± 2.3	3.3
Botton et al. (2016)	RT (UG)	BL Knee Extension	39.0 ± 7.3	46.6 ± 7.2	19.5			
		UL Knee Extension	38.0 ± 7.8	50.2 ± 8.3	32.1			
	RT (BG)	BL Knee Extension	35.7 ± 7.6	45.5 ± 8.0	27.5	36.7 ± 8.1	37.0 ± 9.6	0.8
		UL Knee Extension	34.9 ± 6.8	43.1 ± 7.3	23.5	39.1 ± 10.0	39.2 ± 10.2	0.3
Wirth et al. (2016)	RT (SQ)	Back Squat	97.1 ± 29.0	118.0 ± 29.4	21.5	75.6 ± 23.9	75.9 ± 21.0	0.4
	RT (LP)	Leg Press	230.3 ± 57.4	296.8 ± 68.3	28.9	220.7 ± 88.1	226.9 ± 64.7	2.8
Jarvis et al. (2017)	RT	Hip Thrust	161.8 ± 50.4	205.9 ± 63.3	27.3	164.6 ± 36.7	174.0 ± 41.9	5.7
Souza et al. (2018)	RT (NP)	Back Squat	140.8 ± 23.9	171.0 ± 36.9	21.5	126.8 ± 21.3	132.1 ± 20.1	4.1
	RT (TP)		141.2 ± 19.6	166.4 ± 30.3	17.9			
	RT (UP)		149.6 ± 34.7	178.4 ± 36.8	19.2			

Mean ± SD.

BG bilateral training group, *BL* bilateral, *ETG* evening training group, *F* female, *G15* 15% load group, *G35* 35% load group, *G90* 90% load group, *HR* high-repetition group, *HV* high volume, *IR* intermediate-repetition group, *kg* kilograms, *LP* leg press group, *LR* low-repetition group, *LV* low volume, *M* male, *M6* six set training group, *MTG* morning training group, *MV* moderate volume, *NP* non-periodised group, , *RT* resistance training, *S1* 1 set training group, *SD* standard deviation, *SPP* strength-power periodisation, *SQ* squat group, *TP* traditional periodisation group, *UG* unilateral training group, *UP* daily undulating periodised group.

Table 9. Methodological quality evaluation using the modified Downs and Black quality assessment tool.

	Reporting										External Validity			Internal Validity																
														Bias							Confounding									
Study	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	Total
Weiss et al. (1988)	1	1	0	1	1	1	1	0	1	1	1	1	1	0	0	1	1	1	0°	1	1	0°	1	0°	0°	1	1	0	0°	19
Braith et al. (1993)	1	1	1	1	1	1	1	0	0	0	0°	0°	0°	0	0	1	1	1	0°	1	1	0°	1	0°	0°	0°	1	0	0°	14
Moss et al. (1997)	1	1	0	1	1	1	1	0	1	0	1	1	0°	0	0	1	1	1	0°	0	1	0°	0°	0°	0°	1	1	0	1	16
Bell et al. (2000)	1	1	0	1	1	1	1	0	0	0	1	1	0°	0	0	1	1	1	0°	1	1	0°	1	0°	0°	0	1	0	0°	15
Campos et al. (2002)	1	1	1	1	1	0	1	1	1	0	1	1	0°	0	0	1	1	1	0°	1	1	0°	1	0°	0°	1	0	0	0°	17
McBride et al. (2003)	1	1	1	1	1	1	1	0	0	0	1	1	0°	0	0	1	1	1	0°	1	1	0°	0°	0°	0°	0	1	0	0	15
Willoughby (2004)	1	1	1	1	1	0	1	0	1	1	1	1	0°	0	0	1	1	1	1	1	1	0°	1	0°	0°	1	1	0°	1	20
Tricoli et al. (2005)	1	1	1	1	1	1	1	0	1	0	1	1	0°	0	0	1	1	1	1	1	1	0°	1	0°	0°	1	1	0	0°	19
Rana et al. (2008)	1	1	1	1	1	1	1	0	0	1	1	1	0°	0	0	1	1	1	1	1	1	0°	1	0°	0°	0	1	0	1	19
Tanimoto et al. (2008)	1	1	1	1	1	1	1	0	0	0	1	1	0°	0	0	1	1	1	0°	1	1	0°	1	0°	0°	0	1	0	0	16
Terzis et al. (2008)	1	1	1	1	1	1	1	0	1	0	1	1	0°	0	0	1	1	1	0°	1	1	0°	0	0°	0°	0	0	1	0	16
Hartmann et al. (2009)	1	1	1	1	1	1	1	0	0	0	1	1	0°	0	0	1	1	1	0°	1	1	0°	0	0°	0°	0	1	1	1	17
Cormie et al. (2010)	1	1	1	1	1	1	1	0	0	0	1	1	0°	0	0	1	1	1	0°	1	1	0°	1	0°	0°	0	1	0	1	17
Chtourou et al. (2012)	1	1	1	1	1	1	1	0	0	1	1	1	0°	0	0	1	1	1	0°	1	1	0°	1	0°	0°	0	0	0	1	17
Weier et al. (2012)	1	1	0	1	1	0	1	0	0	1	1	1	1	0	0	1	1	1	0°	1	1	0°	1	0°	0°	0	0	1	1	17
Naclerio et al. (2013)	1	1	1	1	1	1	1	0	1	1	1	1	1	0	0	1	1	1	1	1	1	0°	1	0°	1	1	0	1	0°	22
Aguiar et al. (2015)	1	1	1	1	1	0	1	0	1	0	1	1	0°	0	0	1	1	1	0°	1	1	0°	1	0°	0°	1	1	1	1	19
Akagi et al. (2016)	1	1	1	1	1	1	1	0	1	1	1	1	0°	0	0	1	1	1	0°	1	1	0°	1	0°	0°	0	1	0	0°	18
Botton et al. (2016)	1	1	1	1	1	1	1	0	0	0	1	1	0°	0	0	1	1	1	0°	1	1	0°	1	0°	0°	0	1	0	1	17
Wirth et al. (2016)	1	1	1	1	1	1	1	0	0	0	1	1	0°	0	0	1	1	1	0°	1	1	0°	0	0°	0°	0	1	0	1	16
Jarvis et al. (2017)	1	1	1	1	1	1	1	0	1	1	1	1	1	0	0	1	1	1	1	1	1	0°	1	0°	0°	1	1	1	1	23
Souza et al. (2018)	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	0°	1	1	0°	1	0°	0°	1	1	0	0	20

Items 1-10 are related to reporting, items 11-13 are related to external validity, items 14-20 are related to internal validity (bias), items 21-26 are related to internal validity (confounding), item 27 is related to statistical power, item 28 is related to exercise adherence and item 29 is related to exercise supervision.
1 criteria met, *0* criteria not met, *0°* Item was unable to be determined or scored

3.5.1 Description of studies

Figure 1 details the PRISMA flow chart. A total of 22 studies, totalling 761 participants (585 males & 176 females) were eligible for review. Sample sizes ranged from 17 to 120 participants, with experimental and control groups ranging from 5 to 47 participants. Mean ages ranged from 20.0 ± 1.8 to 31.6 ± 9.8 across all studies (table 6). Of the two prescriptive methods (% 1RM, and RM), 12 studies utilised the % 1RM prescriptive approach and 10 employed the RM prescriptive approach.

Fifteen studies assessed lower body strength (seated plantar-flexion, knee extension, knee flexion, leg press, back squat, half squat, Clean & Jerk and hip thrust), three studies assessed upper body strength (bicep curl, triceps extension and bench press) (Akagi et al., 2016; Hartmann et al., 2009; Moss et al., 1997) and the remaining four assessed a combination of upper and lower body strength (bicep curl, leg press, back squat, latissimus-dorsi pull-down, ab-board, back extension, upright row) (McBride et al., 2003; Naclerio et al., 2013; Tanimoto et al., 2008; Terzis et al., 2008). There was an 11.9% greater improvement in maximal strength when assessing lower body vs upper body exercises (table 10). All studies reported pre-and post-intervention data for experimental and control groups (table 7).

3.5.2 Improvements in maximal strength

A summary of the strength developments can be found in table 8. All 22 studies documented statistically significant ($p < 0.05$) improvements in maximal strength for the training groups (31.3% ± 21.9%; 95% CI: 33.1% to 29.5%) in comparison to their respective control groups (3.4% ± 4.3%; 95% CI: 3.9% to 2.9%); 20 studies presented data in absolute values (kg), with two reporting relative ($kg.bm^{-1}$).

The training groups utilising % 1RM load prescription significantly improved maximal strength by 28.8% ± 20.2% (95% CI: 31.4% to 26.2%) compared to 34.5% ± 23.5% (95% CI: 37.0% to 32.0%) for the training groups utilising RM targets ($p < 0.05$) (table 10). When removing data derived from Campos et al. (2002), which were seemingly outliers and skewed the data, maximal strength increased by 24.2% ± 10.81% (95% CI: 23.1% to 15.4%) for the RM target load prescriptive method.

3.5.3 Periodised approaches

Five studies employed a periodised approach to their programming (daily undulating, linear, or block) (Bell et al., 2000; Chtourou et al., 2012; Cormie et al., 2010; Moss et al., 1997; Tricoli et al., 2005). Twelve studies autoregulated load by an increase when a target was met (Bell et al., 2000; Botton et al., 2016; Braith et al., 1993; Campos et al., 2002; Hartmann et al., 2009; Jarvis et al., 2017; McBride et al., 2003; Rana et al., 2008; Terzis et al., 2008; Weier et al., 2012; Weiss et al., 1988; Wirth et al., 2016); eight studies employed mid-point 1RM tests (ranging from every 2 to 6 weeks) (Aguiar et al., 2015; Akagi et al., 2016; Chtourou et al., 2012; Cormie et al., 2010; De Souza et al., 2018; Moss et al., 1997; Tanimoto et al., 2008; Willoughby, 2004); one study did not report how they adjusted load (Naclerio et al., 2013); and one study increased the volume but kept the load constant (Tricoli et al., 2005).

3.5.4 Training variables

Training interventions ranged from 4 to 18 weeks across all studies, with 2-3 sessions per week being prescribed. Further analysis detailed a 4.9% to 5.5% greater improvement in maximal strength, measured via direct 1RM assessments in multiple movements/exercises across all 22 studies, when prescribing an intervention over a longer duration (> 6 weeks). The magnitude of the improvements, however, decreased after 6 weeks (table 10). Nine studies implemented an intervention containing only one exercise (Aguiar et al., 2015; Akagi et al., 2016; Braith et al., 1993; Cormie et al., 2010; Hartmann et al., 2009; Jarvis et al., 2017; Moss et al., 1997; Weier et al., 2012; Weiss et al., 1988), with four of those employing a multi-joint exercise (e.g., back squat) (Cormie et al., 2010; Hartmann et al., 2009; Jarvis et al., 2017; Weier et al., 2012). Eleven studies employed between 2-5 exercises within the intervention (Bell et al., 2000; Botton et al., 2016; Campos et al., 2002; Chtourou et al., 2012; De Souza et al., 2018; McBride et al., 2003; Rana et al., 2008; Tanimoto et al., 2008; Tricoli et al., 2005; Willoughby, 2004; Wirth et al., 2016), with two studies prescribing > 5 (Naclerio et al., 2013; Terzis et al., 2008). Six studies employed single-joint or isolated exercises only (Aguiar et al., 2015; Akagi et al., 2016; Botton et al., 2016; Braith et al., 1993; Moss et al., 1997; Weiss et al., 1988), with the rest prescribing multi-joint or a combination of the two. Maximal strength increased by 5.4% more in multi-joint, compound exercises compared to single-joint, isolation exercises (table 5). Exercise specifics for the training groups were 1-6 sets of 3-28 repetitions, with 1-5 minutes rest periods. Training intensities ranged from 15-120% baseline 1RM testing scores or 3-28RM. All studies either employed a 'traditional or normal' speed of movement (1-2 seconds for eccentric and 1 second for concentric) or did not control for tempo of movement.

3.5.5 Participants and training status

Four out of the 22 studies recruited trained or 'technically proficient' participants. One study defined trained as a minimum of one year resistance training (Jarvis et al., 2017), whereas another study did not provide a definition (Moss et al., 1997). One study required a minimum 1RM in the bench press of 100 kg; however due to recruitment issues this was reduced to 60 kg (Hartmann et al., 2009). The fourth study required the participants to be technically proficient in the back squat (Cormie et al., 2010). One study reported the participants had previous strength training at recreational level but underwent no strength training for three months leading up to the study (Tricoli et al., 2005), and one study accepted participants who were training less than twice per week for six months leading up to the study (Aguiar et al., 2015).

The remaining studies recruited non-resistance trained participants ranging from three months to five years without any form of resistance training. Ten studies used University or College students; seven described their participants as 'healthy', and four described them as 'untrained'. The remaining two studies recruited either University or team-sports athletes. The control group across all studies were reported to have 'maintained normal daily activities' or to have 'undertaken no resistance or endurance training' throughout the duration of the intervention period, however no study reported how this was controlled for.

3.5.6 Methodological quality

The mean ± SD methodological quality rating score was 17.7 ± 2.3 out of a possible 29, with a range of 14 - 23. Only four studies achieved a methodological quality rating of good (> 20) (De Souza et al., 2018; Jarvis et al., 2017; Naclerio et al., 2013; Willoughby, 2004). Other studies scored a ‘moderate’ rating. All studies scored 0 for attempting to blind participants from the intervention and its outcomes. It was not possible to determine whether participants were recruited over the same time and whether the intervention was concealed from participants and administrators across all studies. All studies reported the aims and/or hypotheses; the main outcome measures; the intervention employed; the point estimates of random variability; and employed appropriate statistical analysis. Four studies did not report full participant characteristics (Bell et al., 2000; Moss et al., 1997; Weier et al., 2012; Weiss et al., 1988) and four different studies failed to clearly describe their main findings (Aguiar et al., 2015; Campos et al., 2002; Weier et al., 2012; Willoughby, 2004). It was not possible to determine whether the sample represented the population in one study (Braith et al., 1993); however, all studies did recruit both experimental and control groups from the same population. No retrospective unplanned subgroup analyses were reported in any of the studies. Six studies reported adherence or compliance to the intervention (Aguiar et al., 2015; Hartmann et al., 2009; Jarvis et al., 2017; Naclerio et al., 2013; Terzis et al., 2008; Weier et al., 2012), which was ≥ 92%, whilst 11 studies incorporated supervised training sessions in to their interventions.

Table 10. Sensitivity analysis comparing maximal strength development across four methodological approaches.

	Prescriptive method		**Exercise Type**		**Exercise Focus**		**Training Duration (weeks)**		
	% 1RM	***RM**	**Comp**	**Iso**	**Upper Body**	**Lower Body**	**6**	**12**	**18**
Sample size (*n*)	313	448	523	450	207	667	101	509	151
Mean strength increase (%)	28.8	24.2	33.8	28.4	22.4	34.3	27.2	32.1	32.7
SD (%)	20.2	10.8	24.4	18.0	19.3	21.6	25.2	21.2	20.8
CI Upper (%)	31.4	25.4	35.9	30.0	25.0	36.0	32.1	34.0	36.0
CI Lower (%)	26.2	23.1	31.7	26.7	19.7	32.7	22.3	30.3	29.3

*Data for RM group and subsequent sub-analyses does not include data presented in Campos et al. (2002)
1RM 1 repetition maximum, *Comp* Compound, *CI* Confidence Intervals, *Iso* Isolation, *RM* Repetition Maximum, *SD* standard deviation

3.6 Discussion

The aim of this review was to compare the effectiveness of two load prescriptive methods on maximal strength development. Through a robust systematic search strategy and quality assessment, 22 research articles met the inclusion criteria, with 12 employing a % 1RM prescriptive approach, and the remaining 10 utilising RM targets (Tables 6 & 10). Despite both methods (% 1RM and RM targets) frequenting S&C practice and research, this is the first review to compare the two methods against one another.

This review highlighted both % 1RM and RM prescriptive methods as effective strategies for increasing maximal strength. Collectively, all training groups across the 22 included studies improved maximal strength following their interventions in comparison to their non-training control groups. When comparing maximal strength improvements from the two different methods, the RM target training groups seemingly increased strength by 5.7% more than % 1RM (table 8). On closer inspection, however, the greater increases in strength following the RM targets method is likely attributed to the 73-114% back squat 1RM improvements following an eight week intervention in healthy, untrained males with a mean body mass of 77.8 kg reported in one study (Campos et al., 2002). The post-testing absolute 1RM values for the training group equated to 246.5 kg, indicating a relative strength ratio of > 3 x body mass (Campos et al., 2002). When comparing to current powerlifting rankings for the back squat alone, this level of lower body strength would equate to approximately 27th in the 2019 world championships (International Powerlifting Federation, 2019). Therefore, it is likely that this study was skewing the RM data. Furthermore, no standardisation of technique was provided for the back squat, thus indicating that a full depth squat might not have been implemented given the loads lifted. This information is vital for readers to fully understand the methods employed, with standardisation across research studies required for better comparisons of approaches.

When removing this data and reanalysing the RM targets results, the mean percentage improvement from pre- to post-testing across the eleven studies fell to 24.2% ± 10.81% (95% CI: 23.1% to 25.3%), indicating % 1RM as the superior method for improving 1RM. This agrees with Carroll et al. (2019) who directly compared relative prescriptive methods against RM targets and found that a relative daily maximum group was more effective in improving vertical jump, RFD, and maximal strength in comparison to the RM group ($p < 0.05$, $g = 0.69$ to 1.26). Carroll et al. (2019) suggested that a potential build-up of residual neuromuscular fatigue from training to failure and reduction in rapid force production in the RM group might explain the lesser improvements. This idea has been presented on an acute level, in which the time course for recovery has been prolonged following a bout of resistance training to muscular failure (Morán-Navarro et al., 2017). A recent review by Davies et al. (2016) observed no statistically significant differences were evident in 1RM improvements when comparing training to failure vs non-failure training. Similarly, Sundstrup et al. (2012) highlighted no greater motor unit recruitment was evident when training to failure vs. heavy loading training. Whilst training to failure may not affect improvements in maximal strength, the prolonged recovery time may be a negative contributing factor and a potential drawback to employing RM targets. Further investigation is required directly comparing these two methods of load prescription to determine the most appropriate approach across multiple athletic populations and training phases.

The present review highlighted important heterogeneity (such as demographics, testing procedures, and training prescriptions) within the included studies, making inferences about the efficacy of these methods challenging and elucidating consensus difficult. Large variation in the participants recruited (age and training status); training prescriptions employed (sets, repetitions, load and rest), exercises prescribed, and the tools used to measure maximal strength (various 1RM procedures, etc.) were evident in the literature. Despite agreement with Carroll et al. (2019), such disparity in methodological approaches made comparisons across the 22 included studies difficult and it is therefore recommended that this initial finding be viewed with caution, with more research perhaps required.

Training prescriptions that exceeded 6 weeks in duration appeared to improve maximal strength greater than shorter interventions, however, the magnitude of these improvements decreased notably when exceeding this duration (table 10). For example, McBride et al. (2003) found larger improvements in the leg press exercise across the first 6 weeks compared to the second 6 weeks of training, irrespective of volume (1RM improvements 0-6 weeks: 26.6% to 27.7% across groups; and 1RM improvements 6-12 weeks across groups: 10.7% to 18.0%), whilst Cormie et al. (2010) found much larger improvements in the back squat at mid-test stage compared to post-test (22.7% vs. 4.5%]. Despite progressive training prescriptions being employed, this data suggests that utilising the same training intervention (e.g., exercises, periodisation approach etc. with small progressions in load prescription) for greater than 6 weeks could result in a plateau in maximal strength development, necessitating variation in training stimuli to elicit further improvement (Kraemer & Ratamess, 2004; Siff, 2008; Suchomel et al., 2016, 2018; Williams et al., 2017). It is also possible that the initial 6 weeks of training would facilitate a rapid increase in neuromuscular adaptations, with hypertrophy becoming more dominant once these have run their course (McBride et al., 2003). Nevertheless, given the interaction between volume and hypertrophic responses to training (Grgic, Schoenfeld, Davies, et al., 2018; Schoenfeld et al., 2017), it would be difficult to make these assumptions when the training frequency prescribed in the included articles in this review did not exceed 3 x week.

Improvements in maximal strength appeared to be influenced by exercise mode (table 10). When comparing multi-joint, compound exercises (e.g., back squat, bench press, clean etc.) with single-joint, isolation exercises (e.g., seated plantar-flexion or knee extension) greater improvement in maximal strength were evident. Multi-joint, compound exercises require greater neuromuscular recruitment, inter-and intra-muscle coordination and better utilisation of muscle stabilisers and synergists than smaller, single-joint exercises (Folland & Williams, 2007; Sheppard & Triplett, 2016; Suchomel et al., 2018). It is pertinent to note that the transference of single-joint exercises to sport-specific actions such as jumping and sprinting is limited and perhaps not appropriate when training for sport performance (Brearley & Bishop, 2019; Suchomel et al., 2018). Similarly, our findings highlighted that greater relative improvements in maximal strength were observed in lower-body vs. upper-body exercises (table 10), perhaps due to the recruitment of larger muscle groups and exposure to greater loads typical of these exercises.

The training prescriptions (exercises, volume, load, and rest) employed within the 22 studies included in this review can be found in table 7. Large variability in approaches for developing maximal strength was evident across both load prescription methods (% 1RM and RM targets), with ranges of 1 to 5+ exercises across a mixture of both single- and multi-joint, volumes of 3-28 repetitions across 1-6 sets, rest periods of 1-5 minutes, and intensities ranging from 60-120% of 1RM or 3-28 RM targets. This heterogeneity highlights a clear disparity in optimal training prescription for developing maximal strength, making the assessment of effective training prescriptions difficult, perhaps highlighting improvements can be observed across multiple strategies. Researchers should therefore seek to develop a greater consensus on the more appropriate methods for developing maximal strength within different demographics.

Training recommendations are linked to important underpinning physiological adaptations (Fleck & Kraemer, 2014; Folland & Williams, 2007; Sheppard & Triplett, 2016; Siff, 2008; Suchomel et al., 2016, 2018; Williams et al., 2017), and that the manipulation of loads and volumes can elicit different adaptations (Suchomel et al., 2016, 2018). This review, however, indicates that there might be poor agreement about the physiological mechanisms underpinning maximal strength training. Adaptations to the neural system, such as the recruitment of additional or higher threshold motor units (Braith et al., 1993; Moss et al., 1997), the recruitment of more fast twitch muscle fibres (type IIx), greater synchronisation of discharge of motor units (Hartmann et al., 2009; McBride et al., 2003), greater efferent drive (Hartmann et al., 2009), increases in corticospinal excitability coinciding with reductions in short-interval intracortical inhibition (Weier et al., 2012), or enhanced neural coordination (Jarvis et al., 2017; Wirth et al., 2016), have all been suggested to underpin improvements in maximal strength. In contrast, increases in muscle cross-sectional area, the conversion of muscle fibre types from type IIa to type IIx, changes in pennation angle, and the secretion of growth promoting hormones have also been suggested to explain maximal strength improvements following training (Botton et al., 2016; Campos et al., 2002; Cormie et al., 2010; Naclerio et al., 2013; Terzis et al., 2008). Whilst disparity in explanations might exist in the literature, this does, however, highlight that maximal strength is a complex quality that can be influenced by both neurological and morphological adaptations. Heterogeneity in physiological measurements (electromyography, corticospinal excitability, dual-energy x-ray absorptiometry scanner, BOD POD, muscle biopsies, blood sampling, or force plate data), the training status and abilities of the participants recruited, and the prescriptions of the training interventions, were noted during our analyses. Such variety in assessment methods, samples and prescriptions might explain this disparity in physiological explanations offered by the studies included in this review. Further research might be needed to understand and isolate the physiologic mechanisms underpinning the prescriptions of maximal strength.

Most studies included in this review (18 articles; table 6) recruited untrained or detrained participants, most of which ranged from 3 months to 5 years without consistent strength training. Despite this heterogeneity, all studies observed increases in maximal strength in their training groups. Those that recruited resistance-trained athletes (table 6) observed notable increases in strength, ranging from 6.8 to 27.3%; studies using non-trained participants observed improvements ranging from 2.8% to 114.0% (87.3% when omitting (Campos et al., 2002)). This supports the suggestion that untrained individuals improve strength to a greater extent and at a faster rate than trained individuals (Ahtiainen et al., 2003). It is important to note, therefore, that data from untrained individuals might not reflect that of trained individuals and that research findings from one group should not be extrapolated to the other.

Trained and untrained individuals respond to training stimuli differently, which can vary based upon their training history and status (Suchomel et al., 2018). It is thought that untrained individuals will benefit from basic resistance training approaches, whereas trained individuals require more sophisticated methods due to a more developed neuromuscular system (Suchomel et al., 2016, 2018). Furthermore, there is growing consensus that a baseline of maximal strength underpins several important performance parameters, and that certain strength levels might be required prior to undertaking more advanced training methods

(Kraemer & Ratamess, 2004; Suchomel et al., 2016, 2018). Therefore, researchers and practitioners should be cognisant of training status when designing training programmes and ensure that the methods employed match the training status of the athletes they are prescribing for. Further research should investigate the use of prescriptive methods on trained and elite individuals specifically.

Often, methods used in practice precede empirical underpinning, and S&C practitioners sometimes utilise strategies before research has validated their efficacy (Kuklick & Gearity, 2015). The availability of other prescriptive methods to S&C coaches and practitioners is apparent in practice; however, the research does not necessarily reflect this. Similarly, recent criticisms of current methods of prescription (% 1RM and RM targets) such as the inflexibility and inaccuracies in training prescriptions following rapid increases in strength or the build-up of residual fatigue (Bosquet et al., 2010; González-Badillo & Sánchez-Medina, 2010; Mackey et al., 2018; Padulo et al., 2012) and the development of new technologies have allowed practitioners to utilise other means for load prescription (Balsalobre-Fernández, Marchante, et al., 2018; Orange et al., 2019). Subjective methods of autoregulation such as RIR or RPE have been suggested as an alternative strategy to prescribe load (Borg, 1982; Helms et al., 2016; Naclerio et al., 2011). Likewise, the utilisation of VBT is also evident in practice. Given the strong relationship between load and velocity, Individuals are profiled and then associated velocities can be used to manipulate the absolute load lifted each session or each working set (Banyard et al., 2018; Banyard, Nosaka, & Haff, 2017; Conceição et al., 2016; Jidovtseff et al., 2011; Picerno et al., 2016). Despite these two methods being prevalent in practice, at the time of this review, peer reviewed evidence is limited and warrants significant future research.

3.6.1 Quality assessment

The quality of the studies included in this review, as assessed by the modified Downs and Black checklist (Downs & Black, 1998), had a mean score of 17.68 ± 2.28, suggesting a moderate rating of methodological quality. Four out of the 22 studies were classed as having a good methodology (≥ 20) (De Souza et al., 2018; Jarvis et al., 2017; Naclerio et al., 2013; Willoughby, 2004), with the remaining studies being classified as moderate (10-19). Although no studies were methodologically poor, there were still some noteworthy findings. Of the 29-point checklist, only 9 of the criteria were met by all the studies, with eight of the criteria met by ≤ 5 studies. In accordance with Davies et al. (2016), no study reported any adverse effects because of the programme intervention prescribed. When researching an intervention, any adverse effects or confounding variables should be reported. This lack of transparency could conceal important biases that affect the quality of this data.

Several internal validity criteria were not met by any study. These were: attempting to blind participants and attempting to blind those measuring the main outcome variables from the intervention. Although, in some cases, this might have improved the quality of the research, blinding participants from a training-programme intervention is difficult, and this might not have affected the overall methodological quality of the evidence (Davies et al., 2016, 2017). Such issues need to be considered by researchers who use similar checklists when evaluating intervention studies such as these, as the methodological limitations of these tools might lead to erroneous conclusions being drawn about the evidence. Two other criteria not explicitly met or reported by any of the studies were whether participants across multiple intervention or control groups were recruited over the same time, and whether assignment of groups were concealed from participants and staff until after the intervention was complete. Failure to meet both of these criteria may have increased the risk of selection bias or participants not being placed in appropriate groups (Davies et al., 2016). This could increase the possibility that a population was sampled until the desired conclusion was reached (Davies et al., 2016, 2017; Grgic, Schoenfeld, Davies, et al., 2018).

Only 11 studies reported that the interventions were supervised, and only seven studies reported any exercise adherence data. Poor adherence could affect the overall success of a training intervention and impact the reported data. Full supervision of a training intervention is necessary for health and safety purposes but to also ensure accurate data is reported. Indeed, adherence should be recorded to ensure that outliers or suspect results are not due to partial completion and alterations in training frequency between groups (Grgic, Schoenfeld, Skrepnik, et al., 2018). Despite the concerns, it should be noted that quality assessment tools that can evaluate strength training interventions are scarce. With a large bias towards clinical trials, a lot of the tools available (Cochrane, PEDro, Downs and Black) do not suit intervention studies in which blinding may be difficult, for example. Therefore, if researchers are to reliably assess methodological quality in the future, a more appropriate and robust tool might be needed if accurate assessments of the evidence are to be made using quality-assessment metrics in applied research such as this.

3.6.2 Strength and limitations

The strengths of this review include the systematic nature of the search strategy, which rigorously followed the PRISMA guidelines (Moher et al., 2009). The data extraction process and the quality assessment tools employed were all in accordance with previous literature and guidance (Davies et al., 2016, 2017; Grgic, Schoenfeld, Davies, et al., 2018; Grgic, Schoenfeld, Skrepnik, et al., 2018; Moher et al., 2009). Despite stringent inclusion criteria, the search terms were inclusive, evidenced by the number of original articles returned (figure 15). This inclusive search strategy was purposeful, to draw out as much evidence as possible. Conversely the ability to control for things such as programme design, participant characterisation, training status (etc.) became challenging, and might explain the heterogeneous sample, making direct comparisons between some studies difficult. This is perhaps reflective of the wide range of programming tools and methods employed within research (and practice), however. The heterogeneity of the studies included in this review also prevented any form of meta-analysis to be undertaken, reducing the statistical impact of the findings.

Volume was not controlled for within this review. Previous research has demonstrated a strong dose-response relationship for physical adaptations such as maximal strength (Ralston et al., 2017; Williams et al., 2017). It is possible that without establishing inclusion criteria that controlled for training volume, the application of data presented in this review could be limited. Nonetheless, the aim of this review was to evaluate methods to prescribe load specifically, and that the inclusion criteria of this review were developed to be sensitive to a breadth of literature.

Some studies failed to report all or relevant strength data (Campos et al., 2002; Weier et al., 2012), whilst two studies only reported relative ($kg.bm^{-1}$) values (Cormie et al., 2010; Willoughby, 2004). Requests were sent to all authors to provide additional data, with only one providing the necessary information. In some cases, a graph digitizer was therefore required to extract the data, potentially reducing the accuracy of some of the values presented in table 3. Despite this potential limitation, this approach highlights the robust and meticulous approach taken to extract and analyse relevant data.

The need for efficacy trials to include a non-training control group is important to ensure full confidence in the intervention under investigation. This inclusion criterion could have potentially limited the return of some related articles. However, Bishop (2008) argues that all efficacy trials (intervention studies) should be characterised by strong control, with a tightly delivered, standardised intervention to a specific, narrowly defined and motivated homogenous group. Indeed, it is this strict control that allows for any effects to be attributed to the intervention under investigation (Bishop, 2008). With this, we did not want to compromise quality for quantity, therefore the decision to be stringent on the control group was upheld. This further highlights the need for researchers to make every attempt to control their studies as robustly as possible to further develop the quality of research in this area.

3.6.3 Practical recommendations

Practitioners should be confident in employing either % 1RM or RM targets as a method of load prescription to improve maximal strength. The two methods, however, have different nuances in strategy, and therefore, are not interchangeable. S&C coaches may favour % 1RM, given the greater improvement in maximal strength over the course of progressive intervention (> 4 weeks) evident from this review. If practitioners would prefer a more autoregulatory method of load prescription, RM targets may be appropriate; however, careful fatigue management would be necessary to protect athletes from the exposure to failure inherent within this method (Morán-Navarro et al., 2017; Shimano et al., 2006; Sundstrup et al., 2012). In fact, potentially prescribing via % 1RM can allow coaches to better manage the build-up of residual fatigue and prevent a state of unplanned overreaching. Moreover, practitioners must ensure that the training interventions they prescribe are appropriate for the individuals they work with, utilising quality research as a frame of reference.

The assumption that % 1RM elicits greater strength improvements based on the results of this review should also be taken with caution. Whilst a recent study showed relative prescriptions was more effective at improving jump performance, RFD, and maximal strength than RM targets (Carroll, Bernards, et al., 2019), more research is required in this area, particularly directly comparing these two methods against one another. Practitioners should evaluate the necessity of training to failure and assess the intervention, and subsequently the method of load prescription, on a case-by-case basis dependent on age, training status, periodised approach and time of season.

Despite the effectiveness of the two methods, practitioners should still be aware of the potential logistical and physiological flaws when using this method. To administer comprehensive and safe 1RM assessments with trained or untrained individuals can be difficult due to the proficiency needed in training at high loads, as well as the challenges logistically when employing it with a team of athletes (Brzycki, 1993; González-Badillo & Sánchez-Medina, 2010). Practitioners should also take in to account the daily fluctuations in force output, strength levels and residual fatigue that may affect an individual's daily maximal intensity capabilities (Mackey et al., 2018; Padulo et al., 2012). Therefore, considering alternative or additional methods such as velocity or RIR may help maximise load prescription and maximal strength adaptations.

3.6.3 Future research

Future research should seek to investigate a direct comparison between % 1RM and RM targets to determine the most effective method of load prescription. Despite being used widely within practice and utilised in isolation across S&C research, the efficacy of these methods has not been investigated and thus requires further attention to evaluate their ability to improve maximal strength. Additionally, current literature using these two methods could be meta-analysed to identify any bias based on sample size and provide a more robust statistical evaluation of the most effective strategy. Future research should also examine other common methods of load prescription such as velocity or RIR to provide practitioners with the most effective strategy to improve maximal strength. Researchers should seek to develop research informed guidelines based around training variables related to the development of maximal strength. Guidance on definitions of what constitutes a trained individual is imperative to further the application of research to practice. Importantly, researchers should employ more robust methodologies when investigating the efficacy of training interventions. Furthermore, if methodological quality is to be assessed within the field of S&C, the development of a more appropriate and specific measurement tool may be necessary to ensure valid judgements can be made. Based on the research returned from this review, and the methodological quality assessment we employed, the following guidelines should be followed wherever possible:

Research design recommendations:

- Ensure the testing methods are appropriate for your hypothesis (e.g., if investigating maximal strength, employ a practical and reliable strength assessment)
- Always try to employ a non-training control
- All groups must be matched in terms of n
- Any resistance training intervention must be progressive in terms of load, volume and complexity

- Resistance training interventions must be clearly described and easy to replicate
- Data must be clearly displayed with absolute and relative values easily extractable
- Where possible, create as 'real world' a training and testing environment as possible whilst not compromising levels of control
- Standardise and report testing procedures in full (protocols, movement technique, equipment etc.)
- Recruit participants from the same population across the same time points for multiple experimental or control groups
- Report exercise adherence and intervention supervision

3.7 Conclusions

This systematic review demonstrates that prescribing load via a combination of a direct measurement of strength (1RM) and then submaximal prescriptions is effective in eliciting maximal strength adaptations. Furthermore, the two approaches highlighted in this review, RM targets and relative submaximal percentages (% 1RM) both have a positive impact on maximal strength development in comparison to non-training controls. % 1RM elicited greater improvements in maximal strength (> 4.6%) in comparison to RM targets. More research, however, is needed to fully investigate the efficacy of both these methods, specifically direct comparisons between the two methods. Multi-joint, lower body, compound exercises appear to be more effective in improving maximal strength than their counter-parts. The law of diminishing returns highlights that the magnitude of change in maximal strength decreases following 6 weeks of training. The heterogeneity of the research in this area is evident from this review and therefore guidelines are required to help practitioners make informed decisions on the best way to prescribe and programme for their athletes. It is, however, important that practitioners look to utilise the research available to them to ensure appropriate prescriptions can be made, considering such things as training status, age, background etc.

Chapter 4.0: Study 2 - "Is it a go day or a slow day?": The perceptions and applications of velocity-based training within elite strength and conditioning

4.1 Study rationale

Study one revealed % 1RM as the more superior method for prescribing load and facilitating improvements in maximum strength. In addition, it revealed disparities between VBT research and practice. The original aim of study one was to compare these methods against two further autoregulatory strategies, RIR and VBT. However, upon completing the systematic searches and assessing eligibility, no training studies utilising VBT or RIR met the inclusion criteria, causing the research aims to be adjusted. Whilst the objectives of this study therefore shifted, this discovery provided a clear justification for the need of this doctoral programme given the lack of robust VBT-related literature.

Research and practice in S&C seldom align: The lengthy peer-review process, rigorously controlled research designs and reductionist scientific models in research rarely compliment the complex, fast-paced (and sometimes chaotic) applied environment. Quite often, "practical applications" sections within studies feel misplaced or disjointed, with practical relevance being an afterthought needed to ensure publication (Thompson, 2020). Indeed, to develop real-world, applied research, one must identify practices, challenges, and potential solutions directly from relevant real-world environments, and solve problems that manifest from naturalistic contexts.

Considering the above, to identify practically applied, coach-relevant research, study two explored the experiences and opinions of elite S&C practitioners currently utilising VBT within their coaching. By doing so, the application and perceptions of VBT could be highlighted, recognising 'real-world' problems that future studies within this doctoral programme could attempt to address. Additionally, understanding the common technologies utilised within practice would inform future quantitative, experimental research designs in the latter stages of the doctoral programme.

4.2 Abstract

VBT is a contemporary prescriptive, programming, and testing tool commonly utilised in S&C. Over recent years, there has been an influx of peer-reviewed literature investigating several different applications (e.g., load-velocity profiling, velocity loss, load manipulation, and reliability of technology) of VBT. The procedures implemented in research, however, do not always reflect the practices within applied environments. The aim of this study, therefore, was to investigate the perceptions and applications of VBT within elite S&C to enhance contextual understanding and develop appropriate avenues of practitioner-focused research. Fourteen high-performance S&C coaches participated in semi-structured interviews to discuss their experiences of implementing VBT into their practices. Reflexive thematic analysis was adopted, following an inductive and realist approach. Three central organising themes emerged: *Technology, applications,* and *reflections.* Within these central themes, higher order themes consisting of drivers for buying technology; programming, testing, monitoring, and feedback; and benefits, drawbacks, and future uses also emerged. Practitioners reported varied drivers and applications of VBT, often being dictated by simplicity, environmental context, and personal preferences. Coaches perceived VBT to be a beneficial tool yet were cognisant of the drawbacks and challenges in certain settings. VBT is a flexible tool that can support and aid several aspects of S&C planning and delivery, with coaches valuing the impact it can have on training environments, objective prescriptions, tracking player readiness, and programme success.

4.3 Introduction

VBT frequents S&C literature, often being referred to as a training method as opposed to more suitably as an encompassing approach with many applications (González-Badillo et al., 2014, 2015; Negra et al., 2016; Ramírez et al., 2015). All of these applications, however, typically have one common denominator – the use of technology (e.g., linear position transducers, accelerometers, laser-optics, smartphone applications) to track and measure movement velocity (Weakley et al., 2021; Weakley, Mann, et al., 2020). VBT can be implemented in many ways, such as testing and monitoring through load-velocity profiling (Banyard et al., 2018; García-Ramos, Haff, Pestaña-Melero, et al., 2018; Thompson, Rogerson, Ruddock, Banyard, et al., 2021) and one repetition maximum (1RM) prediction (García-Ramos, Barboza-González, et al., 2019; Janicijevic et al., 2021; Thompson, Rogerson, Ruddock, Greig, et al., 2021); volume control through velocity loss thresholds or cut-offs (Banyard et al., 2019; Weakley, McLaren, et al., 2020; Weakley, Ramirez-Lopez, et al., 2020); load prescription through the application of specific zones (Banyard et al., 2020; Orange, Metcalfe, Robinson, et al., 2020); autoregulation via load-manipulation (Dorrell, Smith, et al., 2020); or extrinsic motivation via external feedback (Weakley, Wilson, et al., 2020). This multi-faceted nature and the accessibility of velocity-based technology, therefore, makes VBT attractive to S&C coaches.

A range of VBT-specific devices are now available to S&C practitioners. Coaches must strike a balance between factors such as reliability, validity, useability, and cost (hardware and software) when purchasing such technology. Reliability and validity feature strongly in the literature (a recent systematic review (Weakley et al., 2021) returned 44 research studies), with LPTs appearing to be the most reliable and valid tool (Thompson et al., 2020; Weakley et al., 2021). Typically absent from the literature, however, are more practical drivers such as feasibility, cost, and complexity, which has been deemed important in performance testing (Robertson et al., 2017), an area of S&C engrained with technology. Consequently, reliable, and valid devices are typically more expensive, presenting a potential barrier for some teams and organisations with limited budgets. Understanding cost vs. benefit is important in practice and the balance between ease of use and affordability is likely to steer the development of VBT technology.

A systematic literature search of VBT-related methods returned 146 peer-reviewed publications at the time of writing (April 2022), with the most common topic of interest being the reliability and/or validity of VBT-related technology (31.5%), closely followed by load-velocity profiling (28.8%) and velocity loss (19.9%). Other topics of interest were 1RM prediction (8.9%), intervention studies (8.2%), and external feedback (4.1%). With an abundance of recent evidence, understanding how to optimise VBT in practice can be challenging and time-consuming. Recommendations from S&C literature are sometimes unachievable due to restrictions in time, equipment, personnel, or the unpredictability of applied practice (Fullagar et al., 2019; Thompson, 2020). Furthermore, the rigorous and lingering nature of the peer-reviewed process means practical recommendations can quickly become outdated (Thompson, 2020). Practitioners will often develop their own coaching strategies through coach-conversations, social media, or trial and error (Fullagar et al., 2019; Stoszkowski & Collins, 2016). Gaining further insight into approaches being taken in practice, therefore, could help further understanding and bridge the gap between research and applied practice.

One area in need of further understanding is that of elite sport, with experimental literature often recruiting trained individuals, typically benchmarked against relative strength criteria (e.g., > 1.5 $kg.bm^{-1}$). Investigating the perceptions and experiences of elite S&C coaches could help further understanding of elite practice and inform future research. Therefore, the aim of this study was to evaluate the use of VBT within elite S&C contexts. More specifically, this study explored practitioners' perceptions of VBT and how they implement VBT in practice and evaluated alignment to methods and recommendations published in research.

4.4 Methods

4.4.1 Research design and theoretical approach

Following conceptualisation of the research aims, semi-structured interviews were conducted, analysed, coded, and interpreted using reflexive thematic analysis and realist metatheory as described by Braun and Clarke (Braun & Clarke, 2006, 2021). A semantic, inductive approach was adopted by which codes reflected content and meaning of participants' words (Braun & Clarke, 2006, 2021). Thematic analysis was employed to co-construct knowledge with coaches and bridge the gap between research and practice. There is a plethora of quantitative data investigating the efficacy, reliability, and practicalities of various methods of VBT within S&C, however, a paucity of studies evaluating its application within a real-world, applied setting.

4.4.2 Participants

Following institutional ethical approval (ER26914602) in accordance with the seventh revision (2013) of the declaration of Helsinki, 14 high-performance male S&C coaches were recruited via purposive / opportunity sampling. Participants had a mean age of 34.8 ± 6.3 years (range: 29.8 to 49.8 years), with mean coaching experience of 11.6 ± 6.7 years (range: 6 to 26 years) in S&C (table 11). Inclusion criteria included being employed or self-employed, working with professional athletes or coaching amateur athletes competing at a national or international level, and experience of implementing VBT into their practices. All risks and benefits were communicated verbally and in written form. Informed consent was obtained prior to data collection. Sample size was based on the principle of data saturation, with no new participants recruited when data failed to generate new discussion points (Guest et al., 2006).

Table 11. Descriptive characteristics of the participants.

Participant (n)	Sport	Country	Experience (years)	Education	Vocational S&C Qualifications
1	Rugby Union	USA	26	BSc, MSc	N/A
2	Boxing	UK	10	BSc, MSc	ASCC
3	Rugby Union	Australia	7	BSc, MSc, PhD	N/A
4	Multi-sport	China	7	BSc, MSc	CSCS, ASCA-L2
5	Soccer	UK	10	BSc	BASES Chartered Scientist
6	Cycling	UK	12	BSc, MSc	ASCC
7	Multi-sport	USA	10	BSc	CSCS
8	Soccer	UK	10	BSc, MSc, PhD	ASCC, BASES
9	MMA	China	12	BSc, MSc	ASCA-L3, PCAS-Elite
10	Taekwondo	UK	5	BSc, MSc	N/A
11	Cycling	UK	6	BSc, MSc	ASCC, CSCS
12	MMA	USA	25	BSc, MSc, PhD, PGCE	ASCC, CSCS, ASCA-L2
13	Multi-sport	Australia	17	BSc, MSc	ASCA-L3, PCAS-Associate
14	Multi-sport (disability)	Netherlands	6	BSc, MSc	CSCS, ASCA-L2

USA United States of America, *UK* United Kingdom, *BSc* Bachelor of Science, *MSc* Master of Science, *PhD* Doctor of Philosophy, *PGCE* Postgraduate Certificate in Education, *ASCC* Accredited Strength and Conditioning Coach (United Kingdom of Strength and Conditioning Association), *CSCS* Certified Strength and Conditioning Specialist (National Strength and Conditioning Association), *ASCA* Australian Strength and Conditioning Association, *PCAS* Professional Coach Accreditation Scheme (Australian Strength and Conditioning Association), *BASES* British Association of Sport and Exercise Science, *N/A* Not Applicable

4.4.3 Procedures

Prior to data collection, an interview guide was created (appendix B) and agreed upon by the research team, which included practicing coaches and experienced researchers with expertise in qualitative methods. Pilot and bracketing interviews were completed to refine the interview guide, ensure that questions reflected the research aims, and to partition out subjective assumptions to meet the expectations of realist research (Braun & Clarke, 2006, 2019; Clarke & Braun, 2018). The interview guide consisted of three mains sections (appendix B): the first was designed to settle the interviewee by talking about their background, providing their S&C 'autobiography' and coaching philosophy; the second focused solely on VBT-related technology, what they used and why they used it; and the final section focused on their use of VBT, detailing specific methods, why they implemented them, and any specific benefits or drawbacks they felt ascertained to VBT.

The semi-structured interview guide provided a framework for each interview. Participants were asked the same fundamental questions yet were free to explore thoughts, perceptions, practical experiences, with the flow of the interview being dictated by the coaches. All interviews were conducted remotely (Zoom Video Communication Inc, version 5.8.4, London, United Kingdom), with links and recordings password protected. All data was anonymised, and participant numbers used for any future reference of interview scripts. Following data saturation, all interviews were transcribed *verbatim* for data analysis by an external company.

4.4.4 Data analysis

Braun and Clarke's six-point approach to reflexive thematic analysis was followed (Braun et al., 2019; Braun & Clarke, 2006), a method common in sport-related thematic analyses (Bell et al., 2021; Burnie et al., 2018; Smothers et al., 2021). This six-stage approach allows for a non-linear, iterative, and recursive data analysis, which is important for qualitative research (Terry et al., 2017) (appendix C). Reflexive methodology promotes organic coding and theming, allowing for flexibility and depth of analysis (Braun & Clarke, 2019; Clarke & Braun, 2018). Importantly, reflexive thematic analysis recognises that researchers actively interpret data through the lens of their theoretical judgements and scholarly knowledge (Attia & Edge, 2017; Braun et al., 2019; Braun & Clarke, 2019; Gough & Madill, 2012). The principal investigator is experienced in VBT research, publishing four studies to date in this area (Banyard et al., 2019; Thompson et al., 2020; Thompson, Rogerson, Ruddock, Banyard, et al., 2021; Thompson, Rogerson, Ruddock, Greig, et al., 2021), and is a practising S&C coach. Throughout data collection, analysis, and interpretation, the principal researcher distinguished their experiences from that of the participants to maintain credibility and transparency of the research, allowing for the deep exploration of answers without using leading questioning (Price & Martin, 2018).

In conjunction with Braun and Clarke's reflexive thematic analysis model, Tracy's eight "big tent" criteria were considered to ensure the quality of the data (Tracy, 2010) (appendix C). VBT is prevalent in quantitative research (Banyard et al., 2019; Thompson et al., 2020; Thompson, Rogerson, Ruddock, Banyard, et al., 2021; Thompson, Rogerson, Ruddock, Greig, et al., 2021; Weakley et al., 2021; Weakley, Mann, et al., 2020) and applied practice, making it a relevant, timely and *worthy topic*. A *rich rigor* of sample size, appropriate participant experience, interview length and depth, and data collection / analysis process (reflexive thematic analysis) was maintained throughout (Golafshani, 2003; Weick, 2007). A combination of self-reflexivity, triangulation, and member reflections ensured *credibility* in the data (Richardson, 2000; Tracy, 2010). At different stages of the thematic process, three members of the research team met to confirm and triangulate protocols and data (e.g., interview guide, codes, and themes) (Brewer & Sparkes, 2011; Côté et al., 2016; Morse et al., 2002). Finally, by utilising large descriptive quotes and direct language from the conversations, the findings will be meaningful to other S&C coaches, ensuring *resonance* (Tracy, 2010).

4.5 Results

Fourteen interviews were conducted lasting a total of 18:11:40 hours (mean = 01:17:59 hours, SD = 00:15:45 mins, range = 00:48:51 to 01:49:45 hours). Data were organised in to three central order themes, and then further broken down into higher order themes: technology (drivers for buying), applications (testing, monitoring, programming, feedback, and educational tool), and reflections (benefits, drawbacks, and future use) (Figures 16-18). All themes were inductively developed based on the transcribed data. Anonymised raw data quotations are used as part of the main text to contextualise each theme.

Technology

The first central organising theme was technology, consisting of a single higher order theme, 'drivers for buying technology' (figure 16). Participants utilised a variety of technologies, including LPTs (Gymaware, Tendo), IMUs (PUSH), infra-red laser optic technology (Flex), and 3D cameras (Elite Form). Many referred to Gymaware as the gold standard, with participants feeling the reliability of LPTs were their main attribute. IMUs, however, were considered to have superior user interfaces, flexibility, and price point. The 3D cameras were preferred because of squat rack integration and minimal footprint, whereas the infrared technology was seen as a valid wireless version of LPTs.

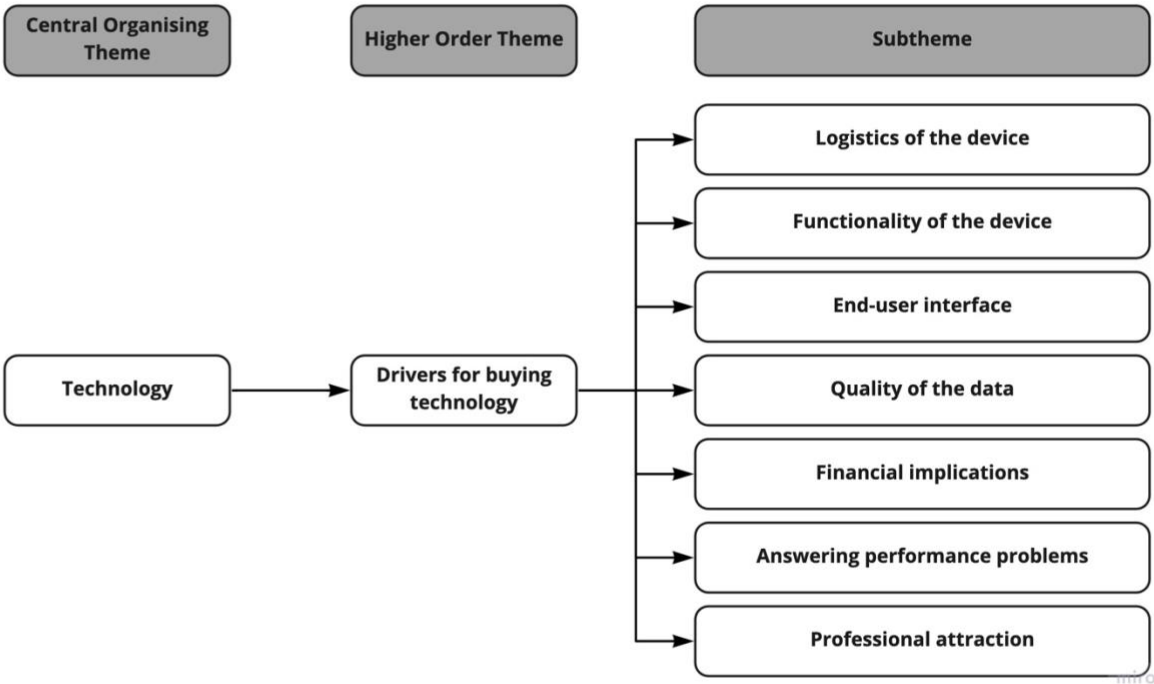

Figure 16. Schematic representation of the central order theme for technology, with accompanying higher-order and subthemes.

Drivers for buying technology

This higher order theme describes participants' motivations for purchasing VBT technologies, and comprised seven subthemes: *logistics of the device, functionality of the device, end-user interface, quality of the data, financial implications, answering performance problems,* and *professional attraction*.

Logistics of the device was a salient reason for most coaches, which included accessibility and suitability of the device, and consistency across the organisation. A few participants indicated that having regular access to technologies that suited their training environments or were consistent with other departments in their organisations were essential, e.g., "there are others available but the ones that, the things that we wanted to do, such like trap bar jumps, clean pulls, landmine punch etc. this all really is the bar" (P2).

Function of the device represented how well the device worked, and included usability, portability, connectivity, being a stand-alone, wireless unit, integration, and reliability. When referring to usability, participants indicated that being simple and user-friendly was integral. Others felt the plug and play nature and quick set-up of some devices made them attractive choices. Interestingly, some coaches felt being simple for athletes to use was also important, promoting autonomy and intuitiveness within training sessions.

> "But if I was to be the one deciding the kit I would, I think for me I would take into account the ease of use. Like if we're just looking for a general measure of meeting velocity if it wasn't horrifically unreliable then I'd probably go for the quickest and easiest one which the athletes can just work really easily" (P11).

Terms such as "feedback" and "visuals" emerged when referring to *end-user interface*. Participants suggested that the type of feedback that the device could provide was important, but that feedback must be robust, instant, and efficient. One coach also indicated that the visualisation of the feedback was important, preferring data to be presented as graphs and figures as opposed to just numbers.

> "Also, for me it's what it looks like, it's the platform that it's put on. Because I've seen some apps or some feedback and visually, they look poor, so I think they need to look good visually and display the right things. Yeah, I've always been keen on the visual aspect, and I've always seen data as, I don't want to see data as just numbers, I think we need some type of like a visual, a graph or a graphic in there" (P5).

The *quality of the data* (i.e., reliability and validity) was seen as essential for most participants, with a couple of coaches favouring validity, e.g., "…because if I trust the numbers to help guide my programming, if they're not accurate I feel like I can't actually do my job" (P3).

Despite this, it was apparent that *financial implications* (i.e., cost of the device and available budget) impacted which device coaches picked, e.g., "…it's probably cost, reward, and ability to actually implement in our setting" (P14). Interestingly, a few coaches felt *answering performance problems* or *professional attraction* were more important for their organisations. This referred to choosing technology that would influence performance programs or return to play strategies or would attract new members and athletes to their facility.

Applications

Applications represented the second central organising theme. Within this theme, four higher-order themes emerged: 'testing', 'monitoring', 'programming', and 'feedback'. These were then broken down further into subthemes (figure 17). Information regarding the phase of periodisation, frequency of use, and exercise selection was also considered.

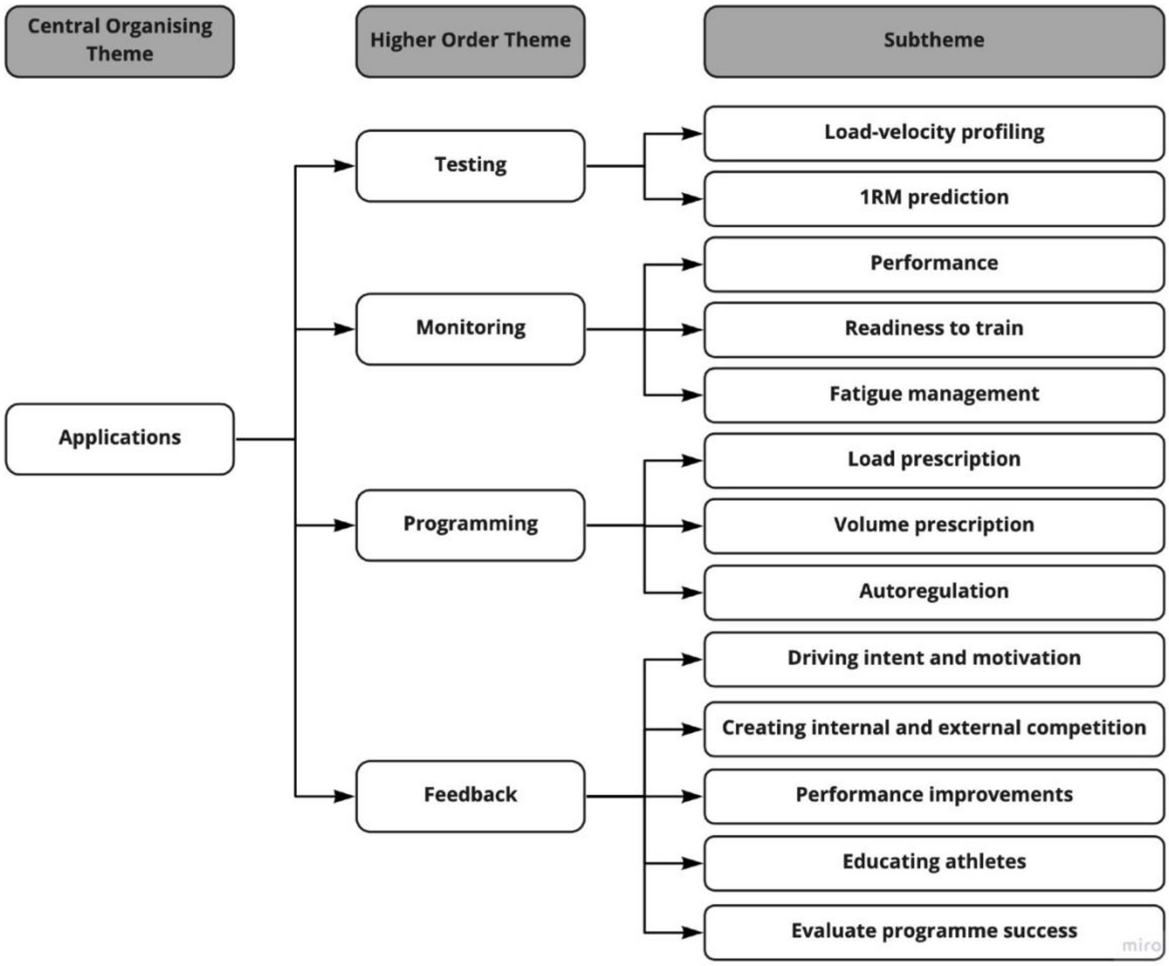

Figure 17. Schematic representation of the central order theme for applications, with accompanying higher-order and subthemes.

Regular VBT use within training was reported, specifically during maximal strength, strength-speed, speed-strength, and competitive phases (e.g., peaking or tapering), typically 1-3 sessions per week. VBT was employed during key lifts only, often involving a triple extension (e.g., Olympic lifting), a ballistic exercise (e.g., jump squat, trap-bar jumps), or lower and upper compound lifts (e.g., back squat, deadlift, bench press etc.). More advanced programming techniques such as contrast or cluster set training were mentioned, with one coach utilising VBT for overshoot repetitions (a heavy single repetition).

Testing

Load-velocity profiling was the main performance diagnostic reported, with varying protocols evident. Athletes were only profiled during key compound or ballistic lifts. Both the multi-point method (a profile constructed from multiple loads) and two-point method (a profile constructed from two loads) were utilised across the sample, e.g., “but if I need to do a quick and dirty estimation of their strength, then things like two-point methods and all that sort of stuff is really beneficial” (P3). Four different approaches for selecting loads emerged from the interviews, consisting of estimated or known percentages of 1RM (e.g., 40, 60, 80% 1RM), using absolute loads (e.g., 40, 60, 80 kg), selecting specific velocities (e.g., 1.0, 0.8, 0.6 $m.s^{-1}$), or via relative load (1.4, 1.2, 1.0 kg / BM). Some coaches also described the inclusion of ballistic (e.g., jump squat) exercise during the lighter loads of non-ballistic (e.g., back squat) LVP to reflect a more practically representative and valid approach to profiling. Linear regression was the only statistical approach reported, utilising the R^2 value to determine the percentage of explained variance. One coach utilised the data to predict maximum force, velocity, and power.

> “So, from those three different loads you can then build essentially your power curve. Well, the first thing we’ll do sorry is draw that linear regression line. So, from your three different progressive loads you’ve got, you can then predict V-max at F-zero and F-max and V-zero” (P12).

LVPs were utilised by some coaches to *predict 1RM*, typically using normative data (e.g., 0.25 $m.s^{-1}$ represents velocity at 1RM, V_{1RM}) as the point of extrapolation to determine changes in maximal strength or autoregulate load. One coach, however, undertook sets to failure to determine MVT (final repetition velocity in a set to failure) to predict the maximal load, e.g., "I love using plus sets or APRE (autoregulatory progressive adjustable exercise) as a sense of getting velocity cut-offs and estimating 1RMs through those methods" (P4).

Monitoring

In this higher order theme, participants described subthemes of measuring velocity to monitor *performance*, *readiness to train,* and *fatigue management*. Approaches to performance or fatigue monitoring included acute measurement of velocity on a sessional basis to compare with historic data and identify increases in strength or residual fatigue. In some instances, this would then dictate the load or volume prescribed for the day.

> "And I like to use it to autoregulate their load as well…using the history tab to see what they've lifted in the last session again it can help to direct us or direct that player to show them that they might be fatigued, they're lifting the same load as the last session, but their velocity is a lot lower, so do they need to bring their load down because they are fatigued, they are, they've trained hard on the pitch and their fatigue is kicking in" (5).

Programming

Three main subthemes emerged from the higher order theme, programming. These applications included *load prescription, volume prescription,* and *autoregulation.* When utilising VBT to *prescribe load*, all coaches set velocity targets or velocity zones to achieve specific adaptations, e.g., "We saw that trap bar jumps performed at 1.2-1.4 $m.s^{-1}$ in terms of mean velocity was the optimal zone for them to increase RFD" (P2). Zones were set via individualised LVPs, normative data taken from research or VBT 'experts, historical data, or coach experience. Most provided single-repetition targets, with a couple of coaches preferring to set average set targets, e.g., "When we get towards the games then we can train with that and just use velocity zones to say look, I want you to hit these zones for these repetitions" (P14).

Volume prescription described velocity loss thresholds to regulate volume, terminating a set when a specific drop in velocity occurred (e.g., 10%). One coach utilised VBT to ensure their athletes didn't train too close to proximity of failure (i.e., V_{1RM}) to reduce the impact of fatigue.

> "…using more of a percent velocity loss during the set to determine how many repetitions to, or what point to stop…20 high quality repetitions in the push press, for example, and then I'll say it doesn't matter to me how many sets it takes you to do it, but as soon as your percent velocity drops to 10% then I want you to stop your set" (P7).

The final emerging subtheme was *autoregulation*, which involved regulating load or volume in response to fatigue or strength improvements, micro-adjusting load through generalised amounts (e.g., 2.5kg-5kg) on an intra- or inter-session basis.

> "And as soon as they go over 0.5, you know, constantly then we'll say that's not where we want you, we need to add a load to the bar, and then keep lifting as fast as you can. Again, if they go below 0.5 it might be one repetition, then it doesn't matter, just make sure you keep it above; if they go under there numerous times then obviously the load is too heavy and then it gives us a great guideline as to how we can alter their loading prescriptions" (P9).

Feedback

The fourth and final higher order theme emerging from applications was feedback, which involved subthemes of *driving intent and motivation*, *creating internal and external* *competition, performance improvements, educating athletes,* and *evaluating programme success.* Feedback was the most mentioned application, potentially because of its simple nature.

Coaches described how VBT could be used to drive intent and motivate athletes, e.g., "…it's more of a way of, I suppose, increasing the intent surrounding how fast we've moved the bar… we're quite big on wanting to drive intent and wanting to cue athletes" (P8). Specifically, external motivation was provided visually or audibly using the technology live within a session, helping to engage athletes, ensure maximal effort was applied during each repetition, and motivate athletes to train harder and faster.

> "We use it for extrinsic motivation, simple feedback, you know, it's a very simple tool that most people use for targeting; here's your target, hit your target, maintain an involvement, an engagement in the exercise" (P12).

VBT was seen as an effective way to *create internal* (with oneself) or *external* (with training partners) *competition* e.g., "I'm going to use it to create a bit of competition there or give them a carrot to chase on that front" (P6). Additionally, VBT was used to track long and short-term *performance improvements* (e.g., performing faster velocities at the same load or changes to LVP and/or power curves). This performance was then used to infer changes in physical qualities such as strength, power, and acceleration, relating this change to the relevant physiological adaptations.

> "I'm pushing them and the data's pushing them as well and there's other boys that have, they've got the same on the bench, but their velocity is going up. So that's another way that we can track load as well and use that to feedback to the coaches and to the players" (P5)

Finally, VBT was used to *evaluate and educate* coach and athlete. The feedback provided by VBT technology could create positive conversation between athletes, coaches, and performance staff. These conversations included evaluating loads and fatigue levels for the day, evaluating the success of a programme, or whether changes are required short- or long-term. They were also used to educate athletes based on underpinning physiology and scientific principles.

> "No, it's still this is what you've hit, this is what you've got to and we will classify that as a good power effort. Or we missed a loading, the loading was too light because your velocities are creeping, and we need to put more load on the bar. So yeah, I use it for that type of double checking, is the programming correct, do you know what I mean"? (P12).

Reflections

The final central organising theme was coach reflections. Three higher-order themes emerged, which included 'benefits', 'drawbacks', and 'future use', with multiple subthemes emerging further (figure 18). A few coaches expressed frustrations with traditional prescriptive methods (e.g., % 1RM) and their inability to account for confounding training factors (e.g., competition congestion, technical and tactical training etc.). VBT was thought to be a flexible alternative, objectively adjusting and benchmarking loadings for athletes on a regular basis. Similarly, many implemented VBT to reliably determine 1RM, assess performance, make programming decisions, and provide additional data for athletes and coaches.

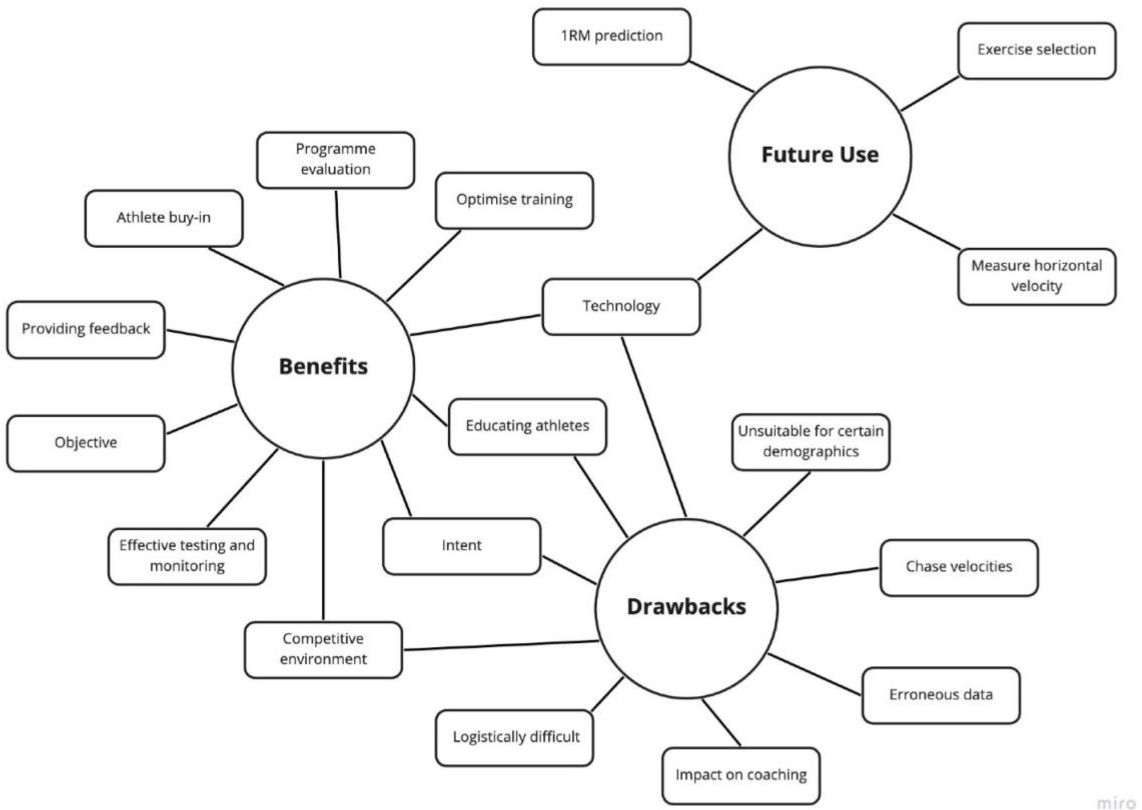

Figure 18. Schematic representation of the central order theme for reflections, with accompanying higher-order and subthemes.

Within this central organising theme, four subthemes emerged as both a 'benefit' and a 'drawback' (figure 18). *Technology* was described as a benefit due to access to cloud-based portals, the integrative nature of some devices, and their portability, flexibility, and simplicity. A few coaches, however, indicated that *technology* could also be a drawback because of on-going costs/subscriptions, maintenance and repair requirements, availability, and potential connectivity issues. *Educating athletes* was thought to facilitate progression, promote autonomy and accountability, and provide athletes with training variety. Conversely, some coaches felt it was often difficult to educate athletes to an adequate level to exploit those benefits. The requirement to move with *intent* was criticised by some coaches, suggesting this was difficult if used with inexperienced individuals. Nevertheless, some saw this as an advantage, suggesting it could encourage athletes to train at their maximal intensity and promote high velocity movements, irrespective of the training age. Finally, some coaches saw the benefits of creating a *competitive environment*, however, others felt that it could dishearten those that were slower than the rest of the group, potentially meaning they avoid important exercises.

Benefits

The first higher order theme was benefits, which included *optimising training, programme evaluation, athlete buy-in, providing feedback, an objective tool,* and an *effective testing and monitoring strategy* as subthemes, in addition to the ones above. A consensus amongst most coaches regarding the ability to optimise different elements of the training process emerged. These included optimising adaptations across the force-velocity curve, managing volume and load prescriptions more accurately, tracking player readiness and managing fatigue, e.g., "…fantastic to track player readiness as well… are we doing too much? Are we doing too little? Are players fresh enough for the weekend? Who could do with more or less training?" (8), and a way to individualise training.

> "Individualisation is like the biggest one where I think VBT is you're able to individualise for the system, for the athlete every session every day basically in terms of what you're asking them to do and what kind of state their central nervous system, a better term, is in during that specific session" (P7).

A few coaches discussed the ability to *evaluate programmes* and be an effective *testing and monitoring tool*. The acute tracking of an individual's physical performance and effectiveness of a block of training was beneficial to some coaches. *Providing feedback* was also described as a benefit to coaches, specifically as it could be used to drive athlete buy-in, motivate athletes, drive engagement, and quantify and regulate effort.

> "I've also heard that just hearing a sound, whether a clap or in this case a beep, can create a 7% increase in output as well. So, if you're getting constant repetition of those sound feedback, that's continually driving intent, so that's another great purpose for it" (P9).

Finally, the *objective* nature of VBT promoted quantifiable strategies, providing confidence in decision making, e.g., "I think because it's objective you're probably more likely to get stronger or get better improvements in the variables you're chasing." (P11)

Drawbacks

The second higher order theme was drawbacks, with subthemes of *chasing velocities, unsuitability for certain demographics, erroneous data, logistically difficult,* and *impact on coaching* arising. Some coaches indicated that VBT was *unsuitable for some demographics*, suggesting implementation of VBT must come at the correct time, and was potentially inappropriate with weaker or inexperienced individuals, e.g., "…but I guess there's times when it's inappropriate, and that would be, you know, essentially weak athletes who need just the building blocks, the fundamentals" (P1).

Chasing velocities emerged as a major drawback to many coaches. Providing velocity feedback frequented interview transcripts as negatively impacting exercise technique to achieve or beat a specific velocity, e.g., "…put that number in front of people to actually chase, that's what their intent and their thinking goes towards and then the technical aspects of how you want them to lift it, that kind of goes out the window" (P6). *Erroneous data* because of technical flaws or poor data quality also frustrated coaches, sometimes impacting prescriptions, load adjustments, and feedback. *Logistical difficulties* disadvantaged a few coaches, with some feeling VBT was problematic in team settings and could be labour intensive and time consuming to implement, reducing the flow of a session. A few coaches also indicated that VBT could negatively *impact their coaching*, presenting terms such as “iPad coach” and expressing concerns over coaches being distracted or lazy, and not always present within the weight room “…you don’t want to become like an iPad coach where your athlete could be doing something that looks terrible, but the numbers look great and that’s all I’m seeing” (10).

Future use

The final higher order theme was future use, with four subthemes emerging: *1RM prediction,* integrated *technology, measure horizontal velocity,* and *exercise selection*. Several coaches indicated a desire to utilise VBT, specifically the LVP to predict 1RM regularly, however, current methods were unreliable, time-costly, and interrupted sessional flow. Additionally, a few coaches expressed a desire to utilise more integrated *technology* (e.g., synch multiple units to one iPad), measure *horizontal velocity* more accurately, and have a greater *exercise selection* available.

4.6 Discussion

The aim of this study was to evaluate the use of VBT within elite S&C. More specifically, this study explored practitioners’ perceptions of VBT, how they implement it in practice, and evaluated alignment to peer-reviewed research. Three central organising themes emerged: technology, applications, and reflections, with each one containing specific elements pertinent to the devices used, the approaches implemented, and the benefits and drawbacks of VBT.

VBT was seen to be complementary to traditional prescriptive methods (e.g., % 1RM) by coaches, with many suggesting it should be used to enhance current practices. A continuum of applications from simple feedback to full periodisation were described. Some coaches believed VBT offered greater accuracy in programming, ensuring the desired physiological adaptation was being elicited. Frustration with traditional methods (e.g., % 1RM) was also articulated, with some coaches lamenting poor flexibility with these approaches, suggesting strength levels could vary by 18% per day and be affected by additional training, competition, or other confounding variables. Regular and simple programme evaluation was a well-articulated advantage of VBT. By tracking improvements across the full force-velocity spectrum, coaches were more confident in stimulating the correct physiological adaptations. One coach expressed the improvements visible across the full curve were upwards of 20% in some athletes, whereas maximal strength improvements (1RM) might only be 1-2%. Suchomel et al. (2021) recently explicated athlete monitoring as having two overlapping purposes: managing fatigue and programme efficacy, which can be challenging when using methods such as % 1RM alone (Suchomel et al., 2021). An individual's 1RM (i.e., maximal strength) is fluid, and can be impacted by additional stressors such as poor nutrition, sleep deprivation and residual fatigue (Bartholomew et al., 2008; Greig et al., 2020; Moore & Fry, 2007; Reilly & Piercy, 1994; Shattock & Tee, 2020). VBT, however, allows practitioners to account for such variation in strength through its basic principles (Suchomel et al., 2021).

Participants divulged other benefits of VBT. Feedback, in particular driving intent, creating motivation, and a competitive environment, were believed to be major advantages. Coaches expressed the positive impact VBT had on the training environment, promoting healthy competition between athletes, full engagement and buy-in to a training programme, and ensuring maximal intent was achieved during each repetition. Despite this important application of VBT, research in this area is limited. Weakley et al. (2019; 2020) found a 6.6-7.6% improvement in concentric barbell velocity at 65% and 75% 3RM back squat when providing visual or verbal kinematic feedback. Similarly, Jiménez-Alonso et al. (2020) found mean velocity was more reliable in lighter loads (e.g., 40% 1RM) when providing verbal velocity feedback during the bench press. This data suggests that simple velocity feedback can have a positive impact on training environments and kinetic and kinematic data and is an avenue for future research.

VBT was used throughout different cycles of a periodised plan, with many coaches agreeing its place was best suited to key exercises when programming and testing. Some coaches preferred to utilise VBT during maximal strength phases, whereas others felt it was better suited to explosive blocks such as pre-competitive, peaking, tapering, or speed-strength. VBT was also implemented with traditional compound lifts, ballistic exercises, cluster sets and contrast training, demonstrating its flexibility and utility within other forms of training.

Research investigating the efficacy of VBT in alternative loading strategies or training blocks is somewhat limited. Similarly, no longitudinal studies have been conducted to investigate the use of VBT over multiple training blocks or the course of a macrocycle (intervention durations are typically < 8 weeks). Studies have investigated the impact of load manipulation and velocity loss as two methods of autoregulating prescriptions to optimise programming, however, these are often limited to maximal strength or traditional compound exercises (Banyard et al., 2020; Dorrell, Smith, et al., 2020; Orange, Metcalfe, Robinson, et al., 2020; F. Pareja-Blanco et al., 2017; Fernando Pareja-Blanco, Alcazar, et al., 2020; Pérez-Castilla et al., 2018). In practice, VBT seems to be more versatile, having a more prominent place within speed-strength-type training blocks or when utilising more explosive, ballistic-type exercises where the aim is to move light-to-moderate loads as fast as possible.

Implementing VBT during explosive training seems physiologically and mechanically logical. Sporting actions (e.g., sprinting, jumping, and change of direction) typically occur in time periods < 250 ms (Andersen & Aagaard, 2006), and therefore maximising the trade-off between force production and acceleration (F = ma) is essential for sporting success (Turner et al., 2020, 2021). Optimising impulse (force x Δ time), RFD, and power (work / Δ time), and their associated neuromuscular adaptations (e.g., motor unit recruitment, intramuscular coordination, rate coding, musculotendinous stiffness etc.) therefore, is the goal of any long-term periodised plan (Brearley & Bishop, 2019). Lighter, dynamic effort training requires maximum intent and velocity to ensure acceleration of the barbell or system is maximised. VBT can provide necessary feedback to ensure this happens. Similarly, VBT can ensure loading is optimised (force x velocity trade-off) and individualised, maximising mechanical output. More research is needed, however, to determine the effectiveness of VBT to optimise load during a power-type training block and its appropriateness to physical performance.

When utilising VBT to autoregulate, most coaches set velocity zones or targets, adjusting load (kg) on the barbell to maintain velocity across the session. These zones, however, would often be based on generalised or normative data, individualised historical data, or coach experience and estimations. These zones would typically be squad wide, meaning all athletes would work at the same velocity irrespective of strength levels. Large between-participant variability in velocity during the free-weight back squat has been observed, suggesting that large, generalised zones would be suboptimal (Banyard et al., 2018). Conversely, Dorrell, Moore, et al. (2020) found no significant differences in strength and jump height improvements when performing a six-week intervention using group-based vs. individualised load-velocity profiles, suggesting that the between-participant variability seen on an acute level may not impact longer-term adaptations. This study was only six weeks long however, potentially limiting the opportunity for improvements to be fully realised. Interestingly, coaches here described individualisation as a key benefit of VBT despite refraining from individualising targets based on LVP data due to the time cost of the protocols. Coaches preferred to adopt simple, quick, and generalised methods over complex, individualised approaches, meaning that normative data and pre-determined zones may be logistically more advantageous.

A variety of LVP-based protocols emerged from the interviews, including multiple ways to determine loads performed (e.g., % 1RM vs. kg vs. kg/BM vs. velocity), number of increments (e.g., 2-6) and exercises used (e.g., back squat, loaded jumps, landmine punch throw, bench press). These different strategies used to profile athletes were often dictated by environment, personal preference, and experiential knowledge. For example, one coach used relative strength to set loads for a deadlift LVP, and then did a set to failure to determine last-repetition velocity and estimate the V_{1RM}. This method was established through a VBT practitioner workshop and blog posts. Interestingly, few coaches utilised peer-reviewed research for VBT-related decisions. Many were determined through social media posts, coach-conversations, or their own personal experience, conforming to previous research indicating only 1.8% of practitioners acquire knowledge from literature (Stoszkowski & Collins, 2016). This highlights discrepancies between research and practice, with coaches suggesting access, time, and recommendations unsuited to applied environments as reasons. Further research such as the present study is vital to understand what happens in practice to ensure research can align better to practitioners' requirements.

LVP is a diagnostic tool that investigates the relationship between load lifted and movement velocity (Thompson, Rogerson, Ruddock, Banyard, et al., 2021). These two variables possess an inverse association, typically in a linear fashion, with R^2 values > 0.9 often being reported

(García-Ramos, Pestana-Melero, Pérez-Castilla, et al., 2018; McBurnie et al., 2019; Weakley, Mann, et al., 2020). Some coaches deemed the R^2 value important, using a target of > 0.9 to determine a valid profile. Multiple LVP strategies have emerged from research, often utilised to provide specific velocities targets for athletes (García-Ramos, Barboza-González, et al., 2019; Fernando Pareja-Blanco, Walker, et al., 2020; Pérez-Castilla, García-Ramos, et al., 2020). Despite this recommendation, coaches in the present study utilised LVPs to determine performance changes over time, as opposed to as a prescriptive tool, with only a handful of coaches using the profile for predictive means. In fact, some coaches expressed their frustrations with profiling, suggesting it can be too time consuming and stagnate the flow of sessions. Importantly, most coaches strived for simple methods to assess and monitor their athletes, with profiling often being too complex to implement despite the availability and purported reliability of the two-point method (García-Ramos, Haff, Pestaña-Melero, et al., 2018).

The efficacy of VBT often relies on advanced technology. A variety of devices, including LPTs, wearable IMUs, infra-red laser technology, and two-dimensional (2D) camera systems emerged from the interviews. Coaches typically used technology that fit their training environments, personal preferences, or was a result of circumstance (e.g., a loan or to stay consistent with other subdivisions). Despite the variety of technology being used, most practitioners considered LPTs as the “gold standard” because of their superior reliability and validity, agreeing with the literature (Thompson et al., 2020; Weakley et al., 2021). Interestingly, data quality was not a significant driver for buying technology. Price point and functionality trumped data, with coaches believing that if the device is not user-friendly, the quality of the data is obsolete. This information could be important for technology companies looking to break into this market, perhaps suggesting that more focus should be spent on usability over data in practical contexts.

Two of the main challenges for implementing VBT were set-up and administering time, particularly for the coach, and the impact chasing velocities have on lifting technique. Several participants expressed concerns over creating “iPad coaches”, i.e., too much time spent in session looking at data and troubleshooting technology. Similarly, coaches felt that velocity feedback sometimes encouraged athletes to disregard technique to move the bar as quickly as possible. Other drawbacks included erroneous data, malfunctioning technology, and difficulty implementing with large groups. It is important for practitioners to understand the challenges of using VBT to better plan and organise their practices, optimising the implementation where possible, and overcome pitfalls as described by the coaches here.

4.7 Conclusions

VBT is a versatile tool that can complement the programming, prescription, testing, and monitoring of athletes. S&C practitioners implement VBT in many ways, including profiling, autoregulation of load and volume, fatigue management, and as a feedback tool to drive intent, motivation, and create competitive environments. Despite the recent influx of peer-reviewed research, S&C coaches are developing novel strategies through continued professional development courses, social media content, and practitioner discussions that are not reflected in the literature to date. Coaches value quick and simple strategies – approaches that are often missing from the literature. Coaches, therefore, shape their practices with advice from others to fit VBT into their environments.

Education in this area is integral to further practice. VBT has many uses, however, practitioners need easy-to-digest information about the most effective ways to implement

VBT specific to their environments and what technology fits their budgetary and training needs. Access to such information could help practitioners utilise strategies such as VBT more effectively. It is also the responsibility of researchers to ensure studies are practically led and flexible enough to suit multiple environments, bridging the gap between applied and peer-reviewed worlds.

Chapter 5.0: Study 3 – The reliability and validity of current technologies for measuring barbell velocity in the free-weight back squat and power clean

5.1 Study rationale

This PhD features a series of exploratory and mechanical studies culminating in the assessment of load-velocity profiling to predict 1RM for load autoregulation. Prior to carrying out this research, it was necessary to evaluate the reliability and validity of the VBT technologies most used in research and practice.

It was an important aim of this research to investigate the most utilised velocity-based technologies within elite S&C environments. Additionally, this research sought to provide clear recommendations to coaches from varied settings by incorporating a mix of different devices (e.g., LPT vs. IMU vs. applications) with wide-ranging price points (£9.99 to £2000). The technologies included within this study were therefore identified from practitioner responses directly. Study two revealed that LPTs, IMUs, and smartphone devices were most common in practice, and these devices were therefore evaluated in the present study. Practitioners also described difficulties in implementing VBT and LVPs into their practices in relation to time, logistics, and accuracy – aspects also explored quantitatively in later studies within the PhD.

A true criterion measure (3D motion capture) was required to provide a full evaluation of each device's validity, ensuring coaches can have confidence in the technology they use within their practices. Most research investigating the validity of velocity-based technology inappropriately includes other field-based technology (e.g., LPT) as the comparator. Similarly, once the validity of a device is evaluated, between-day reliability needs to be observed to ensure the device can be implemented regularly by coaches. Additionally, the two exercises selected for this study were based on key exercises typically prescribed within training programmes, which was confirmed in study two. By addressing these issues, this study also sought to address issues of poor methodological rigour within the evidence base and allow researchers and practitioners to be confident in the reliability and validity of common tools based on its findings.

5.2 Abstract

This study investigated the inter-day and intra-device reliability and criterion validity of six devices for measuring barbell velocity in the free-weight back squat and power clean. Ten competitive weightlifters completed an initial 1RM assessment followed by three LVPs (40-100% 1RM) in both exercises on four separate occasions. Mean and peak velocity was measured simultaneously on each device and compared to 3D motion capture for all repetitions. Reliability was assessed via CV and TE. Least products regression (LPR) (R^2) and limits of agreement (LOA) assessed the validity of the devices. The Gymaware was the most reliable for both exercises (CV < 10%; TE < 0.11 $m.s^{-1}$, except 100% 1RM (mean velocity) and 90-100% 1RM (peak velocity)), with MyLift and PUSH following a similar trend. Poor reliability was observed for Beast Sensor and Bar Sensei (CV = 5.1%-119.9%; TE = 0.08-0.48 $m.s^{-1}$). Gymaware was the most valid device, with small systematic bias and no proportional or fixed bias evident (R^2 > 0.42-0.99 LOA = -0.03-0.03 $m.s^{-1}$). MyLift also followed this trend in the back squat. Both PUSH devices produced some fixed and proportional bias, with Beast Sensor and Bar Sensei being the least valid devices across both exercises (R^2 > 0.00-0.96, LOA = -0.36-0.46 $m.s^{-1}$). LPTs and smartphone applications could be used to obtain velocity-based data, with IMUs demonstrating poorer reliability and validity.

5.3 Introduction

Strong inverse linear relationships between load and velocity exist across many resistance-based exercises (Banyard, Nosaka, & Haff, 2017; Chéry & Ruf, 2019; González-Badillo &

Sánchez-Medina, 2010). The facilitation and monitoring of training prescriptions, fatigue management, daily strength estimations, and motivation have all been proposed as benefits to implementing velocity-based measures in to practice (González-Badillo & Sánchez-Medina, 2010; Jovanovic & Flanagan, 2014; Weakley, Wilson, et al., 2020). Nonetheless, the reliability and validity of some technologies such as LPTs, IMUs and smartphone applications designed to measure barbell velocity and facilitate the above still need further investigation in certain exercises. Moreover, comparisons between devices will provide coaches with practical recommendations on the most appropriate technology to utilise in the field.

Research has investigated the reliability of several devices in exercises such as the back squat, bench press, deadlift, and bench-pull, with LPTs (e.g. Gymaware, Tendo, Speed4Lifts etc.) typically considered the most reliable and valid tool for measuring barbell velocity in applied contexts (Banyard, Nosaka, Sato, et al., 2017; Courel-Ibáñez et al., 2019; Dorrell et al., 2019; Garnacho-Castaño et al., 2014; Orange et al., 2019; Pérez-Castilla, Piepoli, Delgado-García, et al., 2019). LPTs utilise an optical encoder and tether-based system that enables the real-time collection of displacement-time data to calculate velocity (Dorrell et al., 2019). Tes of 6.0-8.9% have been observed for mean and peak velocity across three trials at 80% 1RM in three common exercises with the Gymaware (Dorrell et al., 2019). SEMs of 3.9-9.9% in mean and peak velocity have also been observed in the back squat and bench press (Orange et al., 2019; Orange, Metcalfe, Marshall, et al., 2020). Other LPTs such as Speed4Lifts, T-Force and Chronojump have demonstrated good levels of reliability (Courel-Ibáñez et al., 2019; Pérez-Castilla, Piepoli, Delgado-García, et al., 2019) leading to researchers utilising these systems as criterion measures (García-Ramos, Pérez-Castilla, et al., 2018; Garnacho-Castaño et al., 2014; Orange et al., 2019).

LPTs such as the Gymaware can be expensive (≈ £2000) and are sometimes limited to barbell exercises, however wearable or tether free IMUs can be more affordable and versatile within the training environment. IMUs rely on a combination of accelerometers and gyroscopes to measure acceleration data with respect to time (Balsalobre-Fernández et al., 2016), however, different devices can often differ in terms of their reliability. Large CV (0.8-19.1%) and ICC (0.46-0.99) ranges, and fixed and proportional bias, have been observed for the PUSH band across various exercises, equipment (smith-machine vs. free-weight), metrics (mean and peak velocity) and methods (inter- vs. intra-session and set reliability) (Balsalobre-Fernández et al., 2016; Courel-Ibáñez et al., 2019; Lake et al., 2019; Orange et al., 2019; Pérez-Castilla, Piepoli, Delgado-García, et al., 2019). IMUs such as the Beast Sensor and Bar Sensei are comparatively under-investigated (Balsalobre-Fernández et al., 2017; Beckham et al., 2019) and require full validation against a criterion measure. Similarly, smartphone applications (e.g. MyLift) are new tools for measuring velocity and utilise the advanced technology in smartphones such as accelerometers, gyroscopes and magnetometers (Balsalobre-Fernández et al., 2017; Balsalobre-Fernández, Marchante, et al., 2018). Practically perfect ICCs (0.92 to 0.97) and low CVs (2.9% to 5%) in the back squat, bench press, and hip thrust exercises have been observed for the MyLift application (formerly PowerLift) (Balsalobre-Fernández et al., 2017; Balsalobre-Fernández, Marchante, et al., 2018; Pérez-Castilla, Piepoli, Delgado-García, et al., 2019), however, research in this area is still limited and further validation is therefore required.

Many studies have investigated the concurrent validity of LPTs, IMUs, or smartphone applications utilising other LPTs as the criterion measure (Balsalobre-Fernández et al., 2016, 2017; Balsalobre-Fernández, Marchante, et al., 2018; Courel-Ibáñez et al., 2019; García-Ramos, Pérez-Castilla, et al., 2018; Orange et al., 2019), which is problematic given LPTs still produce measurement error (Courel-Ibáñez et al., 2019; Pérez-Castilla, Piepoli, Delgado-

García, et al., 2019). 3D motion capture is considered the gold-standard for measuring human movement due to its sophisticated technology, ability to measure all three planes of motion, small measurement error, and excellent repeatability (Ford et al., 2007; Munro et al., 2012). Surprisingly, only two studies to date have employed 3D motion capture as the criterion measure when measuring barbell velocity (Dorrell et al., 2019; Lake et al., 2019). Dorrell et al. (2019) reported R^2 values of 0.91 to 0.99 for peak and mean velocity across three exercises in the Gymaware, whereas Lake et al. (2019) observed proportional bias in the PUSH in the bench press when employing least-products regression (LPR). Both studies, however, were limited to one or two loads, preventing analysis of the full LVP.

Most of the literature in this area predominantly investigates strength-based exercises. Nevertheless, weightlifting exercises such as the power clean are also very common in practice given their favourable inter- and intra-day reliability and strong influence on physical skills such as jumping and sprinting (Comfort, 2013; Tricoli et al., 2005). The power clean, like other weightlifting derivatives, stimulates high force generation and impulse due to the requirement to lift heavy loads with high velocity (Kipp & Meinerz, 2017; Tricoli et al., 2005). Technical proficiency and consistency of such movements are integral to their impact on physical development (Kipp & Meinerz, 2017; Stone et al., 2006) and thus perfecting this competency is essential. The reliability and validity of velocity-based devices when tracking such movements have, to date, never been investigated.

Methodological errors and unrepresentative procedures such as the use of smith machine exercises, inaccurate estimations of relative loads, or limited evaluation across multiple sessions (Balsalobre-Fernández et al., 2016; Courel-Ibáñez et al., 2019; Garnacho-Castaño et al., 2014; Pérez-Castilla, Piepoli, Delgado-García, et al., 2019) have rendered much of the reliability and validity data in this area problematic, particularly within practical contexts. Moreover, exercises employed within this research tend to be limited to strength-based compound exercises. Assessments of reliability and validity of velocity-based devices used during explosive exercises and weightlifting derivatives such as the power clean are scarce, despite being prevalent in practice. Therefore, the aim of this research was to assess the inter-day and intra-device reliability and criterion validity of six common velocity-measuring systems (Gymaware, PUSH x 2, Bar Sensei, Beast Sensor, MyLift) in competitive weightlifters in the free-weight back squat and power clean exercises. Whilst evidence for some of these technologies is scarce at the time of writing, we hypothesised that the Gymaware LPT would demonstrate the greatest reliability and validity of the devices, with the IMUs (PUSH, Bar Sensei and Beast Sensor) and smartphone application (MyLift) demonstrating lower levels of reliability and validity, comparatively.

5.3 Methods

5.3.1 Participants

Ten healthy competitive weightlifters (mean ± SD; age: 25.0 ± 5.6 y, body mass: 73.6 ± 13.9 kg, stature: 169.6 ± 6.6 cm), with a minimum competition history of regional level within 12 months prior to data collection, regular weightlifting training, and strength levels of > 1.5 $kg.bm^{-1}$ in the back squat, were recruited. A purposive sampling method was conducted given the specific population in question. The sample size was determined by the availability of this elite population and in conjunction with similar research in this area (Balsalobre-Fernández et al., 2016, 2017; Balsalobre-Fernández, Marchante, et al., 2018). All participants were informed about the potential benefits and risks of the study before providing informed consent prior to data collection. Ethical approval was granted by the local institutions review board in accordance with the 7th revision (2013) of the declaration of Helsinki.

5.3.2 Study design

The study assessed the reliability and validity of six velocity-based devices for measuring concentric mean and peak velocity against 3D motion capture in the free-weight back squat and power clean. Participants attended the laboratory on four separate occasions to complete an initial 1RM assessment, followed by three identical LVP sessions. All sessions were separated by 48-96 hours to ensure adequate recovery time, with all data being collected systematically and independently. Velocity was recorded simultaneously on each device for each repetition.

5.3.3 Methodology

During the baseline session, mass (kg) (InBody 720, Biospace, Korea), stature (cm) (Harpenden, Holtain Ltd, Wales), squat depth (cm) and power clean and back squat 1RMs were determined. The 1RM protocols were completed as per the National Strength and Conditioning Association (NSCA) guidelines (Haff & Triplett, 2016), and participants were habituated with the requirement to move loads with '*maximal intent and velocity*'. The 1RM assessment consisted of an incremental protocol (50-100% estimated 1RM) that culminated in the determination of the participants maximum load that could be lifted for one repetition for each exercise. When participants reached the estimated 1RM, loads were increased by 0.5-5 kg to find a true 1RM. A maximum of five attempts were allowed at 1RM and rest periods between sets were three to five minutes. Calibrated, International Weightlifting Federation (IWF) approved 20 kg bar and bumper plates (Werksan, Turkey) were used throughout this study. Participants undertook a standardised, individualised warm up protocol consisting of 5 minutes of cycling at 100 W (Ergomedic 874E, Monark, Sweden) and a combination of mobility, dynamic flexibility, and light barbell work.

The three subsequent visits were procedurally identical. Following completion of the standardised warm up, participants completed incremental load assessments ranging from 40-100% 1RM (10% increments) in the power clean and back squat. Throughout the protocol, participants performed 3 repetitions for light loads (≤ 60%), 2 repetitions for moderate loads (70-80%) and 1 repetition for heavy loads (≥ 90%), with 3-5 minute rest periods between sets (Banyard, Nosaka, Sato, et al., 2017). All concentric portions of each repetition were instructed to be performed with '*maximal intent and velocity*' to maximise the reliability of the movement. International Powerlifting Federation (IPF) and IWF technical and competition rules and regulations guidelines were adhered to for the back squat and power clean movements, respectively (International Powerlifting Federation, 2019; International Weightlifting Federation, 2019). The bar was placed in a high-bar position during the back squat and was situated on the superior aspect of the trapezius muscles. A lift was deemed successful when the greater trochanter was situated inferior to the lateral epicondyle of the knee at the lowest point of descent and the individual was able to fully extend the lower limbs on ascent. A power clean was deemed successful if the bar was caught across the glenohumeral joints and the participant could fully extend the lower extremities to finish the lift, and the greater trochanter finished superior to the lateral epicondyle of the knee at the lowest point of displacement during the catch phase. All lifts were assessed by an accredited S&C coach and retrospectively via a smartphone camera system (iPhone 7, iOS 11.4).

5.3.4 Equipment set-up

A 12 camera, 3D motion capture (Raptor, Motion Analysis Cooperation, USA) set-up was used as the criterion measure, sampling at 250 Hz and recording three-dimensional time-displacement data. The capture volume was central to the set-up, with the cameras evenly spaced around it. A full calibration was performed prior to each session, with a measurement error of < 0.3 mm accepted (Dorrell et al., 2019). Retro-reflective markers were placed on either end of the barbell to create a virtual mid-point on which velocity measurements were based (Dorrell et al., 2019).

The six devices tested can be seen in table 12. 4th generation iPad minis (Apple, USA) ran the software for each IMU and LPT device (iOS 11.4), with an iPhone 7 (Apple, USA) used for the smartphone app. The MyLift smartphone application and beast sensor IMU were only used for the back squat due to the capabilities of the two devices at the time of data collection. The MyLift application required an input of descent displacement prior to each repetition, which was measured for everyone during the baseline visit.

Table 12. The specifications of each velocity-based device.

Device	Type	Technology	Cost (£)	Sampling rate	Location of device
Gymaware	Linear Position Transducer	Optical encoder (Records displacement-time curve data to determine changes in bar position)	£1950	20 millisecond time points down-sampled to 50 Hz	Tether attachment 100mm from the end of the right hand-side of the barbell
Bar Sensei	Inertial Measurement Unit	Not reported	£305 approx.	Not reported	Placed on the left-hand side of the barbell, directly inside the collar using the sleeve provided by the manufacturer
PUSHbody (PUSH band 2.0 located on the forearm)	Wearable Inertial Measurement Unit	3 axis accelerometer and gyroscope providing 6 degrees of freedom in coordinate system. (Integration of acceleration data with respect to time)	£250 approx.	1000 Hz down-sampled to 200 Hz	Worn on the right forearm immediately inferior to the elbow crease with the on/off button located proximally as suggested by the manufacturer
PUSHbar (PUSH band 2.0 located on the barbell)	Inertial Measurement Unit	3 axis accelerometer and gyroscope providing 6 degrees of freedom in coordinate system. (Integration of acceleration data with respect to time)	£250 approx.	1000 Hz down-sampled to 200 Hz	Placed on the right hand-side of the barbell, directly inside the collar using the bar sleeve provided by the manufacturer
Beast Sensor	Wearable Inertial Measurement Unit	3-axis accelerometer, gyroscope and magnetometer. (Integration of vertical acceleration data with respect to time)	£250 approx.	50 Hz	Worn on the superior aspect of the right wrist using a wrist band provided by the manufacturer
MyLift (PowerLift at the time	Smartphone application	Manual frame-by-frame inspection of slow-motion video. (Pre-defined range of motion / time inputted prior to data collection)	£9.99	240 Hz (720p video quality)	Located directly behind the participant and fixed in position using a tripod positioned at hip height so the full barbell was

of data collection)	visible on the iPhone 7 (iOS 11.4.1) screen

5.3.5 Data processing

Positional marker data were identified, rectified, and gapped-filled using the Cortex software (v5.3.3, Motion Analysis Corporation, USA) before being analysed using custom-written MATLAB codes (R2017a, MathWorks, USA). A residual analysis of marker displacement (2 Hz to 13 Hz) was performed from a sample of data to determine the most appropriate cut-off filtering frequency for both lifts. Following this, a zero lag, second-order Butterworth low-pass filter was applied to the data, with a cut-off frequency of 6 Hz for back squat and 8 Hz for power clean. A barbell virtual midpoint was created by taking the mean of the diametric markers.

Vertical velocity of the concentric phase was calculated for the virtual midpoint position. The finite central difference method was employed for the differentiation of marker data (Hamill et al., 2014). The lowest and highest point of vertical displacement defined the start and end of the concentric phase for the back squat, respectively (Dorrell et al., 2019; Lake et al., 2019). The start of the power clean was defined as the first instance of positive vertical velocity coinciding with the first instance of vertical displacement. The end of the power clean was defined as the highest point of vertical displacement that coincided with the last instance of positive velocity, representing the initial point of contact during the catch phase (Kipp & Meinerz, 2017; Stone et al., 2006). Peak velocity was represented by the instantaneous highest velocity that occurred during the pre-defined concentric phase, and mean velocity represented the average velocity that occurred over the same phase.(Dorrell et al., 2019; Lake et al., 2019). All devices used in this study were operated as per the manufacturer’s instructions and all directly measured or calculated barbell velocity (table 12).

5.3.6 Statistical analysis

Univariate and multivariate outliers and skewness and kurtosis analyses were performed to determine if the data were normally distributed. Data were analysed using SPSS 24.0 (USA) and a custom-built spreadsheet (Microsoft Excel, USA) (Hopkins, 2015). The validity of the experimental devices was assessed against the criterion measure using LPR and expressed as an R^2 value in conjunction with 95% CI of the slope and intercept to assess fixed and proportional bias (Dorrell et al., 2019; Hopkins, 2000; Lake et al., 2019; Mullineaux et al., 1999). 95% LOA were also used to assess for systematic bias between the criterion and the other devices. Inter-day and intra-device reliability were analysed using a combination of TE and CV.

5.4 Results

Data was collected for ten participants across three repeat sessions. Each back squat LVP consisted of ten incremental loads, with nine being completed for the power clean. This totalled 57 pieces of data per participant and 570 data points for the total sample.

5.4.1 Reliability

Back Squat: Gymaware and MyLift produced the highest levels of reliability in the back squat (table 13), however, CVs and Tes typically increased as relative load increased. CVs > 10% were observed for 90% 1RM (peak velocity) and 100% 1RM (mean and peak velocity) for the Gymaware, and 90% and 100% 1RM (mean velocity) for MyLift (table 13). Comparable CV data was evident for PUSHbody (40-80% 1RM) and PUSHbar (40-70% 1RM), however, larger Tes were typically observed. Larger CVs and Tes were evident for the heavier loads (90-100% 1RM) for both PUSH devices compared with Gymaware and MyLift for mean velocity, with comparable or slightly lower CVs evident in peak velocity. Larger CVs and Tes were observed for both Bar Sensei and Beast Sensor across most relative loads compared to the other technologies (table 13). Typically, Tes and CVs were smaller for mean velocity compared to peak velocity for all devices.

Power Clean: The Gymaware produced smaller CVs and Tes across all relative loads compared to the PUSH and Bar Sensei devices (table 13). Light and moderate loads (40-70% 1RM) for PUSHbody displayed comparable CVs and Tes to the Gymaware, however heavier loads (> 80% 1RM) were higher in both velocity metrics. Larger CVs and Tes were observed for the PUSHbar for both mean and peak velocity. Bar Sensei had the least favourable reliability data for mean velocity but was comparable to the Gymaware for peak velocity.

Table 13. Test-retest reliability data for six devices in the back squat and power clean.

Load (%)	**Back Squat**				**Power Clean**			
	TE ($m.s^{-1}$)		**CV (%)**		**TE ($m.s^{-1}$)**		**CV (%)**	
	MV	**PV**	**MV**	**PV**	**MV**	**PV**	**MV**	**PV**
				Gymaware				
40	0.04	0.08	4.5	5.6	0.05	0.09	3.6	3.7
50	0.03	0.07	3.4	4.9	0.03	0.08	2.2	3.7
60	0.02	0.08	2.9	6.0	0.03	0.07	2.4	3.1
70	0.03	0.10	4.5	8.3	0.04	0.05	3.2	2.5
80	0.04	0.09	7.0	8.6	0.04	0.08	3.3	3.8
90	0.04	0.09	9.5	12.6	0.08	0.07	8.9	3.9
100	0.03	0.15	13.6	22.0	0.04	0.06	4.3	4.0
Full	0.04	0.10	9.8	11.3	0.05	0.07	4.9	3.3
				PUSH Body				
40	0.03	0.09	3.5	6.0	0.06	0.08	4.9	4.9
50	0.04	0.15	4.1	9.9	0.06	0.08	5.2	5.2
60	0.04	0.11	5.4	9.1	0.05	0.08	4.5	4.5
70	0.03	0.10	5.0	8.9	0.09	0.12	7.7	7.7
80	0.03	0.07	5.2	6.8	0.10	0.14	10.2	10.2
90	0.07	0.11	15.6	11.0	0.09	0.13	11.3	11.3
100	0.04	0.08	14.9	11.4	0.09	0.12	11.4	11.4
Full	0.05	0.11	10.6	11.3	0.08	0.11	8.3	8.3
				PUSH Bar				
40	0.06	0.09	5.2	5.7	0.20	0.36	21.5	21.5
50	0.08	0.10	9.2	7.5	0.18	0.33	19.0	17.9
60	0.05	0.12	5.1	9.4	0.17	0.42	18.9	25.4
70	0.04	0.09	5.9	8.3	0.13	0.22	14.6	13.4
80	0.09	0.09	14.3	8.8	0.14	0.25	16.3	15.6
90	0.09	0.12	20.3	14.2	0.15	0.31	18.1	22.2

100	0.06	0.09	15.4	11.6	0.10	0.23	13.3	17.5
Full	0.07	0.11	14.5	11.0	0.21	0.32	18.6	20.5
Bar Sensei								
40	0.08	0.14	9.1	9.4	0.23	0.20	20.4	7.7
50	0.09	0.10	13.5	7.6	0.16	0.15	13.8	6.5
60	0.07	0.08	8.8	8.0	0.13	0.13	12.1	5.8
70	0.07	0.09	10.7	10.2	0.13	0.19	11.8	8.8
80	0.08	0.24	18.3	35.8	0.13	0.13	14.9	6.1
90	0.08	0.12	19.1	18.0	0.15	0.14	17.7	7.9
100	0.13	0.12	60.5	28.5	0.14	0.15	18.4	8.5
Full	0.09	0.13	22.1	18.7	0.16	0.17	15.9	8.7
Beast Sensor								
40	0.05	0.10	5.1	6.2				
50	0.06	0.11	7.6	7.4				
60	0.08	0.15	12.0	11.8				
70	0.12	0.27	22.4	25.8				
80	0.22	0.33	72.3	54.0				
90	0.21	0.48	75.8	119.9				
100	0.15	0.29	40.6	65.1				
Full	0.14	0.30	42.4	53.2				
MyLift								
40	0.04		4.2					
50	0.03		3.7					
60	0.04		5.5					
70	0.03		4.9					
80	0.04		6.8					
90	0.05		12.6					
100	0.03		13.8					
Full	0.05		9.7					

% percentage of one repetition maximum, *CV* coefficient of variation, *Full* full dataset combined, *MV* mean velocity, *PV* peak velocity, *TE* typical error.

5.4.2 Validity

Back Squat: Gymaware demonstrated the strongest validity when compared to 3D motion capture during the back squat (table 14, figures 19 & 20). No fixed or proportional bias was observed for either device when measuring mean or peak velocity for the back squat, with R^2 values ≥ 0.95. The MyLift application followed a similar trend, with R^2 values ≥ 0.88 (table 14, figure 19). Small systematic bias was also evident for the two devices for both mean and peak velocity (figures 19 & 20).

Table 14. Least products regression for 6 devices in the back squat in comparison to 3D motion capture.

Load	R^2		Slope (95% CL)		Intercept (95% CL)	
(%)	MV	PV	MV	PV	MV	PV
			Gymaware			
40	0.95	0.97	1.010 (0.824, 1.196)	1.033 (0.896, 1.170)	-0.027 (-0.221, 0.167)	-0.042 (-0.263, 0.178)
50	0.95	0.98	0.990 (0.808, 1.172)	0.971 (0.866, 1.075)	-0.004 (-0.173, 0.166)	0.054 (-0.100, 0.209)
60	0.98	0.99	1.046 (0.931, 1.160)	0.983 (0.908, 1.059)	-0.056 (-0.152, 0.040)	0.031 (-0.073, 0.136)
70	0.97	0.99	1.073 (0.917, 1.229)	0.957 (0.870, 1.044)	-0.060 (-0.172, 0.052)	0.067 (-0.040, 0.174)
80	0.99	0.99	0.990 (0.892, 1.088)	0.979 (0.885, 1.073)	-0.002 (-0.061, 0.058)	0.040 (-0.064, 0.144)
90	0.99	0.96	1.014 (0.943, 1.084)	0.910 (0.761, 1.059)	-0.014 (-0.048, 0.020)	0.110 (-0.040, 0.261)
100	0.97	0.97	0.965 (0.826, 1.104)	0.936 (0.813, 1.059)	-0.001 (-0.042, 0.039)	0.066 (-0.043, 0.174)
Full	0.99	0.99	0.991 (0.979, 1.004)	0.970 (0.931, 1.009)	-0.005 (-0.014, 0.003)	0.054 (-0.003, 0.110)
			PUSH Body			
40	0.92	0.94	0.968 (0.730, 1.207)	1.026 (0.819, 1.233)	0.031 (-0.214, 0.275)	0.051 (-0.265, 0.368)
50	0.96	0.76	0.975 (0.816, 1.134)	0.852 (0.459, 1.245)	0.022 (-0.125. 0.168)	0.291 (-0.261, 0.844)
60	0.95	0.45	0.813 (0.659, 0.967)†	0.648 (0.069, 1.227)	0.160 (0.035, 0.285)*	0.562 (-0.170, 1.294)
70	0.88	0.60	0.842 (0.594, 1.090)	0.723 (0.238, 1.208)	0.128 (-0.043, 0.300)	0.425 (-0.127, 0.976)
80	0.92	0.37	0.746 (0.569, 0.922)†	0.482 (-0.033, 0.997)†	0.153 (0.048, 0.259)*	0.638 (0.114, 1.162)*
90	0.79	0.53	0.624 (0.365, 0.883)†	0.912 (0.217, 1.607)	0.173 (0.048, 0.298)*	0.227 (-0.380, 0.835)
100	0.58	0.48	0.790 (0.247, 1.333)	1.320 (0.195, 2.445)	0.004 (-0.184, 0.193)	-0.144 (-0.956, 0.727)
Full	0.97	0.80	1.028 (0.984, 1.072)	0.994 (0.918, 1.070)	-0.025 (-0.057, 0.007)	0.133 (0.053, 0.213)
			PUSH Bar			
40	0.69	0.91	1.224 (0.835, 1.613)	1.185 (0.894, 1.476)	-0.326 (-0.755, 0.102)	-0.271 (-0.735, 0.193)
50	0.95	0.89	1.000 (0.814, 1.186)	1.063 (0.763, 1.362)	-0.062 (-0.245, 0.120)	-0.019 (-0.444, 0.405)
60	0.83	0.84	0.757 (0.479, 1.036)	0.881 (0.574, 1.188)	0.143 (-0.106, 0.393)	0.212 (-0.196, 0.621)
70	0.84	0.80	1.082 (0.691, 1.473)	1.091 (0.655, 1.528)	-0.135 (-0.440, 0.170)	-0.019 (-0.525, 0.487)
80	0.87	0.60	0.745 (0.505, 0.985)†	0.818 (0.271, 1.365)	0.099 (-0.061, 0.259)	0.267 (-0.308, 0.842)
90	0.92	0.56	0.858 (0.657, 1.059)	0.951 (0.257, 1.644)	0.010 (-0.098, 0.118)	0.128 (-0.525, 0.781)
100	0.39	0.41	0.661 (-0.013, 1.335)	0.890 (0.027, 1.752)	0.023 (-0.236, 0.282)	0.100 (-0.652, 0.851)
Full	0.97	0.86	1.010 (0.969, 1.050)	0.982 (0.888, 1.076)	-0.082 (-0.115, -0.050)*	0.078 (-0.037, 0.193)
			Bar Sensei			
40	0.82	0.96	0.702 (0.437, 0.968)†	0.840 (0.051, 0.509)†	0.352 (0.098, 0.607)*	0.280 (0.051, 0.509)*
50	0.75	0.93	0.599 (0.313, 0.885)†	0.784 (0.605, 0.962)†	0.394 (0.143, 0.645)*	0.377 (0.123, 0.631)*
60	0.67	0.82	0.660 (0.285, 1.035)	0.968 (0.599, 1.336)	0.303 (0.009, 0.597)*	0.163 (-0.302, 0.628)
70	0.86	0.66	0.778 (0.520, 1.035)	0.825 (0.346, 1.303)	0.188 (0.015, 0.361)*	0.372 (-0.135, 0.880)
80	0.66	0.52	0.871 (0.362, 1.380)	0.680 (0.144, 1.217)	0.121 (-0.156, 0.398)	0.566 (0.120, 1.012)*
90	0.23	0.10	0.309 (-0.147, 0.765)†	0.332 (-0.470, 1.133)	0.326 (0.112, 0.540)*	0.777 (0.191, 1.362)*
100	0.01	0.02	0.359 (-0.233, 0.950)†	0.132 (-0.807, 0.171)†	0.147 (-0.056, 0.349)	0.737 (0.171, 1.303)*
Full	0.87	0.80	1.028 (0.945, 1.111)	0.712 (0.625, 0.799)†	0.010 (-0.048, 0.068)	0.485 (0.386, 0.583)*
			Beast Sensor			
40	0.64	0.10	0.646 (0.250, 1.042)	0.319 (-0.442, 1.080)	0.354 (-0.058, 0.765)	1.079 (-0.193, 2.351)
50	0.71	0.12	0.719 (0.347, 1.091)	0.470 (-0.590, 1.531)	0.282 (-0.048, 0.612)	0.763 (-0.849, 2.375)
60	0.49	0.00	0.414 (0.067, 0.761)†	0.038 (-0.857, 0.933)†	0.511 (0.250, 0.771)*	1.320 (0.100, 2.539)*
70	0.46	0.00	0.499 (0.062, 0.936)†	-0.097 (-1.043, 0.848)†	0.406 (0.139, 0.673)*	1.353 (0.165, 2.541)*
80	0.58	0.02	0.499 (0.154, 0.844)†	0.345 (-1.716, 2.407)	0.377 (0.224, 0.531)*	0.742 (-1.716, 2.952)
90	0.12	0.58	0.271 (-0.172, 0.713)†	0.927 (0.281, 1.574)	0.368 (0.199, 0.538)*	0.273 (-0.252, 0.798)
100	0.20	0.15	0.236 (-0.146, 0.619)†	0.385 (-0.357, 1.127)	0.188 (0.041, 0.335)*	0.626 (0.141, 1.110)*
Full	0.80	0.57	0.835 (0.736, 0.933)†	0.622 (0.493, 0.751)†	0.159 (0.092, 0.227)*	0.506 (0.346, 0.667)*
			MyLift			
40	0.96		1.161, (0.934, 1.388)		-0.142 (-0.370, 0.086)	
50	0.94		1.052 (0.833, 1.271)		-0.036 (-0.234, 0.163)	
60	0.88		0.847 (0.591, 1.104)		0.133 (-0.075, 0.341)	
70	0.95		0.936 (0.768, 1.104)		0.055 (-0.063, 0.173)	
80	0.93		0.884 (0.694, 1.074)		0.070 (-0.043, 0.183)	
90	0.92		1.004 (0.766, 1.243)		0.003 (-0.109, 0.114)	
100	0.85		1.004 (0.658, 1.351)		0.001 (-0.096, 0.097)	
Full	0.99		1.017 (0.992, 1.042)		-0.003 (-0.021, 0.015)	

% percentage of one repetition maximum, *MV* mean velocity, *PV* peak velocity. If the 95% confidence interval for the intercept does not include 0, then fixed bias is present (*); if the 95% confidence interval for the slope does not include 1, then proportional bias is present (†)

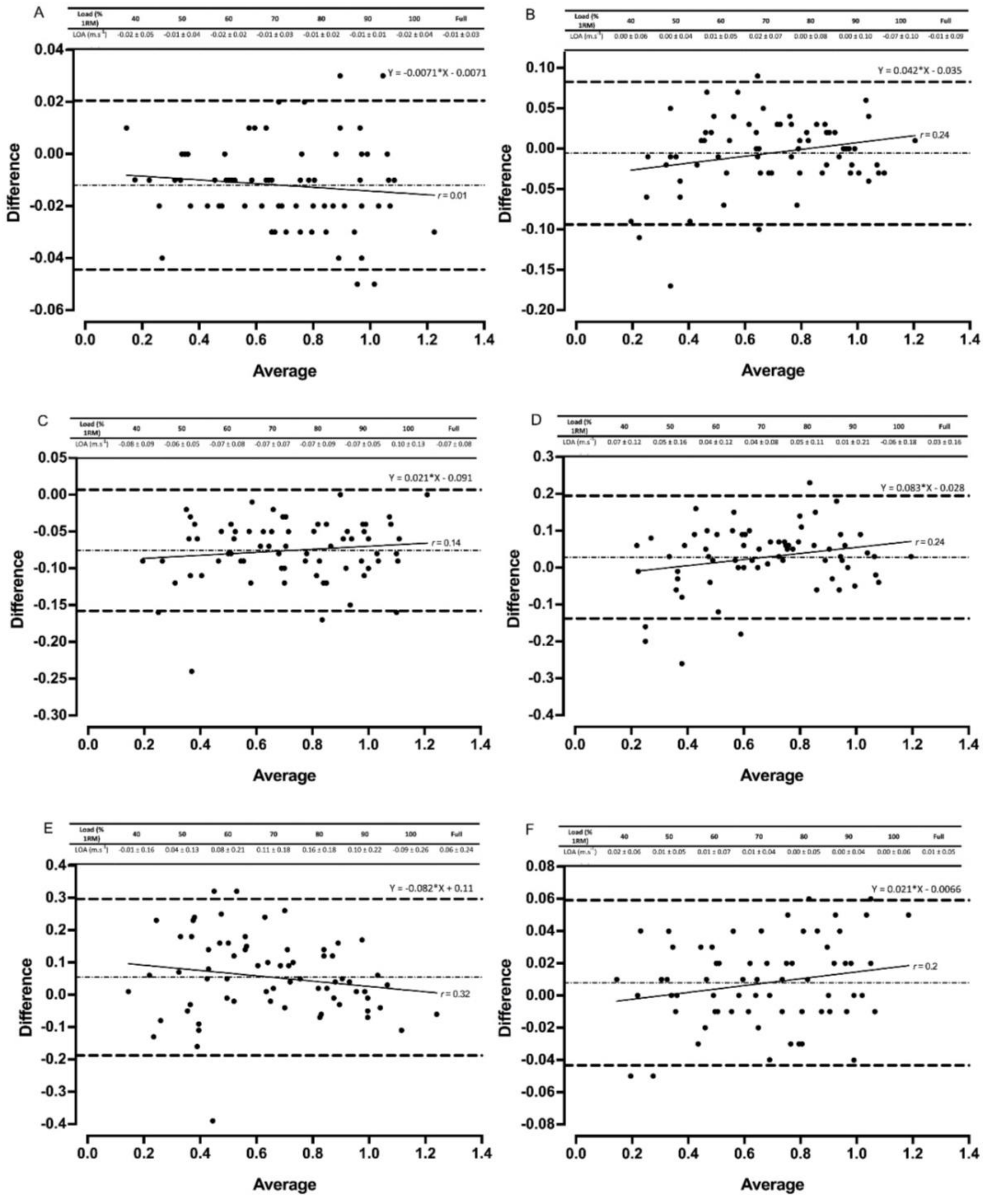

Figure 19. Bland-Altman plots exhibiting variation in velocity-based devices vs. 3D motion capture for full datasets for mean velocity in the back squat. The mean systematic bias (-·-) and 95% confidence intervals (---) are displayed with the regression line (—) and the *r* value. The table above displays the limits of agreement (LOA) ± 95% confidence intervals and coefficient of variation (CV) for each relative load. Gymaware (A), PUSHbody (B), PUSHbar (C), Bar Sensei (D), Beast Sensor (E) and MyLift (F) devices are all shown.

The two PUSH devices produced R^2 values of 0.80 to 0.97 as revealed from the LPR (table 14). Fixed and proportional bias was evident for loads of 60, 80, 90% 1RM, and 80% 1RM for mean and peak velocity, respectively. Peak velocity was over-estimated in both devices as shown by the LOAs. Smaller mean systematic bias was evident in the PUSHbody than the PUSHbar for mean velocity (figures 19 & 20).

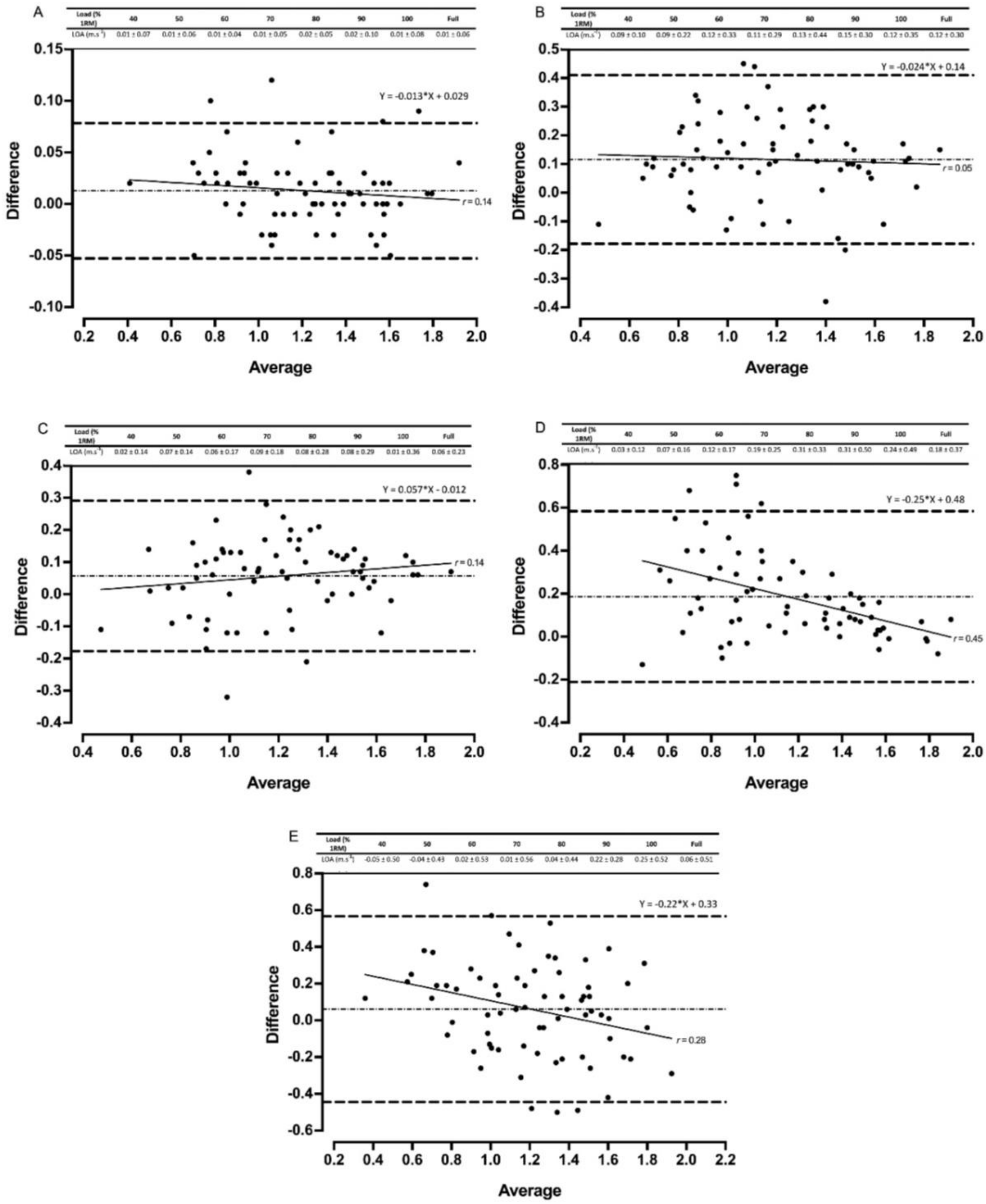

Figure 20. Bland-Altman plots exhibiting variation in velocity-based devices vs. 3D motion capture for full datasets for peak velocity in the back squat. The mean systematic bias (-·-) and 95% confidence intervals (---) are displayed with the regression line (—) and the r value. The table above displays the limits of agreement (LOA) ± 95% confidence intervals for each relative load. Gymaware (A), PUSHbody (B), PUSHbar (C), Bar Sensei (D), Beast Sensor (E) devices are all shown.

Fixed and proportional bias was evident across the full datasets for the Beast Sensor (mean and peak velocity) and Bar Sensei (peak velocity only) (table 14). Systematic bias was also present for both devices across both velocity metrics (figures 19 & 20).

Power Clean: Of the four devices that were used to assess the validity of the power clean exercise, the Gymaware demonstrated the strongest validity when compared to the criterion measure. No fixed or proportional bias was observed, with R^2 values > 0.75 for all relative loads apart from 90% and 100% 1RM for mean velocity (table 15). Mean velocity was slightly underestimated in the Gymaware, but no systematic bias was present when measuring peak velocity (figures 21 & 22). The three IMUs displayed fixed and proportional bias across multiple relative loads and the full datasets for both mean and peak velocity (table 15). PUSHbar was the only IMU to demonstrate no fixed bias across any of the relative loads and full dataset. Both PUSH devices overestimated mean (up to 0.26 $m.s^{-1}$) and peak (up to 0.74 $m.s^{-1}$) velocity, whilst Bar Sensei underestimated both velocity measures (up to 0.36 $m.s^{-1}$) (figures 21 & 22).

Table 15. Least products regression for 4 devices in the power clean in comparison to 3D motion capture.

Load	R^2		Slope (95% CL)		Intercept (95% CL)	
(%)	MV	PV	MV	PV	MV	PV
			Gymaware			
40	0.93	0.91	1.165 (0.913, 1.417)	1.067 (0.787, 1.348)	-0.254 (-0.598, 0.090)	-0.172 (-0.841, 0.498)
50	0.95	0.93	0.944 (0.768, 1.120)	1.042 (0.806, 1.279)	0.042 (-0.192, 0.277)	-0.110 (-0.660, 0.441)
60	0.95	0.95	0.900 (0.731, 1.068)	0.974 (0.798, 1.150)	0.096 (-0.119, 0.312)	0.044 (-0.347, 0.435)
70	0.78	0.95	0.788 (0.443, 1.133)	1.061 (0.869, 1.253)	0.235 (-0.180, 0.650)	-0.133 (-0.545, 0.280)
80	0.86	0.91	0.831 (0.553, 1.110)	1.058 (0.801, 1.314)	0.167 (-0.148, 0.482)	-0.119 (-0.641, 0.403)
90	0.42	0.86	0.553 (0.023, 1.082)	0.949 (0.641, 1.257)	0.463 (-0.087, 1.014)	0.110 (-0.480, 0.700)
100	0.64	0.86	0.848 (0.334, 1.361)	0.879 (0.589, 1.170)	0.140 (-0.358, 0.368)	0.243 (-0.275, 0.762)
Full	0.94	0.96	0.956 (0.902, 1.009)	0.967 (0.918, 1.017)	0.032 (-0.030, 0.94)	0.069 (-0.036, 0.174)
			PUSH Body			
40	0.38	0.27	0.713 (-0.021, 1.448)	0.655 (-0.229, 1.540)	0.431 (-0.498, 1.360)	1.213 (-0.351, 2.777)
50	0.50	0.43	0.485 (0.088, 0.881)†	0.663 (0.041, 1.285)	0.702 (0.214, 1.191)*	1.173 (0.102, 2.244)*
60	0.50	0.24	0.529 (0.103, 0.955)†	0.629 (-0.279, 1.537)	0.625 (0.123, 1.127)*	1.164 (-0.332, 2.661)
70	0.66	0.43	0.407 (0.167, 0.647)†	0.641 (0.043, 1.239)	0.703 (0.461, 0.999)*	1.149 (0.212, 2.086)*
80	0.54	0.27	0.274 (0.067, 0.481)†	0.426 (-0.140, 0.992)†	0.823 (0.607, 1.039)*	1.414 (0.589, 2.239)*
90	0.61	0.60	0.341 (0.118, 0.565)†	0.609 (0.201, 1.017)	0.719 (0.508, 0.930)*	1.126 (0.589, 1.663)*
100	0.34	0.66	0.327 (-0.048, 0.702)†	0.803 (0.329, 1.277)	0.677 (0.350, 1.005)*	0.833 (0.254, 1.412)*
Full	0.72	0.65	0.694 (0.591, 0.797)†	0.808 (0.664, 0.951)†	0.412 (0.298, 0.525)*	0.884 (0.663, 1.105)*
			PUSH Bar			
40	0.62	0.59	0.923 (0.334, 1.512)	0.515 (0.166, 0.863)†	0.302 (-0.357, 0.961)	1.329 (0.617, 2.042)
50	0.54	0.11	0.502 (0.121, 0.882)†	0.256 (-0.331, 0.843)†	0.755 (0.342, 1.168)	1.807 (0.652, 2.961)
60	0.50	0.68	0.662 (0.126, 1.119)	1.070 (0.478, 1.662)	0.568 (0.017, 1.119)	0.216 (-0.883, 1.316)
70	0.24	0.08	0.227 (-0.102, 0.556)†	0.140 (-0.256, 0.535)†	0.951 (0.611, 1.291)	1.889 (1.148, 2.629)
80	0.35	0.06	0.242 (-0.026, 0.510)†	0.128 (-0.281, 0.537)†	0.872 (0.610, 1.134)	1.808 (1.089, 2.527)
90	0.41	0.26	0.395 (0.010, 0.780)†	0.391 (-0.144, 0.926)†	0.703 (0376, 1.031)	1.349 (0.562, 2.137)
100	0.23	0.60	0.286 (-0.138, 0.710)†	0.579 (0.197, 0.961)†	0.725 (0.372, 1.077)	0.966 (0.407, 1.525)
Full	0.62	0.48	0.765 (0.621, 0.910)†	0.536 (0.400, 0.672)†	0.414 (0.270, 0.558)	1.169 (0.925, 1.412)
			Bar Sensei			
40	0.82	0.47	0.761 (0.478, 1.045)	0.591 (0.079, 1.103)	0.218 (-0.198, 0.634)	0.753 (-0.650, 2.156)
50	0.82	0.22	0.621 (0.386, 0.856)†	0.428 (-0.222, 1.077)	0.439 (0.113, 0.765)*	1.212 (-0.455, 2.879)
60	0.73	0.61	0.520 (0.262, 0.777)†	0.623 (0.218, 1.028)	0.545 (0.197, 0.894)*	0.706 (-0.269, 1.681)
70	0.04	0.50	0.081 (-0.243, 0.405)†	0.502 (0.095, 0.910)†	1.085 (0.693, 1.478)*	0.990 (0.047, 1.934)*
80	0.07	0.69	0.110 (-0.198, 0.417)†	0.582 (0.267, 0.897)†	0.985 (0.645, 1.326)*	0.781 (0.102, 1.460)*
90	0.18	0.84	0.213 (-0.151, 0.577)†	0.678 (0.442, 0.913)†	0.821 (0.449, 1.193)*	0.592 (0.128, 1.055)*
100	0.02	0.57	-0.071 (-0.460, 0.318)†	0.507 (0.145, 0.869)†	1.029 (0.657, 1.400)*	0.866 (0.190, 1.542)*
Full	0.73	0.74	0.569 (0.486, 0.652)†	0.608 (0.522, 0.693)†	0.479 (0.377, 0.580)*	0.726 (0.528, 0.924)*

% percentage of one repetition maximum, *MV* mean velocity, *PV* peak velocity. If the 95% confidence interval for the intercept does not include 0, then fixed bias is present (*); if the 95% confidence interval for the slope does not include 1, then proportional bias is present (†)** Insert table 4 and figure 3**

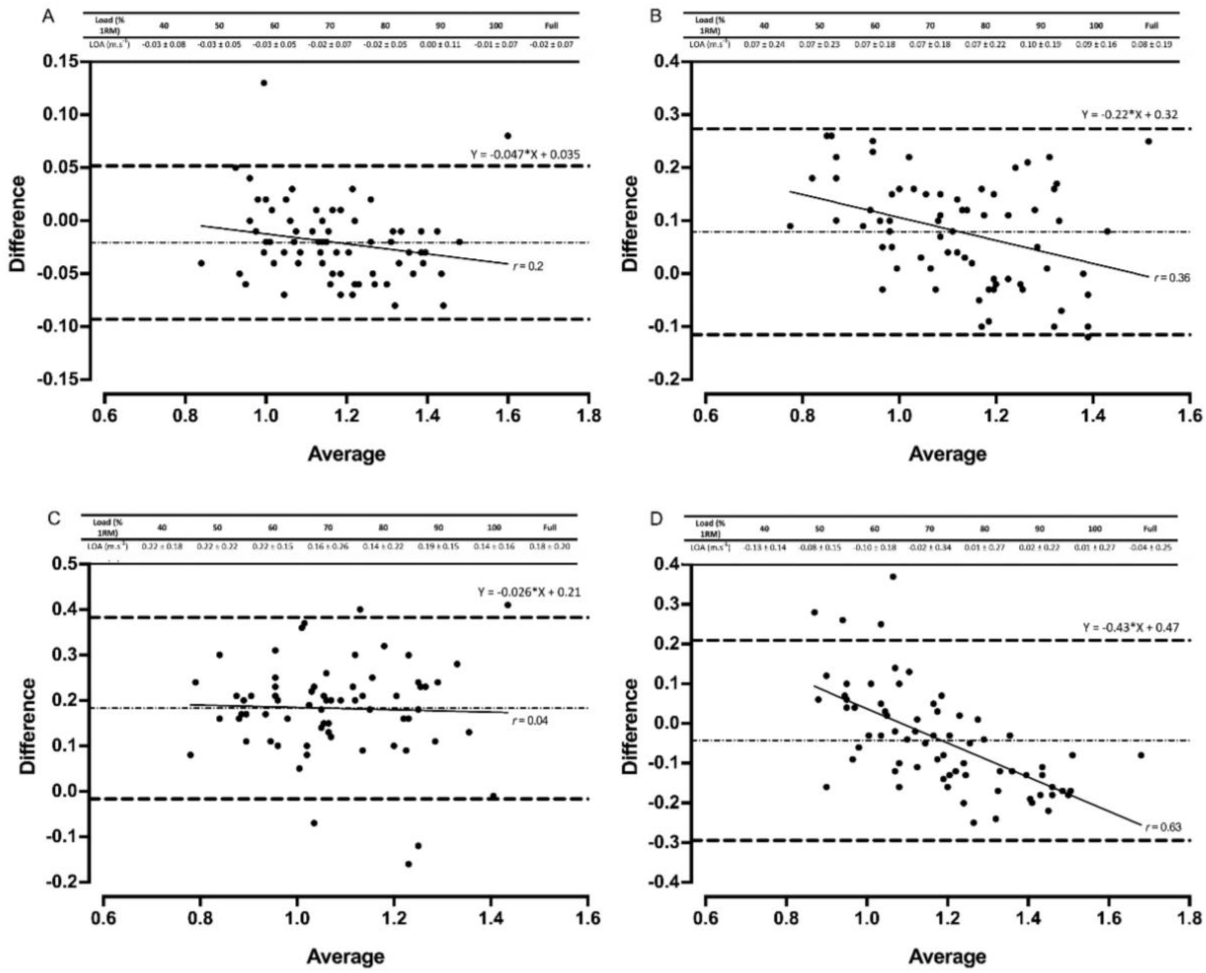

Figure 21. Bland-Altman plots exhibiting variation in velocity-based devices vs. 3D motion capture for full datasets for mean velocity in the power clean. The mean systematic bias (-··-) and 95% confidence intervals (---) are displayed with the regression line (—) and the *r* value. The table above displays the limits of agreement (LOA) ± 95% confidence intervals for each relative load. Gymaware (A), PUSHbody (B), PUSHbar (C), Bar Sensei (D) devices are all shown.

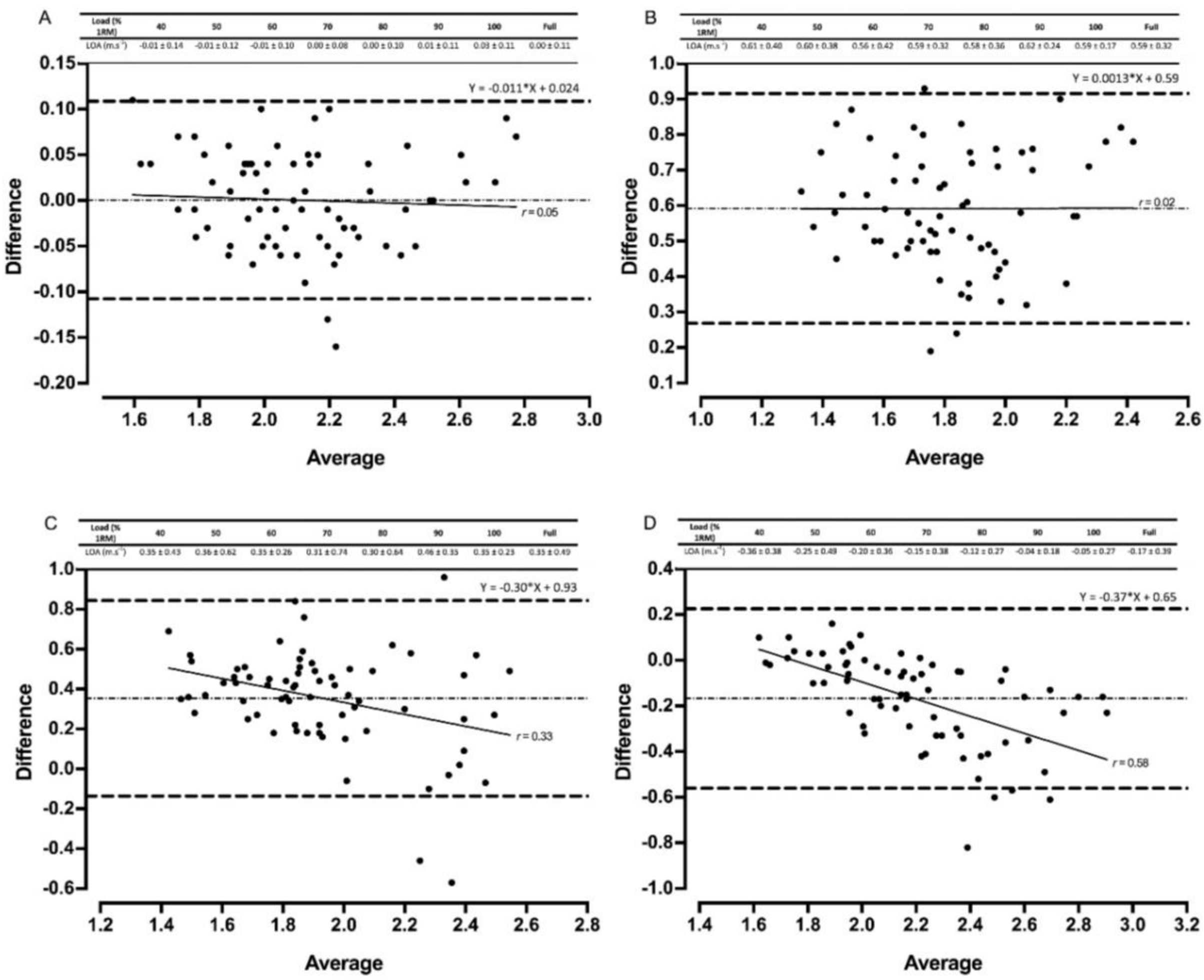

Figure 22. Bland-Altman plots exhibiting variation in velocity-based devices vs. 3D motion capture for full datasets for peak velocity in the power clean. The mean systematic bias (-·-) and 95% confidence intervals (---) are displayed with the regression line (—) and the *r* value. The table above displays the limits of agreement (LOA) ± 95% confidence intervals for each relative load. Gymaware (A), PUSHbody (B), PUSHbar (C), Bar Sensei (D) devices are all shown.

5.5 Discussion

The aim of this research was to assess the day-to-day reliability and criterion validity of six systems that measure barbell velocity, in the free-weight back squat and power clean. The major findings of this research were: 1) Gymaware was the most reliable and valid tool for both exercises when measuring mean and peak velocity; 2) MyLift produced comparable validity and reliability results to the Gymaware; 3) PUSH devices demonstrated good levels of validity and reliability, despite detectable measurement error; 4) Bar Sensei and Beast Sensor exhibited poor reliability and validity.

Gymaware demonstrated the greatest reliability and validity when measuring mean and peak velocity. Practically perfect R^2 values, small systematic bias, and no fixed or proportional bias were evident across all loads, in addition to favourable levels of between-session reliability for all back squat loads except 100% 1RM (figures 19-22, tables 13-15). Our data supports previous research comparing Gymaware to 3D motion capture wherein R^2 values of 0.99 in the free-weight back squat, mean differences (± *SD*) of 0.01 $m.s^{-1}$ ± 0.01 $m.s^{-1}$ and -0.02 $m.s^{-1}$ ± 0.03 $m.s^{-1}$, and between-trial CVs of 7.0% to 8.1% were observed (Dorrell et al., 2019), despite data being limited to one load (80% 1RM). In comparison, our study provides practitioners with useable reliability and validity data across a full LVP in 10% increments. Research elsewhere indicates that Gymaware is valid when compared with sophisticated LPT systems (Banyard, Nosaka, Sato, et al., 2017) and reliable across testing occasions (Orange et al., 2019; Orange, Metcalfe, Marshall, et al., 2020). Despite this, we observed poorer R^2 values during heavier loads in the power clean for mean velocity (table 15), suggesting that the complexities and 3D nature of weightlifting might impact the validity of measuring velocity at heavier loads.. LPTs use a rotary or optical encoder attached to a tether designed to produce time-displacement data to calculate velocity, and account for varying angles of tether retraction by applying trigonometry, limiting potential error in the measurement and processing of velocity (Banyard, Nosaka, Sato, et al., 2017; Dorrell et al., 2019; Harris et al., 2010). Therefore, our data, in conjunction with previous literature, indicates that the Gymaware is a reliable and valid tool for measuring barbell velocity.

MyLift demonstrated comparable validity data to Gymaware for mean velocity in the back squat (figure 19, table 14). Our study is the only one to compare MyLift against 3D motion capture and assess fixed, proportional, and systematic bias, making comparisons with previous research difficult. Perez-Castilla et al (2019), however, assessed the application against an infrared motion sensing system, and found only small systematic bias, but did observe heteroscedasticity. Additionally, research adopting more common validity statistics observed practically perfect correlation coefficients (r = 0.94; SEE = 0.03; ICC = 0.97) when compared with an LPT (Balsalobre-Fernández et al., 2017; Balsalobre-Fernández, Marchante, et al., 2018). CVs and TEs indicated good between-session reliability for loads of 40% to 80% 1RM in our study, supporting that of recent research (ICC = 0.96 to 0.98; CV = 2.85% to 4.97%) (Balsalobre-Fernández et al., 2017; Balsalobre-Fernández, Marchante, et al., 2018). Conversely, poor levels of reliability (CV > 20%) have been observed in the bench press (Courel-Ibáñez et al., 2019), perhaps due to observer error and improper usage (Balsalobre-Fernández, 2020). Therefore, if operated by an experienced professional that understands the specific nuances of different exercises, this device could be an effective tool for practitioners. Future research should look to further investigate the inter-rater reliability using similar devices to determine if prior knowledge of the exercises is an important pre-requisite.

Good levels of reliability were observed for the back squat except for 90% and 100% 1RM loads in three of the six devices (Gymaware, MyLift and PUSHbody). This was supported by between-session reliability data from the criterion measure (CVs = 9.0% to 21.5%; TEs = 0.03m.s^{-1} to 0.14 m.s^{-1}). Further analysis of the LOA at 100% 1RM, however, indicated high, consistent levels of agreement between the devices and criterion measure. For example, the mean velocity of the Gymaware at this load indicated a difference between the mean systematic bias data of 0.01 m.s^{-1} (-0.01 m.s^{-1} to 0.00 m.s^{-1}) over the three sessions. Moreover, it has recently been suggested that heavy loads can alter limb and torso displacement, joint moments, and joint angular velocities, resulting in variability in barbell kinematics (Kellis et al., 2005; Kristiansen et al., 2019). Therefore, it could be suggested that the poor reliability data at these heavier loads could be a result of human movement variability, as opposed to the devices. Reliability data for the power clean also supports this suggestion, particularly in the Gymaware. CVs of < 5% at all but one load indicates the between-session reliability of this device is very strong. This could be because of a greater technical competency required to achieve key positions in this lift (Kipp & Meinerz, 2017). By perfecting the lifts using a technical model (Kipp & Meinerz, 2017), the consistency of torso and limb positioning could have a positive influence on the consistency of barbell kinematics such as velocity.

Both PUSH band devices experienced good validity and reliability in the back squat (figures 19 & 20, tables 13 & 14). Nevertheless, fixed and proportional bias was evident in some loads (table 14) as well as positive and/or negative mean systematic bias (-0.08 $m.s^{-1}$ to 0.15 $m.s^{-1}$), with 95% CI as high as 0.44 for peak velocity. This suggests that PUSH may under- or over-estimate velocity data, which could be problematic in practice. Assessing PUSH's validity using LPR has only occurred once in the literature, in which proportional bias was also evident at 60% and 90% 1RM for mean velocity in the free-weight bench press (Lake et al., 2019). This suggests that the PUSH IMU may not be fully valid, and practitioners should be aware of the LOA if utilising in their practices. Both PUSH devices, however, did demonstrate favourable reliability for the light and moderate loads in the back squat, as well as the PUSHbody in the power clean, supporting research that has reported the presence of heteroscedasticity across sessions (Orange, Metcalfe, Marshall, et al., 2020). Practitioners, therefore, might need to reconsider previously reported recommendations when employing PUSH and take into consideration the device's ability to accurately estimate mean and peak velocity (Balsalobre-Fernández et al., 2016; Chéry & Ruf, 2019; Lake et al., 2019).

The poorest validity and reliability data was observed for Beast Sensor and Bar Sensei (figures 19-22, tables 13-15). Large CVs and TEs, mean systematic biases, and fixed and proportional biases were evident for both technologies across the majority of relative loads, supporting that of previous research (Beckham et al., 2019; Pérez-Castilla, Piepoli, Delgado-García, et al., 2019). Similarly, fixed, proportional, and systematic bias was evident for all three IMUs assessed during the power clean, suggesting that IMUs may not be appropriate for measuring technical and explosive exercises. The 'black-box' technology sometimes employed by IMU manufacturers could contribute to the poor levels of reliability and validity, limiting the option to factor in measurement error (Lake et al., 2019). Some IMUs (PUSHbody; Beast Sensor) have been designed as wearable; being placed on the forearm, for example, which might explain the measurement error observed, particularly in the power clean where movements around the elbow could create variability in the velocity metrics being reported (Orange et al., 2019; Pérez-Castilla, Piepoli, Delgado-García, et al., 2019). Data, therefore, suggests more developments are needed for IMUs to be reliable during these movements.

Affordability and practicality are important in practice. Despite Gymaware performing better across exercises, the device is considerably more expensive than MyLift, for example (≈ £1940 more). Additionally, MyLift requires the manual detection of the concentric phase, potentially reducing the chance of erroneous errors common to 'black-box' technology, however this method limits exercise choice and prevents the use of peak velocity. Similarly, the analysis of videos after the termination of a set also prevents immediate feedback that has shown to be advantageous during resistance training (Weakley, Wilson, et al., 2020). The wearable nature of some IMUs allows for greater flexibility of usage. Practitioners need to consider associated costs, ease of use, and accuracies prior to determining the most appropriate technology to purchase.

While this study has provided some useful practical insights to the use of VBT technologies, its limitations must be presented. Given that each system utilises different technical configurations (sampling rate, repetition detection, technology etc.), a true comparison for each device to the criterion measure was difficult. Nevertheless, comparing such devices provides important practical information for S&C coaches, such as the associated error of different technologies that could potentially influence purchasing decisions or be factored in when looking at changes in velocity over time. Additionally, our definition of the concentric phase for each lift when using the criterion measure was in accordance with previous research and mechanical principia (Dorrell et al., 2019; Lake et al., 2019). Equally, given the exercise-specific nature of the LVP (Balsalobre-Fernández, 2020; Banyard, Nosaka, Sato, et al., 2017), the generalisability of our data may be limited. Finally, inter- and intra-device translation is poor, preventing generalising our data to other LPTs, IMUs or smartphone applications.

5.6 Conclusions

This is the first study to compare multiple systems against a true criterion measure and was the first to investigate a weightlifting derivative. Our results demonstrate that the Gymaware was the most valid and reliable device for the back squat and power clean exercises, closely followed by MyLift for the back squat. IMUs should be used with caution, especially with heavier loads given the over- or under-estimation of mean and peak velocity. PUSH, however, demonstrated good reliability for loads up to 80% 1RM. LPTs offer the greatest levels of reliability and validity but are often expensive and limited to barbell exercises. IMUs and iPhone applications are more affordable but can be limited in validity.

5.7 Practical Applications

Velocity-based methods for prescription (load-manipulation (Dorrell, Smith, et al., 2020; Orange, Metcalfe, Robinson, et al., 2020)) and volume control (Fernando Pareja-Blanco, Alcazar, et al., 2020)), testing and monitoring (load-velocity profiling (Banyard et al., 2018)) frequent applied sport science support and research. Practitioners, therefore, must be confident in the technology they use to ensure effective implementation. The reliability and validity of such technologies is of high importance for coaches and thus, the findings of this research provide useful advice into the most appropriate devices to employ. Based on our data, LPTs such as the Gymaware should be implemented where possible given their superior reliability and validity across exercises and practicalities, budget permitting. Where available funding is limited, iPhone applications such as MyLift are suitable alternatives, however, are restricted in their application across exercises. Similarly, some IMUs (PUSH) can offer reliable data, but practitioners must be aware the measurement error associated with them. When using any technology, practitioners must also consider the poorer reliability at heavier loads. The implementation of velocity-based technology into S&C practice is effective if employing reliable devices, however, ease of use, software usability, economic cost, and durability also need to be taken in to account.

Chapter 6.0: Study 4 - Pooled versus individualised load–velocity profiling in the free-weight back squat and power clean

6.1 Study rationale

Study three revealed that the Gymaware LPT was the most valid and reliable velocity-based tool available for purchase. The Gymaware was therefore utilised for all subsequent studies thereafter. Partially based on the findings of study two and in anticipation of developing a more practical and time-efficient LVP strategy to predict sessional 1RM, a deeper understanding of the LVP in free-weight exercises was required.

At the time of data collection, and at the time of writing this thesis, research investigating the load-velocity relationship in the free-weight back squat was scarce, with methodological and statistical issues common (Banyard et al., 2018; Banyard, Nosaka, & Haff, 2017). These included poor validity and reliability of 1RM predictions, issues with group-based profiling, and poor reliability at heavier loads. This study sought to address these issues and ascertain between-participant variability and within-participant reliability across the full load-velocity spectrum and identify a smallest worthwhile change useful for coaches to understand the smallest meaningful increase in velocity. Similarly, this study was conducted to identify the most appropriate velocity metric to utilise across subsequent studies within this PhD.

6.2 Abstract

Purpose: This study compared pooled and individualised LVPs in the free-weight back squat and power clean. Methods: Ten competitive weightlifters completed baseline 1RM assessments in the back squat and power clean. Three incremental LVPs were completed and separated by 48–72 hours. Mean and peak velocity was measured via a LPT (Gymaware). Linear and non-linear (second-order polynomial) regression models were applied to all pooled and individualised LVP data. A combination of CV, ICC, and LOA assessed between-participant variability and within-participant reliability. Acceptable reliability was defined a priori as ICC

> 0.7 and CV < 10%. Results: Very high to practically perfect inverse relationships were evident in the back squat (*r* = 0.83-0.96) and power clean (*r* = 0.83-0.89) for both regression models, however stronger correlations were observed in the individualised LVPs for both exercises (*r* = 0.85-0.99). Between-participant variability was moderate to large across all relative loads in the back squat (CV = 8.2%-27.8%), but smaller in the power clean (CV = 4.6%-8.5%). The power clean met our criteria of acceptable reliability across all relative loads, however, the back squat revealed large CVs in loads ≥ 90% 1RM (13.1%-20.5%). Conclusions: Evidently, load-velocity characteristics are highly individualised, with acceptable levels of reliability observed in the power clean, but not the back squat (≥ 90% 1RM). If practitioners want to adopt load-velocity profiling as part of their testing and monitoring procedures, an individualised LVP should be utilised over pooled LVPs.

6.3 Introduction

Training intensity is typically derived from direct 1RM assessments, followed by relative, submaximal load prescriptions (e.g. 85% 1RM) (McMaster et al., 2014). Despite 1RMs showing good within-participant reliability (Banyard et al., 2018; McMaster et al., 2014), it is theorised that % 1RM might limit the regulation of acute changes in maximum strength or fatigue (Banyard et al., 2018). Research has indicated that 1RM can significantly increase following acute bouts of resistance training (1 to 4 weeks) (Padulo et al., 2012; Ratamess et al., 2003; Robbins et al., 2012). Significant decreases in 1RM as a result of residual fatigue (24 hours to 1 week in duration) are also evident (Hughes et al., 2019; Ratamess et al., 2003), potentially affecting the accuracy of prescriptions on a week-to-week basis. Regular 1RM assessments are possible, however, practitioners are faced with time constraints, logistical impracticalities, and excessive neuromuscular strain. Such drawbacks have prompted the development of additional aids and approaches to maximal strength testing, such as load-velocity profiling.

Strong inverse relationships have been observed between load and barbell velocity in free-weight (*r* > 0.93) (Banyard et al., 2018; Banyard, Nosaka, & Haff, 2017; García-Ramos, Ulloa-Díaz, et al., 2019; Ruf et al., 2018) and smith-machine exercises (*r* > 0.90) (Balsalobre-Fernández, García-Ramos, et al., 2018; García-Ramos, Pestana-Melero, Pérez-Castilla, et al., 2018; González-Badillo & Sánchez-Medina, 2010; Pestana-Melero et al., 2018; Sánchez-Medina et al., 2014). The application of this method, however, has often been dictated by the procedures employed. For example, the inclusion of fixed-path smith-machines, pauses between eccentric and concentric phases, single-session methodologies, and a failure to investigate the reliability of velocity across a full spectrum of loads questions the practical representation of many of these studies to applied settings. Furthermore, different modalities of training (e.g. smith-machine vs. free-weight or concentric-only vs. eccentric-concentric) produce different kinematic outputs and in turn, LVPs (García-Ramos, Pestana-Melero, Pérez-Castilla, et al., 2018; Pérez-Castilla, Comfort, et al., 2020), highlighting the need for further research that investigates the reliability of velocity across a full spectrum of loads during multiple testing sessions in free-weight, full isotonic exercises.

A paucity of research has begun to investigate more practically representative training methods such as free-weight exercises that utilise the stretch-shortening cycle. Banyard et al. (2017, 2018) observed high ICCs (≥ 0.81), low CVs (≤ 9.1%) and small SEMs (≤ 0.07 $m.s^{-1}$) between three separate LVP trials in loads ≤ 90% 1RM, and a strong relationship between load and velocity (r ≥ 0.93) in the free-weight back squat. Similar values were found in the free-weight prone bench pull, bench press, and deadlift (García-Ramos, Ulloa-Díaz, et al., 2019; Pestana-Melero et al., 2018; Ruf et al., 2018). Recent data, however, has highlighted that the reliability of LVPs is potentially load dependent (Orange et al., 2019); that large between-participant variability at submaximal loads (CVs > 10%) is evident (Balsalobre-Fernández, García-Ramos, et al., 2018; Banyard, Nosaka, & Haff, 2017); and poor reliability of V_{1RM} (ICC = 0.19 - 0.66; CV = 15.7 - 22.5%) can be observed across a range of exercises (Banyard et al., 2018; Banyard, Nosaka, & Haff, 2017; García-Ramos, Ulloa-Díaz, et al., 2019; Pestana-Melero et al., 2018; Ruf et al., 2018). Moreover, individualised LVPs seemingly provide stronger relationships between load and velocity (Balsalobre-Fernández, García-Ramos, et al., 2018; Banyard, Nosaka, & Haff, 2017; Pestana-Melero et al., 2018). With clear uncertainties about the most effective way to construct LVPs, further research in free-weight exercises investigating the individuality of load-velocity characteristics is required.

LVPs are traditionally fitted with either first-order (Banyard, Nosaka, & Haff, 2017) or second-order polynomials (González-Badillo & Sánchez-Medina, 2010; Sánchez-Medina et al., 2014). A small number of studies have compared the two statistical models, however, these have often been limited to smith-machine or upper body exercises (García-Ramos, Ulloa-Díaz, et al., 2019; Pestana-Melero et al., 2018). Nevertheless, Banyard et al. (2018) did investigate this comparison during the free-weight back squat and found no statistical differences, however, the small number of loads (6) used to construct the LVP might account for this. Therefore, further clarification is required to assess the most appropriate statistical model to apply when constructing a full LVP (> 6 loads and < 20% increments). Further investigation is also needed into the strength of the load-velocity relationship when utilising more practically representative methods such as free-weight, isotonic exercises, constructing the profile individually and when employing more explosive movements such as weightlifting derivatives.

Weightlifting derivatives such as the power clean are common in strength and conditioning (S&C) interventions as they train important movement patterns such as the triple extension and are strongly linked to physical characteristics such as sprinting and jumping (Kipp & Meinerz, 2017; Tricoli et al., 2005). Weightlifting stimulates high levels of force generation, RFD, and impulse (Comfort & Mcmahon, 2015; Kipp & Meinerz, 2017), requiring greater acceleration of heavier loads in comparison to biomechanically similar exercises such as loaded squat jumps (MacKenzie et al., 2014). High levels of inter- and intra-session reliability in experienced, novice, and youth lifters (ICC > 0.98; TE = 2.9 kg and smallest detectable differences (SDD) = 3.76 kg) have also been reported when performing this exercise incrementally to 1RM (Comfort, 2013; Comfort & Mcmahon, 2015; Faigenbaum et al., 2012).

The explosive nature of the power clean and the technical competency required to perform this lift could impact load-velocity characteristics. The margin for error to successfully execute this exercise therefore may be smaller than the back squat, and it is proposed that heavier relative loads are likely to be performed at faster velocities and in smaller increments. Importantly, limited research is available that fully assesses LVPs in the power clean. Naclerio & Larumbe-Zabala (2018) investigated the LVP in this exercise, but only measured peak velocity and did not assess reliability or evaluate the most appropriate method to construct the profile. Moreover, our study is the first to evaluate these important considerations when wanting to implement LVPs in weightlifting exercises. Therefore, the primary aim of this study was to investigate the load-velocity relationship of the free-weight back squat and power clean exercises, comparing pooled vs. individualised LVPs and linear vs. non-linear regression models. Secondary aims were to determine between-participant variability and within-participant reliability at each relative load for both exercises.

6.4 Methods

6.4.1 Research design

A repeated-measures, within-participant design investigated the reliability of pooled (all participant data combined) and individualised (one profile for oneparticipant) LVPs in the free-weight back squat and power clean. 1RM assessments were conducted in each exercise, followed by three incremental LVPs utilising loads of: 30%, (back squat only), 40-80% (in 10% increments) and 85% to 100% (in 5% increments), with mean and peak velocity recorded for each repetition.

6.4.2 Participants

Ten (8 male, 2 female) healthy competitive Weightlifters (age: 25.0 ± 5.6 y; body mass: 73.6 ± 13.9 kg; stature: 169.6 ± 6.6 cm), who had competed at a minimum of regional level within the previous 12 months and possessed appropriate relative strength levels (squat > 1.5 $kg.mb^{-1}$ and power clean > 1.15 $kg.bm^{-1}$) were recruited. Participants' relative (absolute) strength values were: 2.1 ± 0.3 $kg.bm^{-1}$ (157.0 ± 35.8 kg) and 1.4 ± 0.2 $kg.bm^{-1}$ (104.4 ± 22.8 kg) for the back squat and power clean, respectively. Informed consent was provided prior to data collection with ethical approval granted by the local institutional ethics committee in accordance with 7th revision (2013) of the declaration of Helsinki.

6.4.3 Methods

Participants attended four separate sessions, each separated by 48-72 hours. Each session occurred at the same time of day with participants asked to perform no additional exercise during data collection. Body mass (kg) (InBody 720, Biospace, Korea), stature (cm) (Harpenden, Holtain Ltd, Wales) and rack height (cm) were all recorded during the initial visit. Participants undertook a standardised, individualised warm-up that included 5 minutes on a cycle ergometer (Ergomedic 874E, Monark, Sweden) at 100W followed by a combination of body weight movements, mobility exercises and light barbell lifts. Baseline 1RM assessments were then conducted in the power clean followed by the back squat. A calibrated IWF approved 20kg Olympic barbell and bumper plates (Werksan, Turkey), and portable squat rack (Mirafit, UK) were used throughout the study. The 1RM protocols started at an estimated 50% 1RM and increased incrementally until 1RM was reached. Multiple repetitions were performed at warm-up loads (5 repetitions @ 50% 1RM; 3 repetitions @ 70% & 80% 1RM) with single repetitions for all remaining loads (85-100% 1RM). Up to five attempts were allowed to determine a true 1RM, with loads being increased by 0.5-5 kg. Rest periods were 3-5 minutes between all sets. Participants were habituated to performing lighter loads with maximal intent and velocity during this visit.

The three subsequent LVP sessions were identical in procedure and consisted of incremental protocols for the power clean, followed by the back squat with loads being determined from baseline 1RM. Three repetitions were performed for lighter loads (30-60% 1RM), two repetitions for moderate loads (70-80% 1RM) and one repetition for heavy loads (85-100% 1RM). Up to five attempts were permitted to achieve the 100% 1RM load. Rest periods were 3-5 minutes between all sets.

Power clean and back squat repetitions were required to meet the IWF, IPF regulations guidelines, as well as previous research (Banyard et al., 2018; Comfort, 2013; International Powerlifting Federation, 2019; International Weightlifting Federation, 2019; Kipp & Meinerz, 2017). A power clean was deemed successful if upon catch, the greater trochanter of the hip was superior to the lateral epicondyle of the knee and the participant was able to fully extend the lower limbs (Comfort, 2013; Kipp & Meinerz, 2017). The back squat required participants to descend, ensuring the greater trochanter was inferior to the lateral epicondyle of the knee at full descent and the participant could fully extend the lower limbs on ascent (Banyard et al., 2018; International Powerlifting Federation, 2019). Technical competency of both exercises was evaluated via a simple 2D video assessment (iPhone 7, Apple, USA) and an experienced S&C coach. Participants were instructed to perform the ascents of both lifts as '*quickly*' and '*explosively*' as possible for all loads, and the descent at a natural speed.

Gymaware was used to measure mean and peak velocities during each repetition and has previously been shown to be reliable and valid when measuring barbell velocity (Dorrell et al., 2019). Mean velocity refers to the velocity recorded across the full concentric phase of the lift (propulsive and braking phases), with peak referring to the instantaneous maximum velocity recorded during the concentric phase. The tether of the device was attached to the right-hand collar of the barbell, 100 mm from the end of the bar. The unit was placed directly under the bar for each repetition, with a tether angle of 0 ± 5°.

6.4.4 Statistical analysis

Normal distribution and relevant assumptions were assessed prior to analysis. First and second-order polynomial regression models were fitted to the pooled and individualised data to assess the relationship between load and mean or peak velocities. Fisher's r to z-transformations were used to determine significant differences between the two regression model correlation coefficients (Banyard et al., 2018).

Pearson correlations (r) and SEE assessed the relationship between load and velocity. The strength of the correlations was determined using the following criteria: trivial (< 0.1), small (0.1 to 0.3), moderate (0.3 to 0.5), high (0.5 to 0.7), very high (0.7 to 0.9) or practically perfect

(> 0.9) (Cohen, 1988). Between-participant variability at each relative load was analysed using CV:

$$\boldsymbol{CV}\ (\%) = \frac{\boldsymbol{between - participant\ SD}}{\boldsymbol{participant\ mean\ score}} \times \mathbf{100}$$

eq.20

Within-participant reliability at each relative load was assessed using ICC (model 3,k), TE, LOA (95% CIs) and CV:

$$\boldsymbol{CV}\ (\%) = \frac{\boldsymbol{within - participant\ SD}}{\boldsymbol{participant\ mean\ score}} \times \mathbf{100}$$

eq.21

Within-participant reliability refers to the reliability between sessions. The reliability of the 1RM data were assessed via one-way repeated measures analysis of variance (ANOVA), partial eta squared effect sizes (η_p^2), ICC, CV, and TE. All three trials were used for all reliability analyses except for LOA. For LOA, trials one and three were utilised to allow for the largest impact of habituation and residual fatigue on the data. Statistical significance was set at $p <$ 0.05 for all relevant statistical tests. Magnitudes of the CVs were determined as: large (> 10%), moderate (5-10%) and small (< 5%) (Banyard, Nosaka, & Haff, 2017). Acceptable reliability was defined *a priori* as: a very high correlation (> 0.70) and a small to moderate CV (< 10%) (Banyard et al., 2018). Individualised CVs (the mean CV from individual CV scores) were calculated for each relative load of both exercises.

6.5 Results

Data were normally distributed and met the assumptions for regression. A very high to practically perfect inverse relationship was found between load and velocity for both exercises (figure 23, table 16). The group's maximum load (kg) during each LVP session demonstrated an acceptable level of reliability in the back squat (p = 0.17; η_p^2 = 0.18; ICC = 0.99; CV = 1.8%; TE = 2.69 kg) and power clean (p = 0.99; η_p^2 = 0.001; ICC = 0.99; CV = 2.0%; TE = 1.84 kg), indicating true 1RMs were observed each session and confounding variables such as residual fatigue were controlled for.

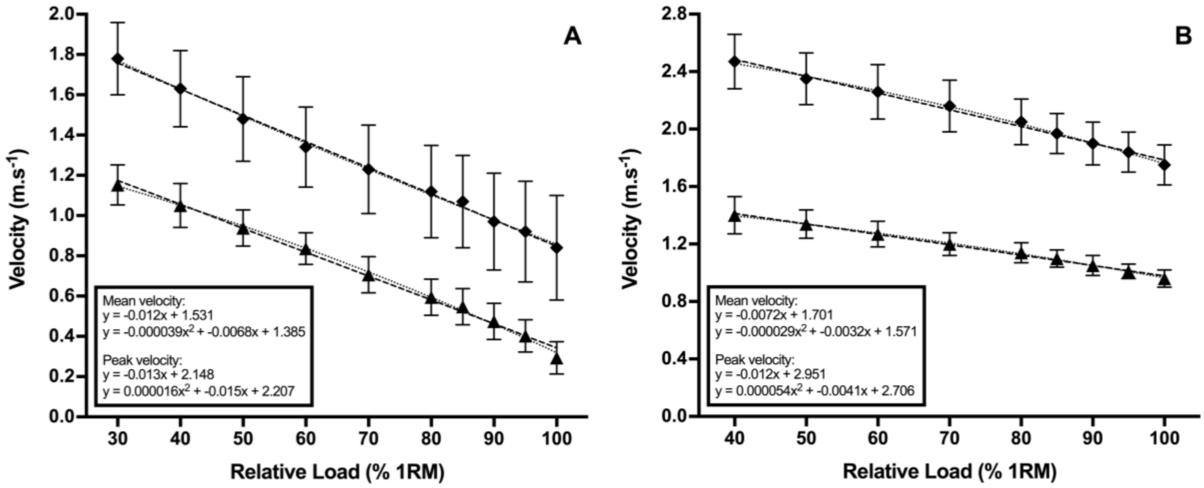

Figure 23. Group mean (SD) values from three load-velocity profiles for mean velocity (m.s^{-1}) (▲) and peak velocity (m.s^{-1}) (◆) for a) back squat and b) power clean. Linear regression (---) and second-order polynomial (····) are presented with respective equations (located in box). *1RM* = one repetition maximum.

Table 16. First- and second-order polynomials correlation coefficients (r) with standard error of the estimates (SEE) for the back squat and power clean. Pooled vs. individualised data.

		First-order polynomial				**Second-order Polynomial**			
		Pooled		**Individualised**		**Pooled**		**Individualised**	
		r	**SEE (m.s^{-1})**	***r***	**SEE (m.s^{-1})**	***r***	**SEE (m.s^{-1})**	***r***	**SEE (m.s^{-1})**
Back Squat	MV	0.96	0.09	0.98-0.99	0.02-0.06	0.96	0.09	0.98-0.99	0.02-0.05
	PV	0.83	0.22	0.96-0.99	0.03-0.11	0.83	0.22	0.98-0.99	0.01-0.05
Power Clean	MV	0.89	0.08	0.87-0.99	0.02-0.06	0.90	0.08	0.92-0.99	0.01-0.04
	PV	0.83	0.16	0.85-0.99	0.02-0.10	0.83	0.16	0.85-0.99	0.01-0.09

First- and second-order polynomials were fitted to the pooled LVP data and indicated very strong to practically perfect relationships between load and velocity for the back squat and power clean (table 16). Individualised LVPs were then analysed using the same approaches.

Individualised LVPs were stronger for all data sets, but substantially stronger for peak velocity in both lifts (table 16). All correlations were statistically significant (p = 0.001). Fisher's r to z-transformations revealed no significant differences (back squat: p = 0.45; power clean: p = 0.50) between the two polynomial regression models. Large CVs for between-participant variability were present in the back squat (> 10%) for several relative intensities for mean (70-100% 1RM) and peak velocity (40-100% 1RM) (figures 24). The power clean presented CVs < 10% for all relative loads (figure 25).

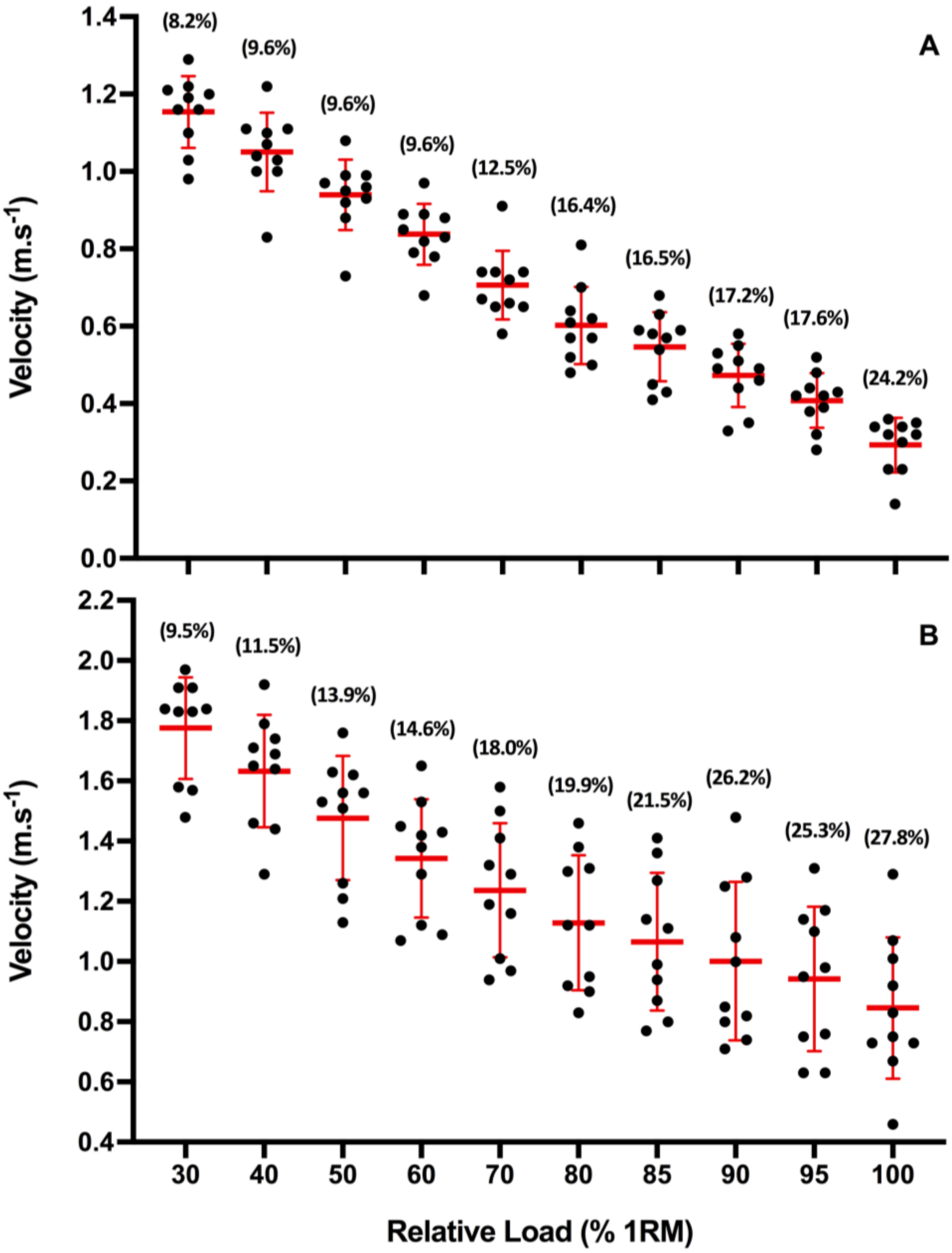

Figure 24. Between-participant variability for mean velocity (m.s^{-1}) (A) and peak velocity (m.s^{-1}) (B) for the back squat. Means (SD) are represented by the horizontal bar (error bars). coefficients of variation (CV) are displayed above each relative load in parentheses. *1RM* 1 repetition maximum.

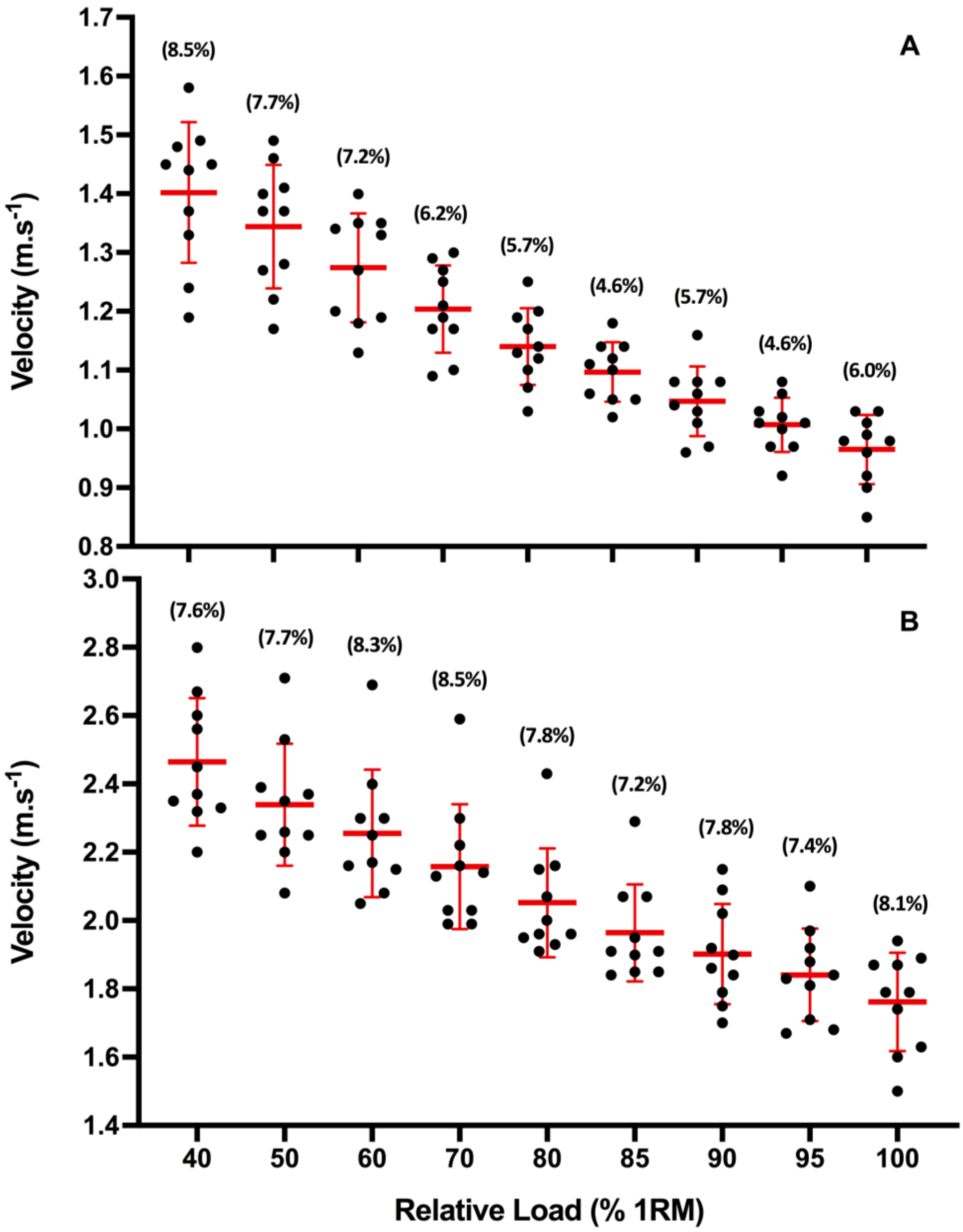

Figure 25. Between-participant variability for mean velocity (m.s^{-1}) (A) and peak velocity (m.s^{-1}) (B) for the power clean. Means (SD) are represented by the horizontal bar (error bars). coefficients of variation (CV) displayed above each relative load in parentheses. *1RM* 1 repetition maximum.

The systematic bias and LOAs (95%) between trials 1 and 3 were: 0.009 ± 0.06 m.s^{-1} (mean velocity) and -0.002 ± 0.14 m.s^{-1} (peak velocity) for the back squat and 0.001 ± 0.05 m.s^{-1}

(mean velocity) and 0.004 ± 0.07 m.s^{-1} (peak velocity) for the power clean (figure 26). Within-participant reliability can be seen in figures 27 and 28. Mean and peak velocity presented ICCs of 0.82 to 0.98, CVs of 2.1 to 4.9% and TEs of 0.03 to 0.07 m.s^{-1} for all relative intensities in the power clean, meeting the criteria for acceptable reliability. The back squat, however, did not meet the criteria for acceptable reliability at relative intensities of > 90% (ICC = 0.75 to 0.86; CV = 13.1 to 20.6%; TE = 0.03 to 0.06 m.s^{-1}) and > 85% (ICC = 0.87 to 0.91; CV = 11.8 to 15.6%; TE = 0.10 to 0.14 m.s^{-1}) for mean and peak velocity, respectively. Mean and peak velocity individualised CVs for each relative load for both exercises can be seen in table 17.

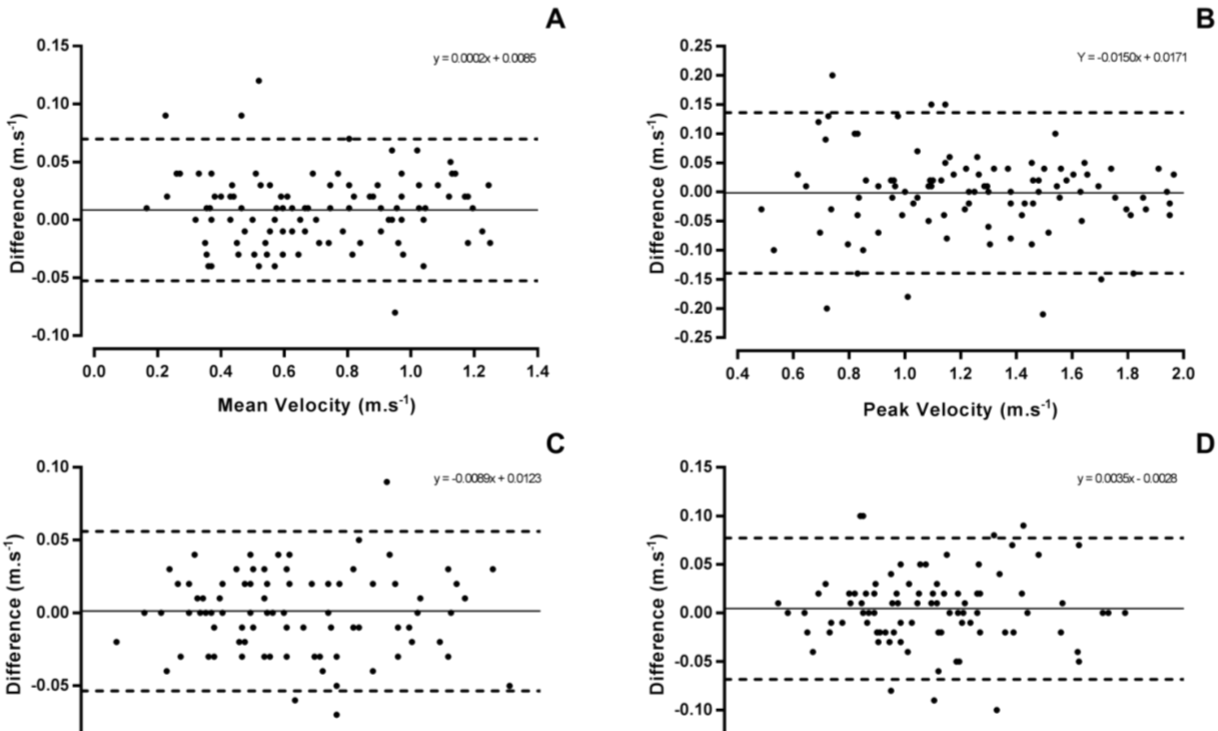

Figure 26. Bland-Altman plots exhibiting variations in mean velocity (m.s^{-1}) (A and C) and peak velocity (m.s^{-1}) (B and D) between trials 1 and 3 measured in 10% increments (30 to 80% 1RM) and 5% increments (85 to 100% 1RM) for the back squat (A and B) (n = 100) and 10% increments (40 to 80% 1RM) and 5% increments (85 to 100% 1RM) for the power clean (n = 90) (C and D). — represents mean systematic bias and --- represents Limits of Agreement (95% confidence intervals).

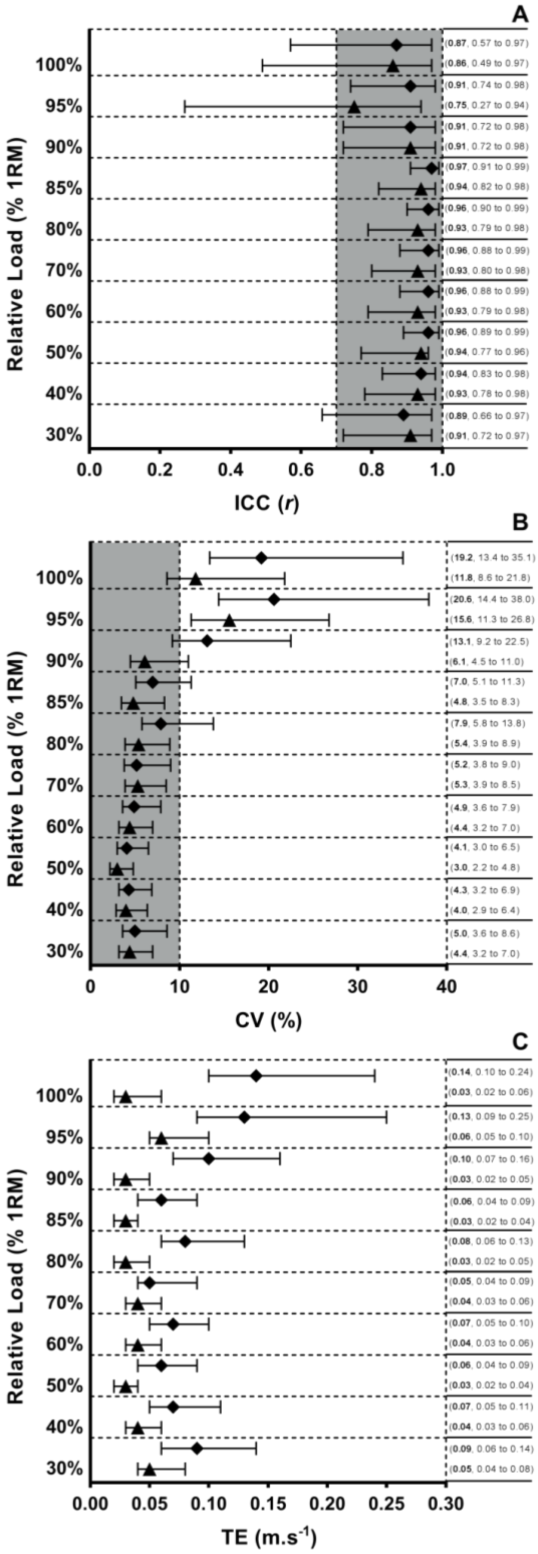

Figure 27. Within-participant reliability of mean velocity ($m.s^{-1}$) (▲) and peak velocity ($m.s^{-1}$) (◆) in the back squat at all submaximal relative loads. Forest plots displaying Intraclass Correlations (ICC) (A), Coefficient of Variation (CV) (B) and Typical Error (TE) (C) with error bars indicating 95% confidence intervals. Right y axis details group mean and 95% confidence values. Grey shaded areas indicate the criteria for acceptable reliability defined a priori. *1RM* = one repetition maximum.

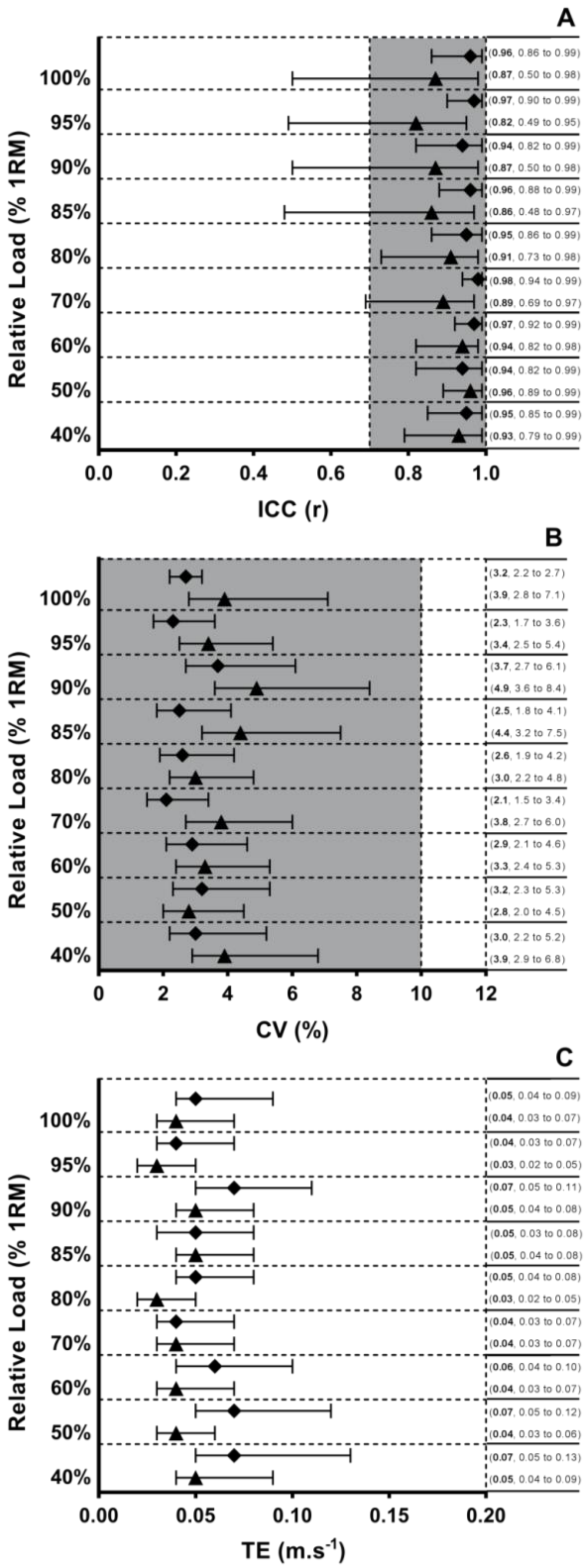

Figure 28. Within-participant reliability of mean velocity (m.s-1) (▲) and peak velocity (m.s-1) (◆) in the power clean at all submaximal relative loads. Forest plots displaying Intraclass Correlations (ICC) (A), Coefficient of Variation (CV) (B) and Typical Error (TE) (C) with error bars indicating 95% confidence intervals. Right y axis details group mean and 95% confidence values. Grey shaded areas indicate the criteria for acceptable reliability defined a priori. 1RM = one repetition maximum.

Table 17. Recommendations for the individualised coefficient of variation (CV) of mean and peak velocity for each relative load performed across both exercises.

	Back Squat		Power Clean	
Load (% 1RM)	Mean Velocity ($m.s^{-1}$)	Peak Velocity ($m.s^{-1}$)	Mean Velocity ($m.s^{-1}$)	Peak Velocity ($m.s^{-1}$)
30	0.04	0.04		
40	0.04	0.04	0.04	0.03
50	0.04	0.04	0.02	0.03
60	0.04	0.04	0.03	0.02
70	0.05	0.05	0.03	0.02
80	0.06	0.06	0.03	0.03
85	0.05	0.06	0.03	0.02
90	0.08	0.09	0.04	0.03
95	0.12	0.13	0.03	0.02
100	0.16	0.14	0.03	0.02

1RM 1 repetition maximum

6.6 Discussion

The primary aim of this study was to investigate the load-velocity relationship of the free-weight back squat and power clean exercises, comparing pooled vs. individualised LVPs and first- vs. second-order polynomial regression models. The primary findings of this investigation were: 1) the back squat and power clean demonstrated strong, inverse relationships between load and velocity, with stronger relationships obtained from individualised LVPs and no statistical differences observed between the two regression models; 2) the back squat demonstrated moderate-to-large between-participant variability whereas the power cleans variability was much lower.

Very high to practically perfect, inverse relationships (r = 0.81 to 0.96) were observed between load and velocity for both exercises (figure 23, table 16), reflecting existing data in the free weight back squat (r and R^2 = 0.93 to 0.99) (Banyard et al., 2018; Banyard, Nosaka, & Haff, 2017). The impact of cross-bridge cycling on force production is thought to underpin this association between load and velocity. As the shortening of a muscle quickens, the time available for actin and myosin to form cross-bridges reduces, inhibiting force production

(Cormie et al., 2011a). Comparable studies for the power clean are scarce, however, it is evident that the LVP of the power clean is unique (figure 23), indicating load-velocity relationships are exercise specific. Naclerio & Larumbe-Zabala (2018) suggested only 46% of variance could be explained when using peak velocity to predict relative load (% 1RM). This suggests a much lower correlation compared to our data, potentially due to technical competency of the elite sample recruited for the present study. Similarly, comparisons to mean velocity with Naclerio & Larumbe-Zabala (2018) data are not possible, limiting the interpretation of their research. Furthermore, the application of the LVP when applied to the power clean may differ depending on the velocity characteristic of interest. Peak velocity is most likely to occur during the second pull phase (Kipp & Meinerz, 2017), providing greater insight into an individual's explosive strength whereas mean velocity may be a more stable metric to monitor and will largely be determined from the first pull and transition phases.

We observed large between-participant variability across relative loads in the back-squat exercise, with CVs of up to 24.2% and 27.8% for mean and peak velocity, respectively (figure 24). This reflects the findings of Balsalobre-Fernández et al. (2018) who observed CVs of up to 24.6% when performing a seated military press in a smith-machine, and Banyard et al. (2018) who, reported large absolute differences between participants across all loads (e.g., 0.33 to 0.68 $m.s^{-1}$) in the free-weight back squat. This variability could be a contributing factor to the poor application of pre-determine generalised predictive equations such as those developed by González-Badillo & Sánchez-Medina (2010). García-Ramos, Haff, et al. (2018) investigated the efficacy of these predictive equations to estimate 1RM and observed large discrepancies from the measured maximal loads (2.8 kg to 11.4 kg) when using mean velocity. Furthermore, greater results were obtained when employing an individualised LVP (0.6 kg to 2.6 kg). Research has shown that individuals with similar 1RM values can produce different force-velocity profiles depending on their neuromuscular properties, such as fibre typing, recruitment patterns, and synergistic coordination (Cormie et al., 2011a; Jiménez-Reyes, Samozino, Brughelli, et al., 2017; McMaster et al., 2014; Rivière et al., 2017). These differences in neuromuscular properties highlights the need to profile athletes individually and can facilitate the development of individualised training programs as well as optimising the efficiency and effectiveness of a training intervention to elicit desired training effects.

Between-participant variability within the power clean was lower than that of the back squat (CVs of < 10%) (figure 25). Similarly, stronger correlations were found for an individualised LVP in comparison to the pooled profiles (table 16). Further, within-participant variability (CVs - figure 28) was lower than between-participant variability (CVs - figure 25) across all relative loads, indicating that individualised LVPs are still favourable in the power clean. This relationship has previously been reported for the bench press and prone bench pull (García-Ramos, Barboza-González, et al., 2019; García-Ramos, Ulloa-Díaz, et al., 2019; Pestana-Melero et al., 2018), reflecting our data, and indicating that individualised LVPs are a more accurate and reliable measurement when training and testing athletes.

Both exercises in this study exhibited strong, inverse relationships (figure 23). The use of second-order polynomials have been proposed as a method of strengthening the predictive model (Banyard et al., 2018; Pestana-Melero et al., 2018). Our data supports that of previous research showing no statistical differences are evident between the two regression models in either exercises ($p > 0.05$) (table 16) (Banyard et al., 2018; Pestana-Melero et al., 2018). Despite this, slightly stronger correlations are evident for the second-order model when employing individualised LVPs and further investigation into the impact on predictive validity is warranted. S&C coaches must be aware of the influence statistical modelling has on the predictive equations and in turn, the affect this could have on approaches such as autoregulation and 1RM prediction.

The secondary aim of this study was to determine the within-participant reliability of the LVPs and velocity measures at each relative load. To our knowledge, this is the first study to examine the between-session reliability of load-velocity profiling in the power clean. Importantly, we observed high repeatability in the 1RM data (kg) across the three sessions in both exercises, indicating that 1RM testing is a reliable method for assessing maximal strength as well as demonstrating the robustness of our methodology. Despite this, previous research has indicated that 1RM can significantly change with respect to strength developments and fatigue build up over a short-time period (Hughes et al., 2019; Padulo et al., 2012; Ratamess et al., 2003; Robbins et al., 2012) and therefore frequent 1RM assessments to monitor changes in strength are not always desirable, particular during in-season competition.

When evaluating the combined LVP data, we observed minimal systematic bias between trials in both exercises (-0.002 to 0.009 $m.s^{-1}$), with 95% confidence intervals of 0.05 to 0.06 $m.s^{-1}$ and 0.07 to 0.14 $m.s^{-1}$ for mean and peak velocity, respectively (figure 26). Given the scale of the unit of measure, the 95% confidence intervals could indicate important methodological considerations. For example, accurate manipulation of load could be compromised if the associated measurement error is not considered by practitioners. The individualised CV scores (table 17) provides practitioners with practical values for confidence to be assumed that meaningful changes are occurring throughout training interventions. The smaller similar CVs observed between mean and peak velocity suggests that both metrics could be interchangeable, however, the poorer within-participant reliability data and LOAs, and stronger correlation coefficients perhaps suggests that mean velocity is the better metric to use to evaluate the effectiveness of training interventions.

Analysing full LVPs could limit their practical use given prescriptions typically occur from specific relative loads (e.g., 85% 1RM). The power clean produced acceptable levels of reliability across all relative loads in mean and peak velocity (figure 28), suggesting it could be utilised as an appropriate tool for practitioners to test and monitor the progress of their athletes. Conversely, the back squat did not meet the reliability criteria for loads > 90% 1RM for mean velocity and > 85% 1RM for peak velocity (CVs = 13.1% to 20.6%) (figure 27). This is in agreement with previous research that observed moderate ICCs (0.55 to 0.63) and large CVs (15.7% to 19.4%) at heavier loads (> 90% 1RM) when measuring mean velocity in the free-weight back squat and deadlift (Banyard et al., 2018; Banyard, Nosaka, & Haff, 2017; Ruf et al., 2018). Practitioners, however, could look to utilise LVPs of 30-90% 1RM using mean velocity given the low to moderate CVs and TEs (3.0% to 6.1% and 0.03 $m.s^{-1}$ to 0.05 $m.s^{-1}$, respectively) (figure 27).

Small horizontal movements and the influence of the stretch-shortening cycle have previously been attributed to the poorer within-participant reliability at heavy loads (Banyard et al., 2018; Banyard, Nosaka, & Haff, 2017; Ruf et al., 2018). Furthermore, biomechanical deviations could affect the path of the barbell, altering kinematic variables such as barbell velocity. For example, significant inter- and intra-individual variability in barbell velocity, and hip, knee, and ankle angular velocity at 90% 1RM back squat have previously been reported (Kristiansen et al., 2019). Superior within-participant reliability in the power clean vs. the back squat observed in our study further reinforces this argument. The power clean is technically more complex, with a requirement to produce faster velocities to successfully complete a lift (figure 23). This smaller margin for error requires greater consistency in the biomechanical positioning achieved from repetition to repetition. For example, differences of ≥ 8cm in forward barbell displacement, ≤ 0.19 $m.s^{-1}$ in barbell velocity, and ≤ 33° resultant acceleration angle in the second-pull phase can all dictate the success of a repetition (Kipp & Meinerz, 2017). Larger margins for error when performing compound, non-ballistic exercises such as the back squat could allow for more movement variability, meaning individuals could alter biomechanical positioning (e.g., torso flexion), but still successfully complete the lift. This movement variability, however, will likely impact output variables such as velocity, and the resultant reliability at very heavy loads.

Despite favourable reliability data for the LVP, a full-individualised profile, if performed in a similar way to the present study, may still be time consuming and logistically difficult. Furthermore, if adopting such a method, it is advised that practitioners should aim to do so alongside more traditional 1RM testing given the acceptable reliability of the 1RM data observed in this study when free from confounding variables. This combination will ensure S&C coaches are able to measure the maximum strength capabilities of their athletes (1RM) accurately and reliably and optimally manipulate load session-to-session (LVP). Practitioners, however, must be cognisant of the limitations that surround the construction, application, and utilisation of LVPs if opting to employ them with their practices.

6.7 Practical applications

S&C practitioners wanting to profile an athlete's load-velocity characteristics should ensure an individualised approach is utilised. Practitioners should evaluate the need for profiling their athletes, the time and equipment available, and factor in measurement error associated with each relative load. S&C coaches should not replace traditional methods such as the 1RM with LVPs, but instead, consider the addition of LVPs to assist in testing and monitoring. For example, warm up sets of an incremental protocol utilised during a 1RM assessment could be used to form the light-to-moderate loads of an LVP. Despite this, practitioners should be cognisant to the logistical and time-related issues surrounding individualised LVPs and should adopt a method that will fit in to the scope of their practices. Finally, if undertaking LVPs in the free-weight back squat, practitioners should be mindful of the associated error when performing this method multiple times and attempt to factor this in across sessions.

6.8 Conclusions

Load and velocity demonstrate a very strong to practically perfect inverse relationship in the free-weight back squat and power clean. Large between-participant variability or a smaller within-participant to between-participant variability ratio, however, indicates that load-velocity characteristics are highly individualised. The back squat highlighted poor within-participant reliability in mean and peak velocity during the heavier loads (> 85% 1RM), perhaps due to greater movement variability, however, mean and peak velocity demonstrated high within-participant reliability across all relative loads in the power clean.

Chapter 7.0: Study 5 - Kinetics and kinematics of the free-weight back squat and loaded jump squat

7.1 Study rationale

Study four revealed important issues with load-velocity profiling in free-weight lower body exercises: Mean velocity was a more appropriate metric to use compared to peak velocity, velocities at loads ≥ 90% 1RM possessed poor within-participant reliability, suggesting that predictive equations including these data points could be inappropriate. Similarly, large between-participant variability in the free-weight back squat highlighted the requirement for LVPs to be undertaken on an individualised basis. Finally, the comparable load-velocity relationship between first order and second-order polynomial models applied to the data warranted further investigation into the appropriateness of each model to predict 1RM.

Linking back to study two, and the identification of an alternative, potentially more valid approach to load-velocity profiling that uses ballistic counterparts (e.g., jump squat) during lighter loads to maximise velocity, this penultimate study investigated the mechanical differences between ballistic and non-ballistic exercise. Ideally, LVPs should span the full load spectrum (e.g., bodyweight to 90% 1RM), with an essential principle of VBT being to perform all repetitions, irrespective of load, with maximal intent. Performing light loads (< 70% 1RM) non-ballistically with maximal intent is uncommon in practice, with coaches typically utilising more ballistic, explosive exercises. Therefore, this study wanted to better understand the mechanical differences across multiple loads between back squat and jump squat to determine whether LVPs should include ballistic equivalents to better reflect athletes load-velocity characteristics. A secondary objective of this study was to identify whether the removal of the period of negative acceleration at the end of the concentric phase of the back squat (i.e., to only consider the propulsion sub-phase) provided more comparable data with its ballistic counterpart. If more comparable data was evident, the utilisation of non-ballistic exercise during load-velocity profiling could continue through the application of mean-propulsive velocity.

7.2 Abstract

The study aim was to compare kinetics and kinematics of two, lower-body free-weight exercises, calculated from concentric and propulsion sub-phases, across multiple loads. Sixteen strength trained men performed back squat 1RMs (visit 1), followed by two incremental back squat and jump squat protocols (visit 2) (loads = 0% and 30-60%, back squat 1RM). Concentric and propulsion phase force-time-displacement characteristics were derived from force-plate-data and compared via ANOVA and Hedges *g*. Intra-session reliability was calculated via ICC and CV. All dependent variables met acceptable reliability (ICC > 0.75; CV < 10%). Statistically significant three-way interactions (load × phase × exercise) and two-way main effects (phase × exercise) were observed for mean force, velocity (30-60% 1RM), power, work, displacement, and duration (0%, 30-50% 1RM) ($p < 0.05$). A significant two-way interaction (load × exercise) was observed for impulse ($p < 0.001$). Jump squat velocity (g = 0.94-3.80), impulse (g = 1.98-3.21), power (g = 0.84-2.93) and work (g = 1.09-3.56) were significantly larger across concentric and propulsion phases, as well as mean propulsion force (g = 0.30-1.06) performed over all loads ($p < 0.001$). No statistically significant differences were observed for mean concentric force. Statistically longer durations (g = 0.38-1.54) and larger displacements (g = 2.03-4.40) were evident for all loads and both sub-phases ($p < 0.05$). Ballistic, lower-body exercise produces greater kinetic and kinematic outputs than non-ballistic equivalents, irrespective of phase determination. Practitioners should therefore utilise ballistic methods when prescribing or testing lower-body exercises to optimise athlete's force-time-displacement characteristics.

7.3 Introduction

Effective S&C interventions induce adaptations that underpin specific movement patterns, velocities, forces, and energy demands required for competition (Bird et al., 2005; Kraemer & Ratamess, 2004). Such physical qualities (e.g., sprinting, jumping and change of direction) are underpinned by Newton's 2nd law of motion (F = ma), which states that acceleration is directly influenced by the net force applied to an object or system over a given time, and is directly proportional to its change in velocity (i.e., impulse-momentum) (Turner et al., 2020). Despite this, S&C coaches more commonly focus on variables such as peak power when evaluating performance improvements (Cormie et al., 2011b), often questionably referring to it as a 'physical characteristic' rather than by its mechanical definition (Knudson, 2009; Winter et al., 2016; Winter & Fowler, 2009).

Power (work / Δ time) is a product of force and velocity, as work is force multiplied by displacement and velocity describes the rate of displacement with respect to time (Turner et al., 2020). Nevertheless, peak power often only refers to the work performed over 1 ms (where force is recorded at 1000 Hz), a common problem with most peak metrics (Mundy et al., 2017). Their practical relevance, therefore, is sometimes questionable as the propulsion phase of sprinting and jumping for example, occurs over 150-250 ms (Andersen & Aagaard, 2006). Mean power, on the other hand, might be a more appropriate metric to measure (Lake et al., 2014), but can still be misleading as a change in force application, displacement travelled, or phase duration can all impact it (Mundy et al., 2017). Therefore, understanding an individual's movement '*strategy'* and adhering to strict scientific principia when selecting performance variables (e.g., impulse, velocity, work etc.) could help obtain a clearer picture of an athlete's capabilities during specific tasks rather than a single measurement of power (Turner et al., 2020).

S&C practitioners utilise a variety of methods to develop underpinning mechanical qualities such as power, impulse, force, and velocity, however, literature comparing these strategies is somewhat limited (Cormie et al., 2010; Harris et al., 2008; Hoffman et al., 2005; J. Jones et al., 2018; McBride et al., 2005; Tricoli et al., 2005). Increases in power have been observed from heavy strength training (e.g., > 80% 1RM) through physiological adaptations (e.g., increases in motor unit recruitment and intramuscular co-ordination) that influence the force end of the force-velocity curve (Cormie et al., 2010; Cormie, McCaulley, et al., 2007; N. Harris et al., 2008; Suchomel et al., 2018). Nevertheless, these are often more effective with untrained or weaker athletes, or during the initial stages of a periodised programme (Cormie et al., 2011b; Wilson et al., 1997). Further power development, therefore, typically requires the inclusion of additional lighter (e.g., 30-60% (1RM), more mechanically specific training methods that optimise movement velocity as dictated by the force-velocity-power relationship (Cronin et al., 2000, 2003; Lynn & Noffal, 2012). In practice, methods to implement these faster velocity-type adaptations usually include ballistic (e.g., jump squat) or explosive non-ballistic (e.g., 'speed' back squat) exercises, with the main biomechanical difference being the projection of the body, system, or object into free space during the ballistic task (Frost et al., 2010). Nevertheless, comparisons of the underpinning mechanical demands of both training strategies are limited yet are vital for practitioners to make informed programming decisions.

Performing non-ballistic exercise with maximal intent at loads that optimise the trade-off between force and velocity (e.g., 30-60% 1RM) has been suggested as an appropriate strategy for inducing adaptations that underpin power and RFD (Brandon et al., 2015; Cormie, Mccaulley, et al., 2007; De Villarreal et al., 2011). Nonetheless, inherent within non-ballistic exercise is a period of negative acceleration, commonly referred to as the *'deceleration sub-phase'* (velocity maxima to displacement maxima). The contribution of this sub-phase (e.g., 10-50% of the full '*concentric phase'* (displacement minima to displacement maxima) in loads of 30-81% 1RM) can result in a reduction in kinetic and kinematic output and muscle activation (Elliott et al., 1989; Newton et al., 1996; Sánchez-Medina et al., 2014), potentially reducing adaptive stimuli and limiting dynamic correspondence to key sporting actions such as jumping and sprinting (Cormie et al., 2011b; Cormie, Mccaulley, et al., 2007).

Ballistic exercises typically produce higher mechanical outputs than their non-ballistic counterparts as they exhibit a longer period of positive acceleration (displacement minima to velocity maxima), referred to as the *'propulsion sub-phase'* (Cormie et al., 2011b; Frost et al., 2010; Loturco et al., 2019). As a result, when compared with non-ballistic equivalents, ballistic exercises exhibit higher velocities and larger forces, power, and muscle activity, often making them the preferred choice for S&C coaches when designing 'power-type' training blocks (Cormie, McCaulley, et al., 2007; Elliott et al., 1989; Lake et al., 2012; Loturco et al., 2019; R. Newton et al., 1996). Despite this, ballistic exercise such as the jump squat must contain a landing phase. Previous researchers have observed significant increases in ankle range of motion (disproportionate to knee and hip), ankle eccentric work contribution (% of total eccentric work), and slight increases in ankle landing joint moments because of longer landing durations caused by increasing loads (Fritz et al., 2021; Lake et al., 2021). This change in landing strategy, therefore, must be a consideration for S&C coaches, particularly those working with athletes undertaking return to play protocols or during in-season prescription for athletes that participate in sports where a high number of jumps are common (e.g., 60-100 jumps in a competitive game of basketball) (Fox et al., 2020; Ransdell et al., 2020).

Practitioners, however, must be sure that the appropriate neuromuscular adaptations would still occur if opting alternative methods to traditional ballistic exercise.

The differences in kinetic and kinematic outputs between ballistic and non-ballistic exercise could be due to the influence of the deceleration sub-phase when calculating key mechanical variables (Frost et al., 2008), potentially underestimating the mechanical output of non-ballistic exercise. Researchers have proposed more analogous demands when considering the propulsion sub-phase alone (Frost et al., 2008; Lake et al., 2012). Comparable force, velocity, and power outputs have been reported between the bench press and bench throw exercises when removing this period of negative acceleration (Frost et al., 2008). Similarly, Lake et al. (2012) found no significant differences in mean force and power when comparing the jump squat and back squat over the propulsion sub-phase only, however, this was limited to a single load (45% 1RM). Despite this, no study to date has compared the mechanical demands of lower-body ballistic and non-ballistic exercise across multiple loads that reflect typical 'power' or 'optimal' training prescriptions. Providing this comparison will help to clarify the theoretical and mechanical underpinnings of these two training strategies currently used in practice, whilst using applied data.

Optimal loading has been observed in 0% 1RM (body weight) and 30-60% 1RM for the jump squat and back squat, respectively (Cormie et al., 2011b; Cormie, Mccaulley, et al., 2007). Similarly, research has observed maximal propulsion and concentric impulse to occur at 50-75% body mass during the loaded jump squat (Lake et al., 2021; Mundy et al., 2017), equating to 50% 1RM of an individual with a relative strength level of 1.5 $kg.bm^{-1}$. Therefore, comparing the mechanical demands of training strategies within this range of loads designed to increase key physical qualities such as power and impulse is vital for practitioners to make appropriate programming decisions. Similarly, providing a comprehensive evaluation of the kinetic and kinematic variables that underpin ballistic and non-ballistic exercise across different phases of movement in comparable loads will enable coaches to better understand the appropriateness of ballistic and non-ballistic exercise. Therefore, the aim of this study was to compare the kinetics and kinematics of the ballistic jump squat and non-ballistic back squat across incremental loads (0, 30-60% 1RM) that were calculated over both the full concentric phase (inclusive of the period of negative acceleration) and the propulsion sub-phase only.

7.4 Methods

7.4.1 Experimental approach to the problem

A within-participant, repeated measures design was adopted to compare the kinetic and kinematic differences between ballistic (jump squat) and non-ballistic (back squat) lower body exercise when measured within two different movement phases (concentric vs. propulsion) across five incremental loads (0, 30-60% 1RM) that reflect typical ‘power-type’ training prescriptions. Participants attended the laboratory on two separate occasions, separated by a minimum of 72 hours. The first visit determined back squat 1RM, and incremental protocols in both exercises were performed in the second visit. Vertical force-plate-data was used to derive ground reaction force within which all dependent variables were calculated. Only mean metrics were considered and included force, velocity, power, impulse, work, duration, and displacement. These metrics were used to consider the impact phase of determination (inclusion or exclusion of the negative period of acceleration) had on the two exercises when performed over incremental loads (0%, 30-60% 1RM).

7.4.2 Participants

Sixteen healthy, strength-trained males (age: 26.2 ± 4.1 years; body mass: 83.2 ± 9.3 kg; stature: 174.7 ± 4.3 cm) volunteered for this study after providing informed consent and completing a medical pre-screening questionnaire. A sample size of sixteen participants was calculated *a priori* (G*Power, version 3.1.9.7, Dusseldorf, Germany) using an alpha level of 0.05, statistical power of 0.95 and an MSD of 0.48 (Cohen's *f*) for a repeated measures design. Cohen's *f* was determined from Rossetti et al. (2020) by taking the smallest Cohen's *d* values from the dependent variables that were collected in the present study and then dividing by two. This approach to calculating the MSD was based on parity between exercise modes and outcomes between Rossetti et al. (2020) and the present study. Ethical approval was granted via the institution's ethics board (*ER13605026*) in accordance with the seventh revision (2013) of the declaration of Helsinki. Participants were required to have a maximal back squat of > 1.5 kg.bm^{-1}, be resistance trained for a minimum of 12 months, be technically competent in the free-weight back squat and jump squat exercises and be injury free.

7.4.3 Procedures

Participants were instructed to attend fully rested and hydrated, having abstained from caffeine, and following a similar nutritional intake up to all testing sessions. Each participant confirmed zero alcohol consumption 24 hours before testing and zero lower-body exercise 48 hours before and during the testing period.

The back squat and jump squat exercise techniques were standardised across all participants, using an IWF approved, calibrated 20 kg barbell and competition bumper plates (Werksan, Turkey). A '*high-bar*' position was performed, with the barbell sitting directly on the upper trapezius muscles. A lift was deemed successful when the greater trochanter was positioned lower than the lateral epicondyle of the knee at the lowest descent displacement and the participant could fully extend the hips, knees, and ankles during the ascent. The jump squat was standardised identically to the back squat during the descent phase, but participants were required to take-off following ascent. The standardised technique was verified retrospectively using 2D video by the principal investigator who was an accredited S&C coach.

Loads were selected based on previous literature reporting the optimal loading from a power and impulse perspective (Cormie et al., 2011b; Cormie, Mccaulley, et al., 2007; Lake et al., 2021; Mundy et al., 2017). Similarly, loads were equated across exercises to provide a clear comparison of mechanical demands. Finally, from a practical perspective, to ensure competency and safety, 60% 1RM was deemed the heaviest load appropriate for participants to lift based on an inclusion criterion of > 1.5 $kg.bm^{-1}$.

7.4.3.1 1RM testing (visit 1)

Informed consent, pre-screening questionnaire, body mass (kg) (from the force plate) and stature (cm) (Seca, Leicester, Hamburg, Germany) were recorded. An individualised, standardised warm-up was performed using a combination of static stretching, dynamic mobility, activation exercises, light barbell exercises, and unloaded squats and jumps. Habituation of 1 second of quiet standing before initiating movement and performing all concentric phases with '*maximal intent and velocity'* also occurred.

Participants were guided through an incremental, 1RM protocol in the free-weight back squat that consisted of performing loads with 50% (5 repetitions), 70% (3 repetitions), 80% (2 repetitions), 85%, 90%, and 95% (1 repetition) of an estimated 1RM, followed by up to 5 attempts at finding a true 1RM. Five minutes rest was prescribed between loads (Thompson et al., 2020; Thompson, Rogerson, Ruddock, Banyard, et al., 2021).

7.4.3.2 Force plate testing (visit 2)

Participants performed incremental protocols in the back squat and jump squat, with loads lifted in sequential order. All loads were determined for both exercises as percentages of back squat 1RM. All repetitions were performed on a Kistler portable force plate (Kistler, 9286A, Winterthur, Switzerland) sampling at 1000 Hz. Ground reaction force data were collected and exported using Bioware (Kistler, Winterthur, Switzerland) software.

Before the experimental trials, participants completed the standardised warm-up from visit one. Participants also completed two bodyweight warm-up (using a wooden dowel with a mass of approximately 0.7 kg) sets of both exercises. The following incremental loads were then performed simultaneously in both exercises, with the order of each exercise counterbalanced across participants: 0% (5 repetitions), 30% (3 repetitions), 40% (3 repetitions), 50% (2 repetitions), 60% (2 repetitions). Five minutes and 3 minutes rest were provided between loads and exercises (sets) at each load, respectively. Participants were instructed to perform all repetitions with '*maximal intent and velocity*'.

7.4.4 Data analysis

Raw force data were analysed using a custom-built Microsoft Excel script (Microsoft Excel, Microsoft, Albuquerque, NM, USA) (appendix E). The trial(s) with the highest system (CoM) peak velocity were selected for analysis given their direct relationship with jump height and impulse-momentum. The dependent variables and respective calculations are presented in Table 18. All metrics were calculated as the average recorded across the course of the predetermined phases. In addition, the proportion of time and displacement spent in the propulsion phase relative to the concentric and descent phases were calculated and expressed as percentages.

Table 18. Definitions, Système Internationale (SI) units and calculation methods for all dependent variables from the concentric and propulsion phases.

Dependent Variable (SI Unit)	Calculation
Force (N)	Average of raw vertical ground reaction force data
Velocity ($m.s^{-1}$)	Integrated acceleration data with respect to time (acceleration = net force / body mass (system mass for loaded trials)
	Mean: Average of velocity data
Impulse (N.s)	Mean net force: Average of force less body weight (system weight for loaded trials)
	Integrated mean net force with respect to time
Power (W)	Force x velocity
Duration (s)	Timepoint at phase end – timepoint at phase start
Displacement (m)	Velocity x change in time Change in position (end position – start position)
Work (J)	Power x time

All integration occurred via the trapezium method (Lake, Mundy, et al., 2014)

Dependent variables were selected based on three categories: output, driver, and strategy variables. Output variables (power, velocity, and impulse) refer to instantaneous feedback that might be presented and useful to an athlete or a coach; driver variables (force and work) refer to the underpinning mechanics that help to determine athletic movement; and strategy variables (duration and displacement) refer to a specific approach an individual may undertake to complete a task. The combination of these variables helps provide a clear picture of the demands of both exercises.

The repetition start for both exercises was calculated from an initial 1 second of pre-movement quiet standing. The mean force from this 1 second was used to calculate body weight (system weight for loaded trials), and force SD was also calculated from this period and the mean ± 5 SDs was used as the start threshold on a trial-by-trial basis (Owen et al., 2014). A graphical representation of the propulsion, concentric and '*descent*' phase (start point to displacement minima) is explained in figure 29.

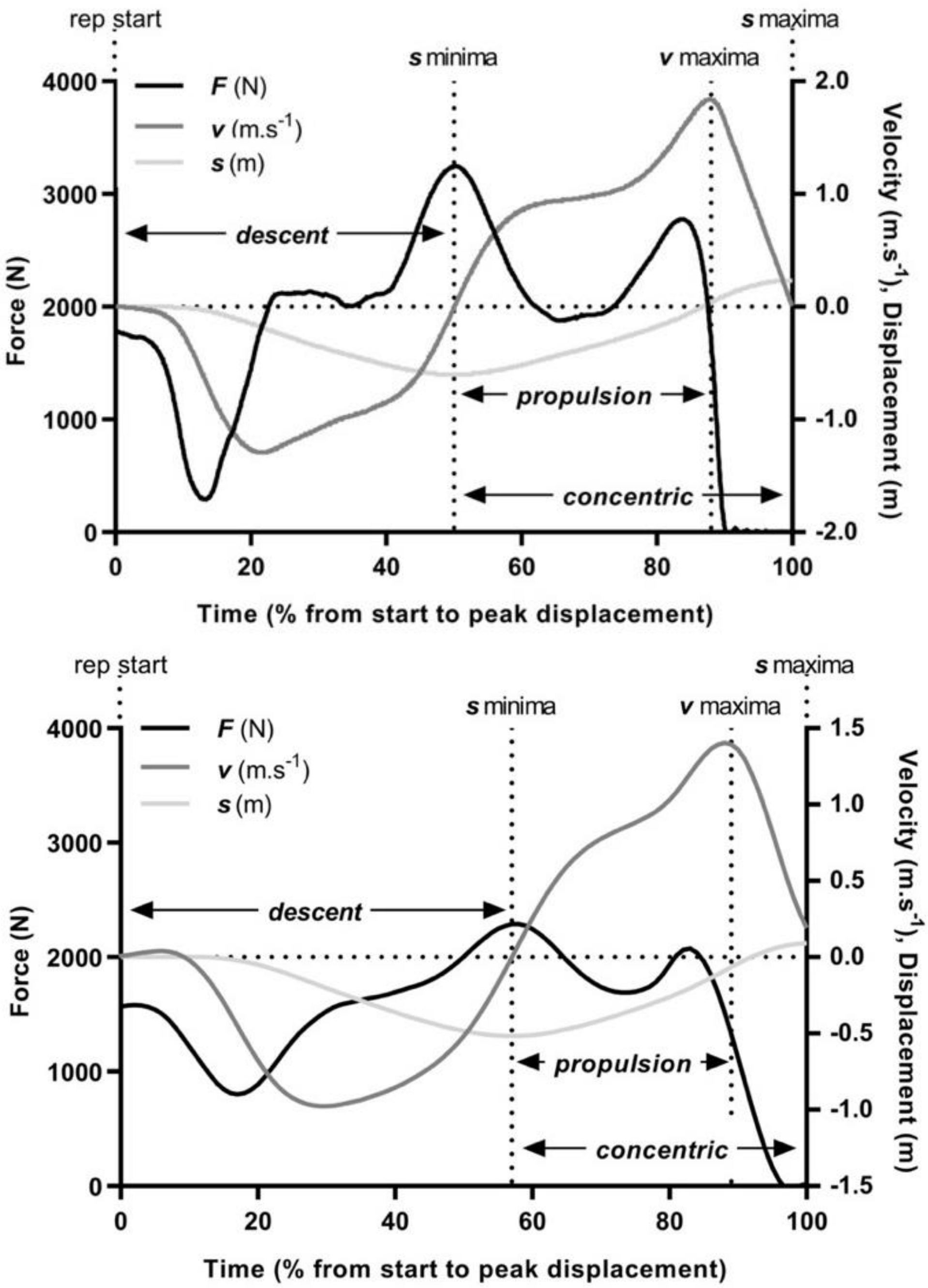

Figure 29. Example calculation methods for the determination of descent (negative displacement, positive and negative acceleration phase), concentric (positive displacement, positive and negative acceleration phase) and propulsion (positive displacement, positive acceleration) phases. Top figure = jump squat, bottom figure = back squat. *F*, Force; *v*, velocity; *s*, displacement.

7.4.5 Statistical analysis

Data were checked for normality via the assessment of skewness, kurtosis, and univariate outliers. Mean and SDs were calculated for all dependent variables. Three-way repeated measures ANOVA was utilised to assess the load × phase × exercise interactions for force, velocity, power, work, displacement, and duration, simple two-way interactions were then calculated, followed by simple main effects using the Bonferroni post-hoc correction. Impulse was analysed via a two-way repeated measures ANOVA (load × exercise), with simple main effects assessed also using Bonferroni corrections, with the alpha level set at $p < 0.05$. Mean differences and 95% CIs were calculated between the two exercises for each load. Meaningful between-exercise differences were assessed using SMDs (*g*), with magnitudes interpreted as: trivial (< 0.2); small (0.2-0.59); moderate (0.6-1.19); large (1.2-2.0); very large (> 2.0) (Hopkins et al., 2009). The proportion of time and displacement (as a percentage ratio) spent in the propulsion phase compared to the concentric and descent phase were also calculated. Intra-session reliability was assessed on the two best repetitions (those with the highest peak velocity in each session) via ICC and CV, with 95% CIs also calculated. ICC thresholds were set as poor (< 0.5), moderate (0.5-0.74), good (0.75-0.9), and excellent (> 0.9), with CV thresholds set as poor (> 10%), moderate (5-10%) and good (< 5%) (Banyard, Nosaka, & Haff, 2017; Koo & Li, 2016).

7.5 Results

All data were normally distributed and met assumptions for parametric analysis. Mean back squat 1RM was 158.8 ± 19.2 kg (1.92 ± 0.3 $kg.bm^{-1}$). The ICC and CV reliability data is presented in appendix D. The mean (SD), differences (95% CI), and statistical significance for all dependent variables are presented in Figure 30.

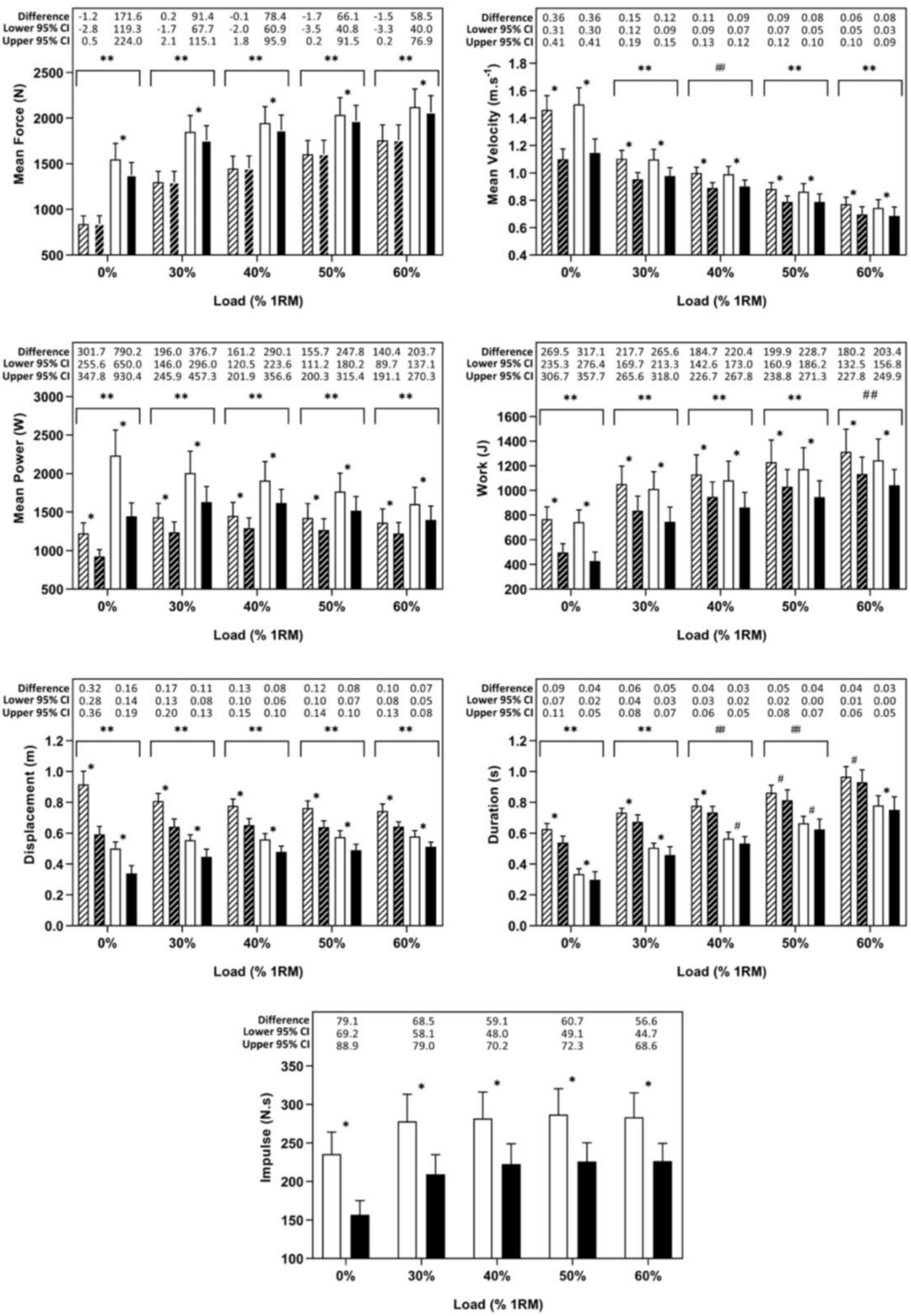

Figure 30. Means and SDs (error bars) for force, velocity, power, work, displacement, duration and impulse across the five loads. White bars = jump squat data, black bars = back squat data. Striped bars = concentric phase, solid bars = propulsion phase. Data above demonstrates mean differences and 95% confidence limits between the jump squat – back squat. ** indicates phase × exercise interactions ($P < 0.001$); ## indicates phase × exercise interactions ($P < 0.05$); * indicates significant main effect ($P < 0.001$).

Three-way repeated measures ANOVA revealed statistically significant load × phase × exercise interactions for force ($F_{(1.37, 20.48)} = 17.02$, $p < 0.001$), velocity ($F_{(2.27, 34.02)} = 6.65$, $p = 0.003$), power ($F_{(1.24, 18.64)} = 82.13$, $p < 0.001$), work ($F_{(1.81, 27.19)} = 7.74$, $p = 0.003$), duration ($F_{(4, 60)} = 48.60$, $p < 0.001$) and displacement ($F_{(1.98, 29.71)} = 136.40$, $p < 0.001$). Statistically significant simple two-way interactions (phase × exercise) were observed for force ($F_{(1, 15)}$ = 31.74-88.53, $p < 0.001$), power ($F_{(1, 15)}$ = 53.09-115.67, $p < 0.001$), displacement ($F_{(1, 15)}$ = 31.91-216.87, $p < 0.001$), and work ($F_{(1, 15)}$ = 10.45-136.32, p = 0.006 - < 0.001) across all five loads. Whereas significant simple two-way interactions were only observed for velocity across loads of 30-60% 1RM ($F_{(1, 15)}$ = 19.27-36.13, p = 0.001 - < 0.001) and duration across loads of 0% and 30-50% 1RM ($F_{(1, 15)}$ = 10.91-176.33, p = 0.005 - < 0.001).

Simple main effects revealed significantly higher velocities ($F_{(1, 15)}$ = 34.05-213.24, $p < 0.001$, g = 1.43-3.80), larger power ($F_{(1, 15)}$ = 34.81-194.42, $p < 0.001$, g = 0.84-2.54), more work ($F_{(1, 15)}$ = 64.99-282.09, $p < 0.001$, g = 1.09-3.02), larger displacements ($F_{(1, 15)}$ = 71.70-298.51, $p < 0.001$, g = 2.54-4.40), and longer durations ($F_{(1, 15)}$ = 9.03-125.56, p = 0.009 - < 0.001, g = 0.45-2.21) in the jump squat compared to the back squat across all five loads, but no differences for mean force ($F_{(1, 15)}$ = 0.02-3.55, p = 0.08-0.90, g = -0.01-0.00) when calculated over the concentric phase. Similarly, significantly larger force ($F_{(1, 15)}$ = 30.48-91.13, $p < 0.001$, g = 0.30-1.06), higher velocities ($F_{(1, 15)}$ = 21.28-70.04, $p < 0.001$, g = 0.94-3.10), larger power ($F_{(1, 15)}$ = 42.48-144.40, $p < 0.001$, g = 0.98-2.93), more work ($F_{(1, 15)}$ = 86.76-282.09, $p < 0.001$, g = 1.30-3.56), larger displacements ($F_{(1, 15)}$ = 72.42-197.49, $p < 0.001$, g = 2.03-3.40), and longer durations ($F_{(1, 15)}$ = 6.58-7302.09, p = 0.022 - < 0.001, g = 0.38-1.05) were observed in the jump squat compared to back squat across all five loads when calculated over the propulsion subphase (Figure 30).

Two-way repeated measures ANOVA revealed a statistically significant load × exercise interaction between the two exercises for impulse ($F_{(2.20, 32.93)}$ = 21.20, p < 0.001), with simple main effects indicating larger impulse in the jump squat compared with the back squat across all five loads ($F_{(1, 15)}$ = 102.26-293.42, p = < 0.001, g = 1.88-3.21) (Figure 2).

The proportion of duration and displacement spent in propulsion subphase in comparison to concentric and descent phases are presented in Table 19. An equal proportion of time and displacement was spent in positive acceleration compared to the concentric phase for both exercises, however, the system CoM was accelerating over a larger displacement during the jump squat when calculated in relation to total descent.

Table 19. Duration and displacement propulsion-concentric and propulsion-descent ratios calculate as a percentage (%).

Load (% 1RM)	Exercise	Duration Propulsive-Concentric ratio (%)	Displacement Propulsive-Concentric ratio (%)	Displacement Propulsive-Descent ratio (%)
0	Back Squat	54.8 ± 5.6	56.1 ± 6.0	64.7 ± 9.3
	Jump Squat	53.4 ± 3.6	54.0 ± 3.3	105.3 ± 3.1
30	Back Squat	67.8 ± 3.7	69.3 ± 3.8	81.4 ± 8.1
	Jump Squat	68.7 ± 1.8	68.6 ± 2.0	104.3 ± 5.8
40	Back Squat	72.5 ± 2.3	73.5 ± 2.9	85.1 ± 7.0
	Jump Squat	72.7 ± 1.7	72.3 ± 2.2	102.8 ± 2.0
50	Back Squat	76.6 ± 1.9	76.6 ± 2.5	86.2 ± 10.0
	Jump Squat	76.9 ± 1.3	75.2 ± 1.9	105.9 ± 5.1
60	Back Squat	80.4 ± 2.4	79.2 ± 2.5	91.0 ± 6.8
	Jump Squat	80.6 ± 1.3	77.5 ± 2.0	103.4 ± 2.6

1RM 1 repetition maximum

7.6 Discussion

This is the first study to examine the kinetics and kinematics of lower-body ballistic (jump squat) and non-ballistic (back squat) exercises performed across incremental loads (0, 30-60% 1RM) and calculated over different movement phases (concentric vs. propulsion). The main findings of this research were that the jump squat exhibited significantly larger mechanical demands than the back squat, irrespective of the phase of interest; and that the proportion of time and displacement spent in the propulsion sub-phase with respect to the concentric phase were comparable across the two exercises, but that a larger propulsion displacement was performed in the jump squat when compared to descent displacement, meaning the propulsion phase in the jump squat occurred over a larger range of motion.

Significantly larger force, impulse, power, work, displacement, higher velocities, and longer durations were observed in the jump squat compared to the back squat across all five loads (Figure 30), regardless of the phase of interest (propulsion vs. concentric). Our data, in part, agrees with the limited available data comparing ballistic and non-ballistic squat-based exercise (Cormie, Mccaulley, et al., 2007; Lake et al., 2012; Rossetti et al., 2020). Significantly more power (Cormie, Mccaulley, et al., 2007; Rossetti et al., 2020), higher velocities (Cormie, Mccaulley, et al., 2007; Lake et al., 2012; Rossetti et al., 2020), larger forces (Rossetti et al., 2020) and displacements (Rossetti et al., 2020) have previously been reported across multiple loads (0-85% 1RM) in the free-weight jump squat compared to the back squat when calculated over the full concentric phase. As ballistic exercise is accelerative, of high velocity, and culminates in the projection of the body, system or projectile into free space, there is a reduced requirement to perform negative acceleration at the end of the concentric phase in comparison to non-ballistic exercise (Frost et al., 2010). Further, this period of negative acceleration has been reported to contribute from 21.9-47.7% of the concentric phase when performed across incremental loads (15-90% 1RM) in the free-weight bench press (Frost et al., 2008; Lake et al., 2012). This sub-phase, therefore, has been offered as a reason for non-ballistic exercises having limited application when performed with maximal intent under submaximal loading, particularly for the purpose of increasing force, velocity, power, or impulse (Cormie, McCaulley, et al., 2007; Newton et al., 1996).

This sub-phase of negative acceleration is of practical relevance to the S&C practitioner. Typically, incremental protocols such as load- and force-velocity profiling begin with light to moderate loads (0-60% 1RM) in non-ballistic exercises (e.g., back squat, deadlift, bench press), with metrics calculated across the full concentric phase (Rivière et al., 2017; Thompson, Rogerson, Ruddock, Banyard, et al., 2021). Our data, however, demonstrates that force-velocity characteristics are significantly lower during non-ballistic exercise when compared with ballistic, potentially underestimating an individual's maximal capabilities. Therefore, researchers and practitioners should incorporate ballistic equivalents (e.g., jump squat, trap-bar jumps, bench press throw) when performing loads < 60% 1RM during athlete testing and profiling (force- and load-velocity) to ensure a valid assessment of mechanical capabilities.

Researchers have suggested that the demands of biomechanically similar non-ballistic and ballistic exercises are more comparable when the kinetics and kinematics are calculated over only the propulsion phase and therefore removing the impact of any negative acceleration (Frost et al., 2008; Lake et al., 2012). Our data refutes this notion as the jump squat exhibited significantly greater mechanical demands in all output and driver metrics (power, velocity (30-60% 1RM), impulse, force, and work), irrespective of the phase of interest, with moderate to very large SMDs observed for all propulsion metrics (Figure 30). Despite the proposed underestimation of non-ballistic kinetics and kinematics when calculated across the full concentric phase (Frost et al., 2008; Lake et al., 2012), the system still accelerates over a significantly larger displacement and longer duration when a movement ends in a point of projection, directly influencing driver and output metrics based on Newtonian laws ($F = ma$). This, therefore, supports the inclusion of ballistic-type exercises to target specific neuromuscular adaptations at appropriate times of a periodised cycle.

Our data highlighted significantly longer periods of acceleration and larger displacements in the jump squat vs. back squat across all loads (figure 30), corroborating earlier findings in upper and lower body exercises (Frost et al., 2008; Lake et al., 2012; Newton et al., 1996). In contrast to previous literature that reported significantly longer periods of acceleration in the bench throw vs. bench press (15-60% 1RM) (Frost et al., 2008), comparable displacements and durations were observed in our study when considering the propulsion sub-phase as a proportion of the concentric phase (Table 19). When comparing propulsion displacement to total descent displacement, however, the jump squat was noticeably higher (> 100%) (Table 19). Similarly, significantly more propulsion work in the jump squat was evident, indicating ballistic training with light-to-moderate loads promotes a larger range of motion of positive acceleration, potentially eliciting adaptations across a longer length-tension relationship.

It is important to consider mechanical principia when understanding the underpinnings of human movement. Impulse was significantly greater in the jump squat exercises across all loads, which is a direct result of significantly greater forces being produced over significantly longer durations (figure 30). Change in momentum (mass × velocity) is directly proportional to impulse, meaning larger forces and longer acceleration results in higher velocities. Similarly, significantly greater power outputs were evident in the jump squat due to significantly greater work (power = work / Δ time; work = force × displacement). The interaction between these variables, therefore, provide insight into the demands of certain exercises. Whilst typically force, velocity and power seem to be the most sought-after metrics (Cormie et al., 2011b; Turner et al., 2020), coaches, practitioners and researchers should also consider the underpinning mechanics to understand the strategies and drivers of human movement.

Understanding the mechanics of human movement is important when creating training interventions. Output variables such as power, velocity and impulse can be effective feedback for athletes, however, are often dictated by specific strategies and drivers. For example, impulse could be of use to a coach, however, understanding how impulse is derived and/or changes from session-to-session or exercise-to-exercise is more useful. An increase in force produced (driver), or duration of force application (strategy) can both increase impulse (Δ force $\times$ Δ time). Maximising force production in the shortest duration possible is therefore thought to be one of the most effective strategies for improving sport performance, suggesting practitioners should select the most appropriate output, driver, and strategy metrics to provide a detailed and nuanced overview of how individuals perform tasks and improve following training interventions.

Although our research provides an in-depth and unique comparison of ballistic and non-ballistic lower-body exercise, it is not without its limitations. Specifically, not including any loads > 60% 1RM limits the application and interpretation of our data across the full load spectrum. Previous research has observed greater performance (e.g., strength and sprinting) and mechanical (e.g., power and force) improvements from heavy strength training, compared to lower-load ballistic training (Cormie et al., 2010; Cormie, McCaulley, et al., 2007; N. Harris et al., 2008). And whilst this study did not assess chronic adaptations, a comparison between light and heavy loads in both exercises would provide a greater level of detail for practitioners to make appropriate decisions and should therefore be an avenue for future research. Secondly, this study did not consider the impact of the eccentric or descent strategy on subsequent kinetics and kinematics of the propulsion and concentric phases. For example, if an athlete were to apply a longer unweighting phase during the ballistic movement, this would determine the rate and magnitude of the force required during the braking phase and would likely influence the resultant impact of the stretch-shortening cycle on propulsion variables (McMahon et al., 2018). Despite an attempt to standardise the descent phase of both lifts, without numerical data to support this, understanding the impact is difficult and therefore warrants further investigation.

7.7 Practical applications

S&C coaches should look to optimise mechanical output throughout a periodised plan via appropriate exercise choice. The most effective way to maximise power, impulse, and RFD is through the combination of training modalities across the full force-velocity spectrum, however, when focusing on specific 'power' training blocks, loaded ballistic exercises (0-60% 1RM) should be utilised over non-ballistic exercises of comparable loads. Nevertheless, this approach could still be 'contrasted' with heavy load exercises (> 80% 1RM) to ensure maximal force production does not decrease. Practitioners would therefore need to select these exercises at appropriate times of a competitive season (e.g., away from fixture congestion) to minimise any unwanted impact of landing. Furthermore, given the greater mechanical outputs observed in the jump squat, it seems logical to replace the lighter and moderate loads in profiling type activities (e.g., LVPs) with their ballistic equivalents to provide a valid reflection of an individual's force-velocity capabilities. Finally, when collecting and analysing force kinetic and kinematic data, practitioners should utilise metrics that detail an athlete's strategy (e.g., duration and displacement) to a task and the mechanical drivers (e.g., force and work) of said task in addition to the more popular feedback or output variables (e.g., power, velocity, and impulse).

Chapter 8.0: Study 6 - A novel approach to 1RM prediction using the load-velocity profile: A comparison of models

8.1 Study rationale

Study five investigated kinetic and kinematic differences between non-ballistic and ballistic free-weight lower body exercise and revealed that all mechanical variables, when calculated across both the concentric phase and propulsion sub-phase, were superior in the jump squat compared with the back squat. LVPs are typically conducted across the full load spectrum in non-ballistic exercise, meaning lighter loads performed (e.g., 0-60% 1RM) could underestimate an individual's load-velocity characteristics and present invalid data for autoregulation. Applying ballistic exercise during these loads, however, might solve this problem given the greater mechanical output evident. Therefore, the jump squat was identified as an integral substitute in loads ≤ 60% 1RM when administering LVPs in the free-weight back squat.

The findings of the previous five studies established the aims and objectives of this concluding study (figure 1). The development of a time-efficient method for load-velocity profiling was identified as a major barrier to implementing VBT, with inaccurate 1RM prescriptions also presenting challenges to coaches (study two). Additionally, the inclusion of ballistic exercise was also offered as an alternative LVP strategy by practitioners (study two), with ballistic exercise demonstrating greater mechanical output than non-ballistic (study five). The reliability and individualised nature of the LVP in the free-weight back squat was established, in addition to poor within-participant reliability in loads ≥ 90% 1RM in mean velocity (study four). Coupled with the potential for a curvilinear relationship between load and velocity in free-weight, lower body exercises (study four), the findings from the previous five studies all contributed to the research design of study six. The sixth study, therefore, was undertaken to identify a time efficient, valid, and practical means for predicting 1RM using load-velocity data.

8.2 Abstract

The study aim was to compare different predictive models in 1RM estimation from LVP data. Fourteen strength-trained men underwent initial 1RMs in the free-weight back squat, followed by two LVPs, over three sessions. Profiles were constructed via a combined method (jump squat (0 load, 30%-60% 1RM) + back squat (70%-100% 1RM) or back squat only (0 load, 30-100% 1RM) in 10% increments. Quadratic and linear regression modelling was applied to the data to estimate 80% 1RM (kg) using 80% 1RM mean velocity identified in LVP one as the reference point, with load (kg) then extrapolated to predict 1RM. 1RM prediction was based on LVP two data and analysed via ANOVA, MSD (g/η_p^2), *r*, paired t-tests, SEE, and LOA; $p < 0.05$. All models reported systematic bias < 10 kg, $r > 0.97$ and SEE < 5 kg, however, all linear models were significantly different from measured 1RM (p = 0.015 - < 0.001). Significant differences were observed between quadratic and linear models for combined ($P < 0.001$; η_p^2 = 0.90) and back squat ($p = 0.004$, $\eta_p^2 = 0.35$) methods. Significant differences were observed between exercises when applying linear modelling ($p < .001$, η_p^2 = 0.67-0.80), but not quadratic (p = 0.632-0.929, η_p^2 = 0.001-0.18). Quadratic modelling employing the combined method rendered the greatest predictive validity. Practitioners should therefore utilise this method when looking to predict daily 1RMs as a means of load autoregulation.

8.3 Introduction

1RM is defined as the maximum external load (kg) an individual can lift for a single repetition (Suchomel et al., 2016). 1RM tests have excellent reliability, relationships with biomechanically similar sporting movements (e.g., back squat and jumping), and can serve as an effective prescriptive tool (% 1RM) (McMaster et al., 2014; Suchomel et al., 2016, 2018; Thompson, Rogerson, Ruddock, Banyard, et al., 2021). Despite this, large demand is placed on the neuromuscular system, often rendering regular 1RM testing infeasible, particularly in multi-faceted sports (e.g., team or court) due to the importance of technical training, busy competitive schedules, and travel (Shattock & Tee, 2020). Frequent maximum testing could therefore create unwanted fatigue, potentially impacting on performances throughout the year (Shattock & Tee, 2020). While this is unlikely to be problematic in settings where 1RMs are relatively stable (e.g., strength sports), maximum strength might fluctuate in athletes competing in these sports due to training priorities (Shattock & Tee, 2020), sleep (Reilly & Piercy, 1994), nutrition (Cribb et al., 2007) and/or fatigue (Enoka & Duchateau, 2008). As a result, alternative strategies such as 1RM prediction from load-velocity profiling data might be an effective strategy to manipulate load (i.e., autoregulation), which is thought to be vital to optimise athletic development (Greig et al., 2020).

Construction of a LVP is based on a near perfect relationship ($r > 0.9$) between load (kg or % 1RM) and velocity (mean, peak, or mean propulsive) which facilitates the development of a statistical model (e.g., linear regression) designed to predict load or velocities through extrapolation (Banyard, Nosaka, & Haff, 2017; Thompson, Rogerson, Ruddock, Banyard, et al., 2021). There is an extensive body of literature investigating the validity and reliability of LVPs to predict 1RM across key exercises such as the bench press (Jidovtseff et al., 2011; Loturco et al., 2017; Pestana-Melero et al., 2018), back squat (Banyard, Nosaka, & Haff, 2017), deadlift (Lake et al., 2017; Ruf et al., 2018), prone bench-pull (García-Ramos, Barboza-González, et al., 2019), half squat (Bazuelo-Ruiz et al., 2015; Conceição et al., 2016; Pérez-Castilla, García-Ramos, et al., 2020), and leg press (Conceição et al., 2016). Formative work by González-Badillo & Sánchez-Medina (2010) concluded, amongst others since, that generalised predictive equations were effective in estimating relative load, reducing the need to repeatedly assess maximal strength. More recent research, however, has demonstrated large between-participant variability in velocity (Banyard et al., 2018; Thompson, Rogerson, Ruddock, Banyard, et al., 2021), limiting the application of these generalised models and suggesting individualised LVPs might provide better estimations of submaximal and maximal load.

The multiple-point method, where models are built using velocity data from multiple incremental, submaximal loads (e.g., 45-85% 1RM in 10% increments) is a common technique to predict 1RM (Bosquet et al., 2010; García-Ramos, Barboza-González, et al., 2019; Pérez-Castilla, Piepoli, Garrido-Blanca, et al., 2019; Pestana-Melero et al., 2018). Similarly, a simplified two-point version has also been suggested, where 1RM is predicted from two submaximal loads (e.g., 45% and 85% 1RM) (García-Ramos, Barboza-González, et al., 2019; García-Ramos, Haff, Pestaña-Melero, et al., 2018). Despite differences in the construction of each approach, practically perfect correlations ($r > 0.9$), goodness of model fit ($R^2 > 0.9$), and low systematic bias between direct and predicted 1RM data (< 10 kg) has been observed (Bosquet et al., 2010; García-Ramos, Barboza-González, et al., 2019; Jidovtseff et al., 2011; Pérez-Castilla, Piepoli, Garrido-Blanca, et al., 2019; Pestana-Melero et al., 2018; Sayers et al., 2018). Whilst these data indicate predictive validity, the studies are limited to isolated, controlled, upper body exercises such as the bench press or prone row, rendering the applicability to exercises beyond these unclear.

The predictive validity of the aforementioned modelling approaches in lower body exercises such as the back squat (Conceição et al., 2016; Fernando Pareja-Blanco, Walker, et al., 2020), half-squat (Bazuelo-Ruiz et al., 2015; Conceição et al., 2016; Pérez-Castilla, García-Ramos, et al., 2020), and leg press (Conceição et al., 2016) are more equivocal. CVs of up to 12% between predicted and actual 1RMs have been observed, and a wider range of model fit to observed data (R2 = 0.79-0.99) reported, indicating possible model accuracy issues for larger, complex movements. In addition to the heterogeneity in results, all the above research (except García-Ramos et al. (2019)) have utilised smith-machine exercises, limiting the practical recommendations to more applied settings that prescribe free-weight exercises.

Despite variety in the construction of the profile (2-point vs. multi-point; start and end loads etc.) most 1RM prediction studies have one similarity: the V_{1RM} as the endpoint of extrapolation. Typically, this value is established either through a direct measure of the V_{1RM} as part of a full profile, or taken from normative data of a similar population, both of which have fundamental flaws for 1RM prediction. The LVP is highly individualised (Banyard et al., 2018; Thompson, Rogerson, Ruddock, Banyard, et al., 2021) and the use of normative velocity data as the endpoint of extrapolation demonstrates large systematic error. Additionally, poor within-participant reliability of V_{1RM} has resulted in large random error in modelled estimates being observed (Banyard et al., 2018; Ruf et al., 2018; Thompson, Rogerson, Ruddock, Banyard, et al., 2021). While the V_{1RM} appears to be unreliable, previous research has shown the velocity observed at submaximal loads demonstrate better reliability (Thompson, Rogerson, Ruddock, Banyard, et al., 2021). A combination of increased movement variability, small horizontal movements, and larger contribution of the stretch-shortening cycle could explain this poorer reliability at V_{1RM} (Banyard et al., 2018; Thompson, Rogerson, Ruddock, Banyard, et al., 2021). Therefore, an alternative approach might be to incorporate a more stable velocity value (e.g., 80% 1RM) as the method of extrapolation for predicting 1RM, potentially reducing the magnitude of error between modelled and directly assessed 1RM values.

When considering sources of prediction error, the statistical model used to generate the LVP must also be evaluated, with linear regression being the most common. To date, only one study has compared linear modelling (first-order polynomial) with an alternative approach such as quadratic modelling (second-order polynomial) for estimating 1RM to determine whether the additional flexibility afforded by this method improves predictive validity (Janicijevic et al., 2021). Quadratic modelling is an extension of linear, by which an extra convention is added (ax^2) to create a hyperbolic profile. Janicijevic et al. (2021) observed a better predictive validity for the multiple-point linear model when compared to polynomial modelling using the smith-machine bench press exercise. Despite relatively small mean differences (2.5-4.1 kg), strong correlation coefficients (r > 0.95), small effect sizes (< 0.2) and small mean systematic bias (-3.2 to -1.0 kg), however, large random error was observed in all models (20 kg in some cases). Such large random error raises concerns over the utility of these 1RM predictive models as the repeatability and potential to control for noise might be compromised and thus, further comparisons are required.

Typically, LVPs are constructed using a combination of light and heavy loads (30% 1RM to 100% 1RM) in a non-ballistic exercise (Thompson et al., 2020; Thompson, Rogerson, Ruddock, Banyard, et al., 2021). Despite this, ballistic equivalents (loaded jump squat) are often more commonly prescribed than non-ballistic exercises at these lighter loads (e.g., bodyweight to 60% 1RM) given the greater mechanical outputs, closer relationship with specific sporting actions (i.e., jumping), and larger periods of positive acceleration (Cormie et al., 2010, 2011b; Rossetti et al., 2020; Thompson et al., 2022; Tricoli et al., 2005). Therefore, by utilising both ballistic and non-ballistic exercises within LVPs, arguably a more reliable, valid, and practically representative model could be developed, enabling greater usability in practice. Furthermore, coupling this more valid data with the sophistication of quadratic modelling might offer improved predictions for a complex, free-weight movement such as the back squat. Therefore, the aim of this study was to investigate whether 1RM could be predicted from load-velocity data. Specifically, to compare whether exercise selection (back squat vs. jump squat and back squat 'combined' method) and model construction (linear vs. quadratic) effects the predictive validity of the LVP using a novel method of extrapolation (80% 1RM) to estimate maximum strength.

8.4 Methods

8.4.1 Participants

Fourteen healthy, strength-trained (relative strength > 1.5 $kg.bm^{-1}$) men (age: 26.0 ± 3.8 years; body mass: 82.5 ± 9.4 kg; stature: 174.7 ± 4.6 cm; relative strength: 1.95 ± 0.2 $kg.bm^{-1}$) volunteered for this study. Ethical approval was granted via the institutions ethics board (*ER13605026*) in accordance with the seventh revision (2013) of the declaration of Helsinki. In addition to relative strength, 12 months resistance training experience and technical proficiency in the free-weight back squat and loaded jump squat exercises were required. Written informed consent was provided prior to testing.

8.4.2 Procedures

Participants attended the laboratory on three occasions, each separated by a minimum of 72 hours. No additional lower body exercise was permitted 48 hours prior to and during data collection. All repetitions were performed using an IWF approved, calibrated 20kg barbell and competition bumper plates (Werksan, Akyurt, Turkey). A high-bar back squat technique was adopted which involved the barbell sitting on the upper part of the trapezius muscles using a neutral grip. Participants adopted a self-selected hip width and foot position, which was recorded and standardized across sessions. A lift was deemed successful when the hip was below the knee at minimum displacement and the lower limbs were fully extended upon ascent. The jump squat was standardised identically to the back squat, but participants were required to fully leave the floor following ascent. Technique and depth were assessed by an experienced, accredited S&C coach and retrospective 2D video analysis (iPhone 7, iOS 14.4.4, Apple, Cupertino, CA, USA) to ensure repetition depth was consistent. The dip function in the Gymaware LPT (Version 2.9.4, Kinetic, Canberra, Australia), which measures displacement of the tether, was also used to check range of motion.

8.4.2.1 1RM testing (visit 1)

Body mass (kg) (Kistler, 9286A, Winterthur, Switzerland), stature (cm) (Seca, Leicester, Hamburg, Germany) and current 1RM estimation was collected during the initial visit. An individualised, standardised warm-up was then performed using a combination of static stretching, dynamic mobility, activation exercises, light barbell work and body-weight jumps. Habituation of performing the concentric phases with '*maximal velocity and intent*' also occurred.

Participants were then taken through an incremental 1RM protocol in the free-weight back squat consisting of performing repetitions across a series of incremental loads: 50% (5 repetitions); 70% (3 repetitions); 80% (2 repetitions); 85%, 90% and 95% (1 repetition) of the estimated 1RM followed by up to 5 attempts to find a true 1RM. 1RM was determined when the participant and primary researcher agreed no more weight could be lifted, or a failed attempt occurred. 3-5 minutes rest was prescribed in between each load.

8.4.2.2 Load-velocity profile (visits 2 and 3)

Visits two and three were procedurally identical. Participants performed an incremental LVP in the back squat and jump squat exercises. All loads were determined as a percentage of the back squat 1RM from visit one. Gymaware (sampling every 2 mm of displacement) and a 4th generation iPad mini (iOS 14.0.1, Apple, Cupertino, CA, USA) were used to measure mean velocity for each repetition (Thompson et al., 2020). The Gymaware was located on the right collar, 10mm from the end of, and perpendicular to, the barbell.

Prior to data collection, participants completed the same standardised warm-up from visit one in addition to bodyweight repetitions (using a wooden dowel) in the back squat and jump squat. The following loads were then performed sequentially in both exercises: 0 load (5 repetitions), followed by 30% (3 repetitions), 40% (3 repetitions), 50% (2 repetitions), 60% 1RM (2 repetitions). The participants then continued with back squat only for loads 70% (2 repetitions), 80%, 90% and 100% 1RM (1 repetition). Participants were given up to three attempts to lift the 1RM achieved in visit one. Five minutes rest was administered between loads, with three minutes between exercises at each load. Participants were instructed to perform the concentric phase of every repetition with *'maximal intent and velocity'*. Mean velocity was defined as the average velocity recorded across the full concentric phase of both exercises. The start and end point of the concentric phase was defined as per the manufacturers data processing and filtering system.

8.4.2.3 1RM prediction

The models and methods employed in the present study have five novel factors: 1) the utilisation of 80% 1RM mean velocity as the constant (reference point) within the predictive equations; 2) a comparison between linear and quadratic predictive models; 3) a combination of ballistic (jump squat) and non-ballistic (back squat) free-weight exercises compared to non-ballistic (back squat) only; 4) a combination of interpolation and extrapolation to estimate maximal load, and 5) model validation by using one set of data to fit the model and then a new set of LVP data to predict 1RM.

Eight LVPs were created for each individual following data collection (table 20). A combination of jump squat and back squat (combined) mean velocity data was utilised for four of the profiles, with back squat only mean velocity data applied for the other four. Moreover, a four-point (e.g., combined (quadratic 4)) and seven-point (e.g., back squat (linear 7)) profile was produced for each of the conditions (table 20). Velocity data for loads between 0 load and 60% 1RM was taken from the jump squat, with anything heavier taken from the back squat when constructing the combined models. All velocity data (0-100% 1RM) was taken from the back squat when constructing the back squat models. A quadratic or linear function was then applied to the data. Models were fit using absolute load (kg) as the independent variable, and mean velocity ($m.s^{-1}$) as the dependent variable. The LINEST function was used in Microsoft Excel (Microsoft Excel, Microsoft, Albuquerque, NM, USA) to determine model parameters for both the quadratic and linear functions (appendix F). Both equations were then rearranged to solve x:

$$\textbf{Quadratic model}: \quad \boldsymbol{y = ax^2 + bx + c} \quad \rightarrow \quad \boldsymbol{x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}}$$

eq.22

$$\textbf{Linear model}: \quad \boldsymbol{y = ax + b} \quad \rightarrow \quad \boldsymbol{x = \frac{y - b}{a}}$$

eq.23

Table 20. Description of all eight one repetition maximum (1RM) prediction models. All loads between and including 0% 1RM and 60% 1RM in the combined method were taken from jump squat data. Loads > 60% 1RM in the combined method were taken from back squat data.

Name	Model	Exercise	Data Points	Loads (% 1RM)
Combined (quadratic 7)	Quadratic	Jump Squat + Back Squat	7	0 load + 30 – 80%
Combined (quadratic 4)			4	0 load, 30%, 50%, 80%
Back Squat (quadratic 7)		Back Squat	7	0 load + 30 – 80%
Back Squat (quadratic 4)			4	0 load, 30%, 50%, 80%
Combined (linear 7)	Linear	Jump Squat + Back Squat	7	0 load + 30 – 80%
Combined (linear 4)			4	0 load, 30%, 50%, 80%
Back Squat (linear 7)		Back Squat	7	0 load + 30 – 80%
Back Squat (linear 4)			4	0 load, 30%, 50%, 80%

The mean velocity at 80% 1RM was taken from session one and applied to session two's profiling data, acting as the reference velocity for each model – i.e., estimating kg's that corresponded to 80% 1RM mean velocity – via a method of interpolation (predictive modelling that can estimate any value within the range of a measured dataset). 80% 1RM was selected as the reference velocity as previous literature has found this to be the heaviest load demonstrating acceptable reliability of mean velocity (Thompson, Rogerson, Ruddock, Banyard, et al., 2021). 1RM was then predicted via a method of extrapolation from 80% to 100% 1RM using absolute (kg) and relative (% 1RM) load only. This was achieved by simply increasing the predicted absolute load (80% 1RM equivalent) by 20% to equate to the predicted 1RM load. Examples of the predictive models can be seen in figure 31.

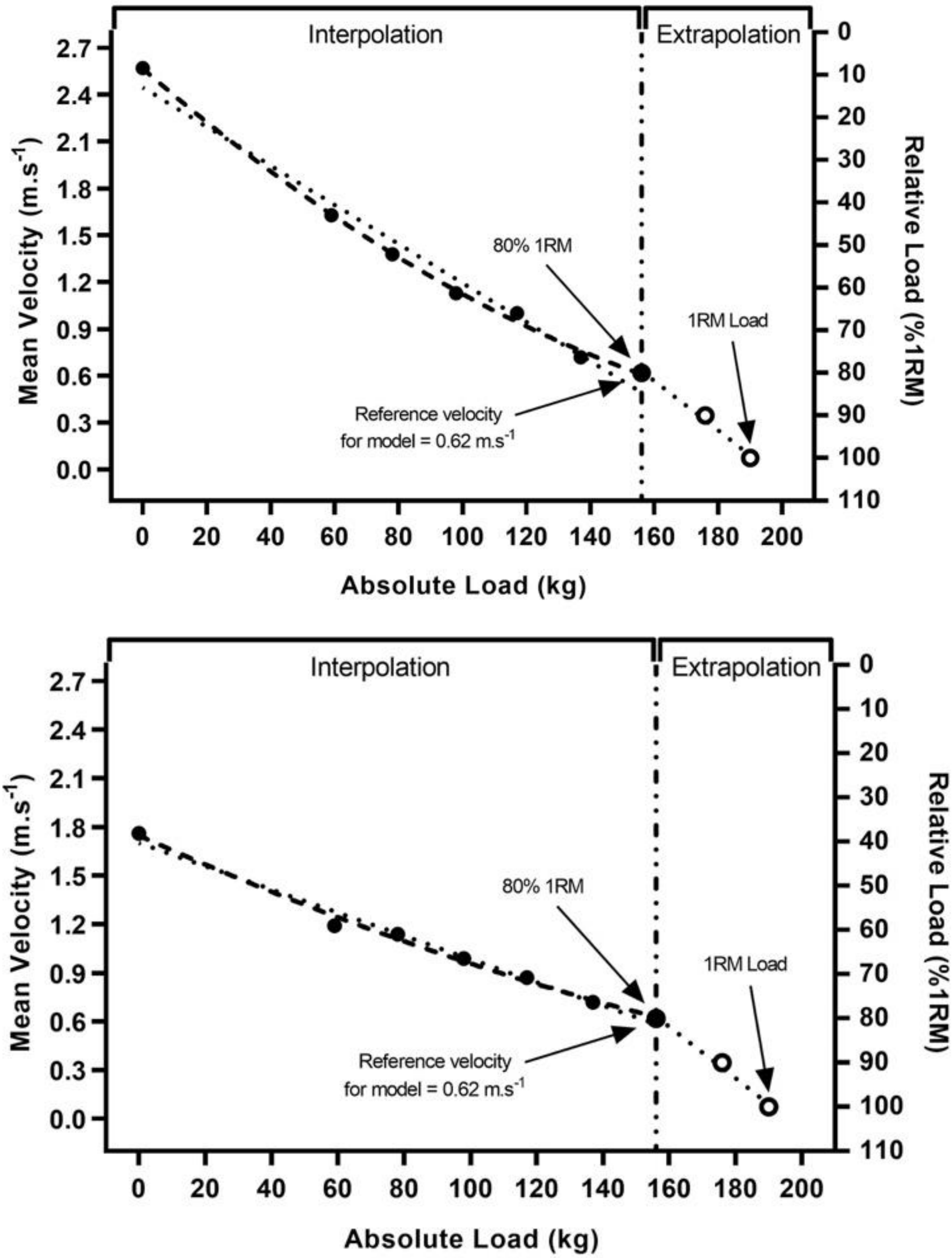

Figure 31. Visualisation of the calculation method for the linear and quadratic one repetition maximum (1RM) prediction models. Reference velocity taken from session 1 and applied to session 2 data. Method of interpolation refers to the prediction of 80% 1RM absolute load (kg) from the LVP data model. Extrapolation refers to the prediction of the 1RM absolute load (kg) from estimated absolute (kg) and relative (% 1RM) load data. (···) indicates linear model, (---) indicates quadratic model. Top = combined method, bottom = back squat.

8.4.3 Statistical analysis

All data were assessed for normal distribution and relevant model assumptions for linear and quadratic variants. The predictive validity of each model was assessed by comparing estimated values to measured 1RMs using paired samples *t*-tests, MSDs (*g*), LOA, *r*, and SEE. Hedges *g* magnitudes were interpreted as: trivial (< 0.2); small (0.2-0.59); moderate (0.6-1.19); large (1.19-2.0); very large (> 2.0) (18). Pearson *r* magnitudes were interpreted as: trivial (< 0.1); small (0.1-0.29); moderate (0.3-0.49); high (0.5-0.69); very high (0.7-0.89) and practically perfect (> 0.9) (Thompson, Rogerson, Ruddock, Banyard, et al., 2021). A two-way repeated measures ANOVA (exercise x model) with Bonferroni post-hoc corrections was used to assess between-model differences and relevant interaction effects using absolute differences (direct 1RM – predicted 1RM) in addition to η_p^2. Where sphericity was violated (assessed via Mauchly's tests of sphericity), the Greenhouse-Geisser correction was applied. Alpha level was set at $p < 0.05$. SPSS (24.0, IBM, New York, NY, USA) and Microsoft Excel was used for statistical analyses.

8.5 Results

All data were normally distributed and met the necessary assumptions prior to analysis, or appropriate corrections were applied. Measured 1RM was 157.0 ± 19.4 kg. Means, SDs and 95% CIs of the predicted 1RM data can be found in table 21. Practically perfect correlations (*r* > 0.97) were observed for all predictive models when compared to the measured 1RM data (table 21). Back Squat (quadratic 7) model yielded the largest SEE (4.06 kg), with the remaining models < 4 kg (table 21). The four quadratic predictive models reported trivial MSDs (*g* = -0.06-0.04), compared to the linear models for the back squat and combined methods, which reported moderate (*g* = 0.52) and small SMDs (*g* = 0.12-0.40), respectively (table 2).

Table 21. 1RM descriptive data (means and SD) with 95% confidence intervals (CI), Pearson correlation coefficient (*r*), standard error of the estimate (SEE), *p* values and Hedges *g* standardised mean differences (SMD) (+ 95% CI) for all eight predictive models. Measured 1RM = 157.0 ± 19.4 kg. 4 = 4-data points and 7 = 7 data-points used to construct the model; $p < 0.05$.

Model Name	Mean (kg)	SD (kg)	95% CI (kg)	*r*	SEE (kg)	*P*	SMD (*g*) + 95% CI
Combined (quadratic 7)	156.34	18.45	120.17-192.51	0.990	2.81	0.391	0.03 (-0.74, 0.81)
Combined (quadratic 4)	157.80	19.34	119.89-195.72	0.997	1.62	0.077	-0.04 (-0.82, 0.74)
Back Squat (quadratic 7)	156.27	18.94	119.15-193.40	0.979	4.06	0.502	0.04 (-0.74, 0.81)
Back Squat (quadratic 4)	158.17	20.70	117.60-198.75	0.996	1.82	0.071	-0.06 (-0.83, 0.72)
Combined (linear 7)	147.13	17.42	112.98-181.28	0.990	2.82	< 0.001	0.52 (-0.27, 1.31)
Combined (linear 4)	149.27	17.72	114.53-184.01	0.994	2.19	< 0.001	0.40 (-0.38, 1.19)
Back Squat (linear 7)	153.36	18.07	117.94-188.78	0.988	3.11	0.001	0.19 (-0.59, 0.97)
Back Squat (linear 4)	154.63	18.59	118.20-191.05	0.987	3.26	0.015	0.12 (-0.66, 0.90)

The mean differences in model predicted and measured 1RM can be seen in figure 32. The four quadratic models produced differences ranging from -1.2-0.7 kg, lower than that of the linear models, which ranged from 2.4-9.9 kg (figure 32, table 21). Small systematic biases were reported for all four quadratic models (-1.17-0.73 kg), with random error ranging from ± 3.09-7.67 kg, whereas the linear models all underestimated the predicted 1RM (2.37 – 9.87 kg), with random error of 5.11-6.34 kg being observed (figure 33).

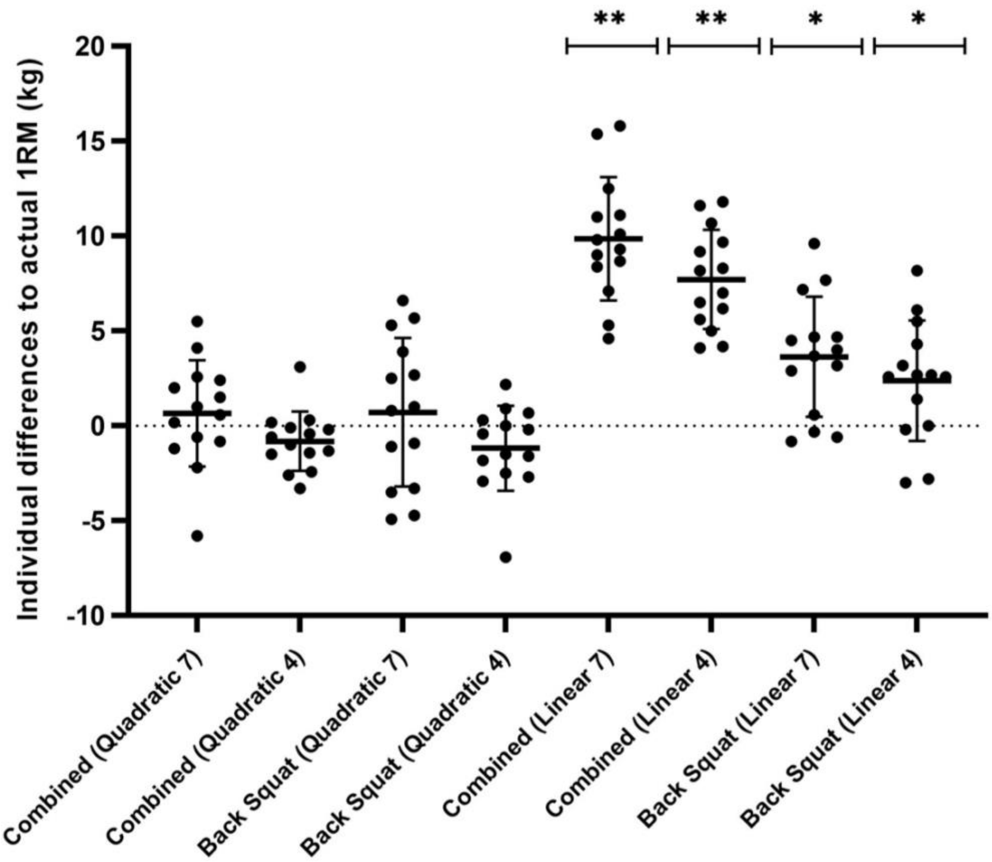

Figure 32. Individual and mean differences for one repetition maximum (1RM) predictive model vs. actual 1RM (represented as actual 1RM minus predicted 1RM). Horizontal lines indicates mean with SDs as error bars. Combined = jump squat and back squat method. *4*, 4-data points; *7*, 7 data-points. ** ($P < 0.001$), * ($P < 0.05$).

A significant two-way interaction was observed between exercise and model ($F(1.65, 21.48) = 23.95$, $p < 0.001$, $\eta_p^2 = 0.65$), with simple main effects observed across models (combined: $F_{(2.01, 26.15)} = 121.47$, $p < 0.001$, $\eta_p^2 = 0.90$; Back Squat: $F_{(1.93, 25.10)} = 7.11$, $p = 0.004$, $\eta_p^2 = 0.35$). When applying back squat only data, Bonferroni tests revealed significant differences between quadratic and linear models (4-point: 3.55 kg (95% CI: 0.22-6.88 kg), $p = 0.034$; 7-point: 2.93 kg (95% CI: 0.01-5.85 kg), $p = 0.049$), but no significant differences between 4-point and 7-point models (quadratic: 1.89 kg (95% CI: -1.55-5.34 kg), $p = 0.670$; linear: 1.27 kg (95% CI: -1.20-3.75 kg), $p = 0.805$). Post hoc tests also revealed significant differences between quadratic and linear models (4-point: 8.52 kg (95% CI: 6.41-10.64 kg), $p < 0.001$; 7-point: 9.20

kg (95% CI: 7.23-11.17 kg), $p < 0.001$) and between the 4-point and 7-point linear models (2.14 kg (95% CI: 0.95-3.33 kg), $p = 0.001$), but not quadratic (1.46 kg (95% CI: -0.52-3.45 kg), $p = 0.235$) when utilising the combined method.

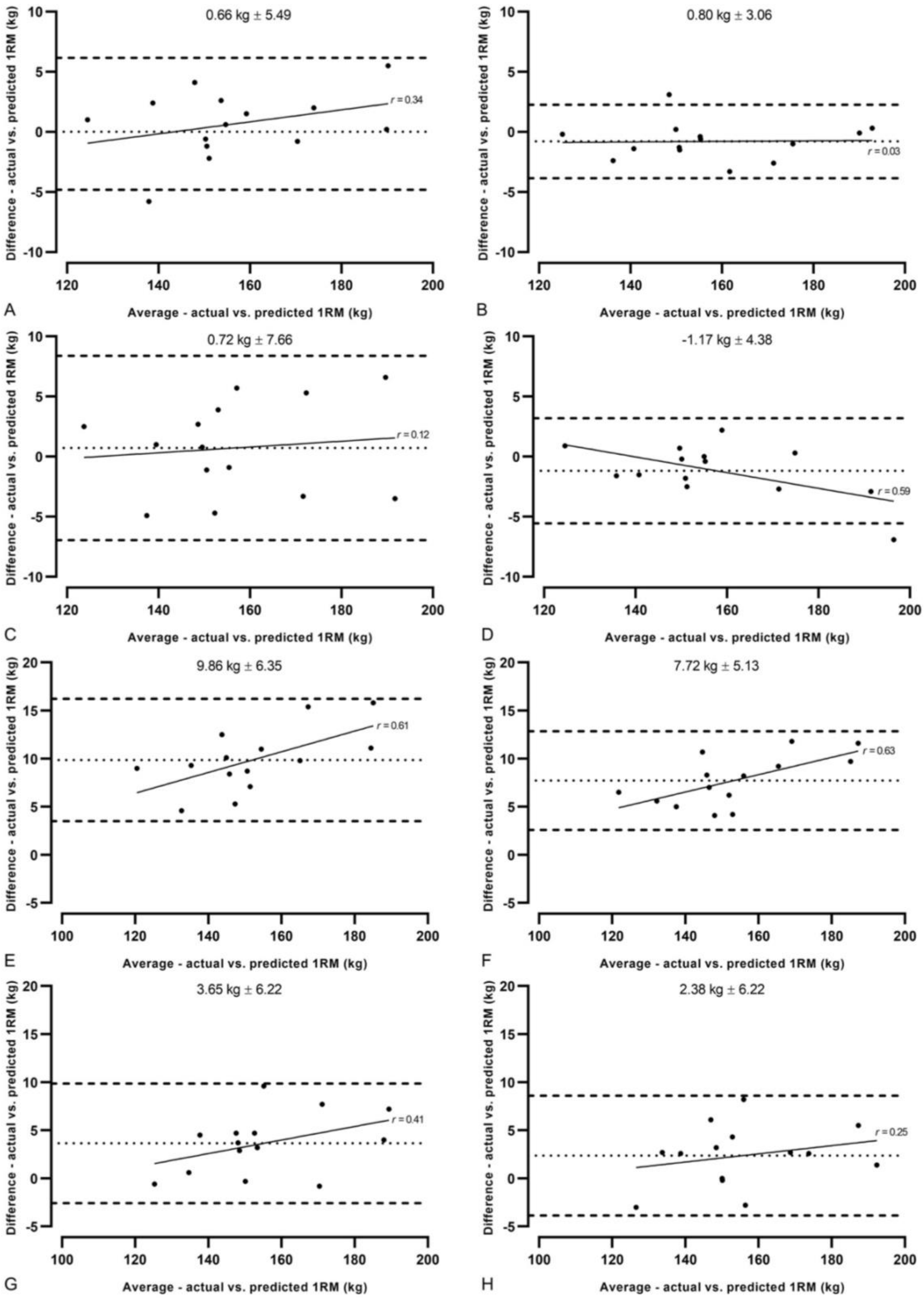

Figure 33. Bland-Altman plots for all eight 1RM predictive models. A-D = quadratic models; E-H = linear models; A, B, E, F = Combined method (jump squat & back squat); C, D, G, H = Back Squat method; A, C, E, G = 7-point models; B, D, F, H = 4-point models. (···) indicates mean systematic bias. (---) indicates 95% limits of agreement. (—) indicates heteroscedasticity of the models (linear regression) with *r* values labelled besides them.

Simple main effects were observed for exercise when applying linear modelling (7 point: $F_{(1, 13)}$ = 51.56, p < 0.001, η_p^2 = 0.80; 4 point: $F_{(1, 13)}$ = 26.60, p < 0.001, η_p^2 = 0.67), but not quadratic modelling (7 point: $F_{(1, 13)}$ = 0.008, p = 0.929, η_p^2 = 0.001; 4 point: $F_{(1, 13)}$ = 0.24, p = 0.632, η_p^2 = 0.18). Mean differences between exercises for linear models were 5.34 kg (95% CI: 3.11-7.58 kg) and 6.21 kg (95% CI: 4.34-8.08 kg) for 4-point and 7-point modelling, respectively, with quadratic models as 0.37 kg (95% CI: -1.27-2.01 kg) and 0.57 kg (95% CI: -1.29-1.41 kg) for 4-point and 7-point modelling, respectively.

8.6 Discussion

The aim of this study was to investigate whether 1RM could be predicted from load-velocity data. Specifically, to compare whether exercise selection (back squat vs. jump squat and back squat, '*combined*' method) and model construction (linear vs. quadratic) effects the predictive validity of the LVP when using 80% 1RM as the model reference velocity. The main findings of this research were that 1RM could be accurately predicted from load-velocity data, and that quadratic modelling demonstrated a greater accuracy than linear modelling. Furthermore, when applying quadratic modelling to LVP data, the combined method was as accurate as the back squat condition, whereas significant differences were evident between the approaches with linear modelling.

The findings of this study (table 21) support recent research highlighting the accuracy of using LVP data for maximum load estimation (Bazuelo-Ruiz et al., 2015; García-Ramos, Barboza-González, et al., 2019; García-Ramos, Haff, Pestaña-Melero, et al., 2018; Janicijevic et al., 2021; Pérez-Castilla, Jerez-Mayorga, et al., 2020a; Pérez-Castilla, Piepoli, Garrido-Blanca, et al., 2019). Despite this, our data did show discrepancies between linear modelled estimated 1RMs and measured 1RMs. Significant differences were observed for all four linear models, with mean differences ranging from 2.4-9.9 kg (figure 32). When applied to free-weight, lower-body exercises, previous literature investigating the predictive validity of LVP data supports our findings. Ruf et al. (2018), Lake et al. (2017), and Banyard et al. (2017) all reported inaccurate estimations of predicted 1RMs ranging from 5-40 kg ($P < 0.05$; ES = -1.24-1.04) in the deadlift and back squat. Interestingly, much smaller SEEs (2.2-3.3 kg vs. 10.6-17.2 kg) and systematic biases (2.4-9.9 kg vs. 20.0-30.9 kg) were observed in the present study compared to previous data (Banyard, Nosaka, & Haff, 2017). These discrepancies may be partially explained by the differences in extrapolation methods applied. Earlier research utilised the V_{1RM} as the reference point for predictive modelling, despite research indicating its poor validity and reliability (Banyard et al., 2018; Ruf et al., 2018; Thompson, Rogerson, Ruddock, Banyard, et al., 2021). As a result, our models were based on the heaviest load (80% 1RM) that demonstrated acceptable levels of reliability (80% 1RM CV = 5.4-5.7% vs. V_{1RM} = 11.8-19.4%) (Banyard et al., 2018; Thompson, Rogerson, Ruddock, Banyard, et al., 2021). Given the superior within-participant reliability of mean velocity associated with submaximal loads (Thompson, Rogerson, Ruddock, Banyard, et al., 2021), it is likely that the magnitude of random error in our model was reduced.

Our predictive modelling involved a process of interpolation of a more reliable mean velocity (80% 1RM), followed by extrapolation from the estimated 80% 1RM to 1RM (kg), whereas previous literature has typically estimated via extrapolation up to the V_{1RM} (Banyard, Nosaka, & Haff, 2017; García-Ramos, Barboza-González, et al., 2019; García-Ramos, Haff, Pestaña-Melero, et al., 2018; Pérez-Castilla, Jerez-Mayorga, et al., 2020a; Ruf et al., 2018). The V_{1RM} method relies on the point of extrapolation aligning fully to the trend of the data, with the model required to capture the underlying values it estimates. Often, when that point of interest is the V_{1RM}, the estimation can be compromised because the rate of change in velocity is not as constant (slope < 1) compared with sub-maximal loads. Instead, interpolation can account for this as the estimation of values fall inside the range of observed data, which is more likely to be captured by the model function, leading to less erroneous estimations. Finally, as combining relative (% 1RM) and absolute (kg) load creates ratio data, they scale proportionally, meaning our method of extrapolation from a predicted 80% to 100% 1RM is more robust for maximal load estimation than extrapolation to V_{1RM}. Future research should look to employ this method of estimation to other exercises to further investigate its predictive validity.

Previous literature applying linear modelling to LVP data have reported smaller differences and associated error than our study. Mean differences of < 5 kg have been reported in the half squat and bench-press exercises from two-point and multiple-point methods (Bazuelo-Ruiz et al., 2015; Pérez-Castilla, Jerez-Mayorga, et al., 2020a; Pérez-Castilla, Piepoli, Garrido-Blanca, et al., 2019), however, this research typically employs smith-machine-based protocols. Despite numerous criticisms regarding smith-machines and their transferability to applied settings, most literature in this space continues to employ them. Research suggests that mechanical outputs such as take-off velocity (directly related to peak velocity), maximum load lifted, and electromyographical muscle activity differ when performing smith machine exercises compared to free-weight, suggesting that the generalisability of this research to broader contexts using free-weight exercise is limited (Cotterman et al., 2005; Pérez-Castilla, McMahon, et al., 2020; Schwanbeck et al., 2009). Future research should therefore seek to elucidate the predictive validity of approaches most represented in practice, such as free-weight, lower body exercises.

This is the first study to compare different LVP-based predictive modelling in a free-weight, lower body exercise. A significant two-way interaction was evident with significant main effects, with all linear models significantly underestimating 1RM in comparison to their quadratic counterparts ($p < 0.05$). Larger LOAs were also evident, irrespective of the exercise employed (table 21, figure 33), indicating the superiority of quadratic modelling for estimating 1RM in the free-weight back squat. Interestingly, the only previous study testing similar hypotheses was in the smith-machine bench press, and reported multiple-point linear modelling as superior to second-order polynomial modelling (Janicijevic et al., 2021). A smith-machine is designed to limit movement in the sagittal and frontal planes, potentially increasing the reliability of velocity data, and creating a more linear trend (Pérez-Castilla, McMahon, et al., 2020). Similarly, lower-body movements are more complex in nature (more joints involved, greater displacement travelled, and a more varied bar path) than upper body (generally, a more vertical, linear bar path), requiring a greater interaction between joint angular forces, moments, and velocities, potentially resulting in a less predictable relationship (Bobbert, 2012). Therefore, practitioners should potentially use more sophisticated 1RM predictive models based on LVP data to account for the less-predictable nature of lower-body, free-weight exercises. In addition, no significant differences were observed in predictive validity based on the number of data points used to construct the profile (4-point vs. 7-point or 2-point vs. multi-point) in this study as well as ours, suggesting both models could be implemented effectively at the start of a training session to update daily 1RMs quickly with only a few loads lifted.

When applying linear modelling, a significantly larger mean difference and larger LOAs were observed for the combined vs. back squat method ($p < 0.001$). Conversely, no significant differences were observed between exercises when applying quadratic modelling, suggesting this model has a greater level of sophistication that can fit various types of LVP data. Previous research has reported greater mechanical output (velocity, force, power) when performing ballistic exercises using light-to-moderate loads compared to their non-ballistic counterparts, primarily because of the large period of negative work (braking) at the end of the concentric phase (Cormie et al., 2011b; Rossetti et al., 2020; Thompson et al., 2022). Despite this, LVPs are typically derived using non-ballistic exercise only, even when starting at 0-30% 1RM (Banyard et al., 2018; Dorrell, Smith, et al., 2020; García-Ramos, Haff, Pestaña-Melero, et al., 2018; Thompson, Rogerson, Ruddock, Banyard, et al., 2021). Capturing load-velocity data this way could be sub-optimal and less valid given the reported lower mechanical output (Cormie et al., 2011b; Rossetti et al., 2020). Therefore, utilising the combined method with quadratic modelling seems the most logical, valid, and effective way to construct a LVP and predict 1RM.

In contrast to previous literature, the current study assessed predictive validity by first constructing the model from initial testing data (i.e., collect LVP data and determine the 80% 1RM velocity), and then subsequently assessing its validity using newly collected data from a second session. This approach provides greater confidence that the predictive models can estimate future observations with suitable accuracy. Furthermore, the use of LVPs as a longitudinal tool relies on the stability of velocity at relevant percentages of 1RM, irrespective of physiological adaptations. Whilst scarce, previous literature suggests that mean velocity is stable following bouts of acute strength training (~ 4-6 weeks) (Benavides-Ubric et al., 2020; González-Badillo & Sánchez-Medina, 2010; Pérez-Castilla & García-Ramos, 2020), providing confidence in the predictive models. Future research, however, should seek to further investigate the stability of the LVP across longer time periods (e.g., full macrocycle) as well as predict 1RM over multiple sessions, as often, predictive models can be misleadingly concluded as valid and reliable when only applied to one session's worth of data.

8.7 Conclusions

Prediction of 1RM based on LVP data might be an effective autoregulatory tool for S&C practitioners over the course of a training cycle. The results of this study provide practitioners with confidence that a quadratic model that uses mean velocity of 80% 1RM and utilises both ballistic and non-ballistic exercises is an effective method for estimating an individual's 1RM in the free-weight back squat, ensuring load manipulation and fatigue management can be achieved on a sessional basis. Given the nature of the protocol, it would also be feasible for a coach to employ this method at the beginning of a training session, estimate an athlete's daily 1RM, adjust relevant working loads, and ensure parity between the loads prescribed and the intended training stimulus on that day. This would also allow coaches to utilise the integration of technology at the start of a training session, freeing up their time and attention for coaching for the remainder

Chapter 9.0: Synthesis

9.1 Achievement of thesis aims and objectives

Autoregulation is the process of acutely manipulating training variables in response to an individual's physiological status and is a vital component of periodisation for optimising prescription and circumventing residual fatigue (Greig et al., 2020). VBT, specifically load-velocity profiling, has been proposed as an effective strategy to achieve this, sometimes through the daily estimation of 1RM (Moore & Dorrell, 2020; Shattock & Tee, 2020). The application of LVPs to predict 1RM has typically been conducted in upper-body, smith-machine based exercises, neglecting a fundamental element of most S&C programmes – lower-body, free-weight exercise such as the back squat. The small amount of research dedicated to this training modality highlights several procedural, statistical, and logistical flaws, often resulting in inaccurate predictions of maximum strength. These flaws were confirmed by elite S&C coaches currently utilising VBT (study two). This doctoral programme, therefore, pursued potential solutions designed to improve the functionality, accuracy, and reliability of LVP-based 1RM prediction methods.

Through the adoption of the ARMSS framework and a pragmatic philosophical approach, the overarching aim of this thesis was to design and evaluate the efficacy of a novel method for predicting 1RM from load-velocity data. Specifically, to develop an efficient, valid, and reliable protocol, using appropriate commercially available technology, that can effectively autoregulate sessional load prescription and optimise training recommendations using LVP data. This aim was achieved through a combination of systematic reviews, qualitative thematic analyses, reliability and validity investigations, regression studies, mechanical evaluations, and efficacy trials, all of which adhere to the three main stages of the ARMSS model: description, experimentation, and implementation (table 7).

Table 22. An overview of thesis studies, objectives, and outcomes in relation to ARMSS model.

Stage of ARMSS	Thesis Objective	PhD Study	Study Objectives	Study Outcomes
1) Defining the problem	1	The Effectiveness of Two Methods of Prescribing Load on Maximal Strength Development: A Systematic Review	• To evaluate the landscape of research investigating the effectiveness of load prescription methods (% 1RM vs. RM targets vs. RPE vs. VBT) • To identify avenues of research for future studies in load prescription • To provide a consensus on the most effective method of load prescription through a PRISMA-based systematic review	• % 1RM and RM target-based literature met our inclusion criteria, with zero RIR or VBT being included • % 1RM was deemed more effective the RM targets based on mean increases in maximal strength and CIs • Physiological adaptations underpinning increases in maximal strength reported as varied • VBT and RIR required more robust research to evaluate effectiveness of being used for load prescription
	2	"Is it a slow day or a go day?": The perceptions and applications of velocity-based training within elite strength and conditioning	• To evaluate the application of VBT within elite S&C • To understand coach perceptions towards the benefits and drawbacks of utilising VBT • To identify the common technologies used in practice and the drivers for purchasing them	• Common applications of VBT included testing, monitoring, programming, and feedback • Typical devices included LPTs, IMUs and camera-based systems • Main benefits to VBT included feedback, driving intent, individualisation, and autoregulation • Main drawbacks included time costly protocols, inaccurate predictions (LVP-based), distracted coaching, and technological troubleshooting

2) Descriptive research	3	The Reliability and Validity of Current Technologies for Measuring Barbell Velocity in the Free-Weight Back Squat and Power Clean	• To identify the most reliable and valid velocity-based technology readily available to practitioners	• Gymaware LPT was the most reliable and valid technology • MyLift smart device application data was comparable to Gymaware for a fraction of the price
3) Predictors of Performance (regression studies)	4	Pooled Versus Individualised Load-Velocity Profiling in the Free-Weight Back Squat and Power Clean	• To determine the relationship between load and velocity in the free-weight in a key strength exercise and Olympic lift derivative • To compare different velocity metrics (mean vs. peak) • To compare group-based and individualised LVPs • To determine the between-participant variability and within-participant reliability of LVP data	• The load-mean velocity relationship was stronger than load-peak velocity • Individualised LVPs were better predictors of performance than pooled or group-based • Second-order polynomial modelling provided a slightly stronger relationship between load and velocity • High between-participant variability was evident in the back squat but not power clean • Loads > 85% did not meet acceptable levels of within-participant reliability in mean and peak velocity, whereas all loads did in the power clean
4) Determinants of key performance predictors	5	Kinetics and Kinematics of the Free-Weight Back Squat and Loaded Jump Squat	• To compare the mechanical demands of ballistic and non-ballistic exercise • To understand the impact the deceleration sub-phase has on kinetic and kinematic output during non-ballistic exercise	• Ballistic exercise demonstrated high kinetic and kinematic output across all variables • When calculating across the propulsion phase only, ballistic exercise was still significantly higher across all mechanical variables

				• The propulsion phase was longer in duration and range of motion during ballistic exercise compared to non-ballistic
5) Efficacy trial	6	A Novel Approach to 1RM Prediction Using the Load-Velocity Profile: A Comparison of Models	• To determine the efficacy of LVP-based 1RM prediction utilising a novel model • To compare linear and quadratic statistical modelling • To compare non-ballistic vs. combined (ballistic and non-ballistic) protocols • To investigate the predictive validity of the models against new LVP data	• LVP-based modelling is an efficacious method for estimating 1RM • Quadratic modelling produced more valid predictions vs. linear • The combined method plus quadratic modelling was the most valid 1RM prediction method • Predicting 80% 1RM and then extrapolating to 1RM is an effective strategy to utilise

To achieve the aim of this thesis, each study addressed a specific objective:

Objective 1. To evaluate the current literature base surrounding load prescription and the effectiveness of a variety of methods. Specifically, to determine the quality of research to date with regards to VBT (ARMSS stage 1).

This objective was addressed via the systematic review (study one) investigating current load prescription methods. Following PRISMA guidelines, only studies pertaining to % 1RM and RM targets met our inclusion criteria, identifying an avenue of research required to explore VBT via a structured programme of study. The most pertinent load prescription method for increasing maximal strength (% 1RM) was identified from this systematic review.

Objective 2. To explore and describe the application and perceptions of VBT and velocity-based technology within different elite S&C contexts (ARMSS stage 1).

Objective two was achieved through a reflexive thematic analysis using semi-structured interviews with elite S&C coaches. There were a variety of applications of VBT including testing, monitoring, load prescription, autoregulation, volume control, and feedback. Coaches felt one of the main benefits of VBT was the individualised prescriptions, and the diagnostics available using LVPs. Drawbacks relating to these applications, however, such as "iPad coaching", time exhaustive LVP protocols, and inaccurate 1RM predictions, were outlined as reasons for sub-optimal implementation and sources of frustration with VBT. Additionally, technologies employed were a variety of LPTs, IMUs, and camera systems. These findings were addressed in the subsequent studies.

Objective 3. To determine the most valid and reliable VBT technology commonly used by S&C coaches (ARMSS stage 2).

In study three, the reliability and validity of VBT technologies was addressed. Gymaware (LPT), PUSH (IMU), Beast Sensor (IMU), Bar Sensei (IMU), and MyLift (smart device application) were compared against 3D motion capture (criterion) with Gymaware demonstrating the highest reliability and validity for both mean and peak velocity. This information provides clear guidance for coaches as to the most appropriate technology to use from a statistical perspective.

Objective 4. To determine between-participant variability, within-participant reliability, and the most appropriate statistical model for LVP data when performed in free-weight, lower body exercises (ARMSS stage 3).

This objective was achieved through study four, using regression to analyse the relationship between load and velocity in the free-weight back squat and power clean. Individualised LVPs yielded stronger load-velocity relationships than pooled LVPs for mean velocity (r = 0.98-0.99 vs. 0.96) and peak velocity (r = 0.96-0.99 vs. 0.83) in the back squat. Second-order polynomial regression demonstrated a slightly stronger load-velocity relationship and smaller SEEs than first-order polynomial regression, despite no significant differences.

Additionally, large between-participant variability (> 10%) was evident for loads > 60% 1RM and 30% 1RM when measuring mean and peak velocity, respectively, in the back squat. Acceptable within-participant reliability was observed at loads $\leq$ 90% 1RM and $\leq$ 85% 1RM for mean and peak velocity, respectively. Smaller LOAs were also evident in mean velocity compared to peak velocity in the back squat exercise.

Objective 5. To compare the mechanical differences between lower-body, free-weight ballistic and non-ballistic exercise when calculated across mean concentric and propulsive metrics (ARMSS stage 5).

This objective was achieved through a biomechanical analysis of the back squat vs. jump squat exercises. The main findings were that ballistic exercise produced higher kinetic and kinematic output across all variables compared with its non-ballistic equivalent. Despite removing the period of negative acceleration (deceleration sub-phase) at the end of the non-ballistic concentric phase (i.e., just considering the propulsion phases of both exercises), these findings were consistent, suggesting that ballistic exercise will provide a better reflection of an individual's maximum mechanical capabilities compared to non-ballistic exercise when performing light-to-moderate loads.

Objective 6. To identify a novel method of 1RM prediction utilising LVPs to address procedural, statistical, and logistical issues identified in the previous studies and the current literature base (ARMSS stage 6).

The final objective was achieved through study six, an acute efficacy trial investigating a novel method for predicting 1RM from load-velocity data. By combining the findings of the previous studies in this PhD, a quick, efficient, and valid method for sessional maximum strength estimation was ascertained. This method combined ballistic and non-ballistic exercise to maximise load-velocity characteristics, employed a lighter load for the point of prediction (80% 1RM) via interpolation, applied a second-order polynomial (quadratic) predictive model, and utilised a four-load protocol to maximise efficiency. This approach produced more accurate 1RM predictions when compared with the more common method that combines non-ballistic exercise with linear regression.

9.2 General discussion

9.2.1 The planning process

The physical preparation of athletes leading to sporting success is largely influenced by effective periodisation and programming (Cunanan et al., 2018), with which strength plays an important role. The multi-factorial nature of sport can affect an individual's readiness to train and compete, with daily fluctuations in strength potentially caused by fatigue, stress, or adaptation (Bartholomew et al., 2008; Moore & Fry, 2007), often requiring coaches to combine strategies to account for the interaction between fitness and fatigue (Chiu & Barnes, 2003; Greig et al., 2020; Shattock & Tee, 2020). With many options available to optimise both long- and short-term planning and programming, it is important that practitioners follow a systematic process to identify the most effective combination of protocols and ensure efficacy within the training environment (figure 34).

During the initial stages of planning, coaches must identify suitable long-term programming strategies to create a training blueprint for athletes (A3, figure 34). Alongside an appropriate periodisation method (e.g., block), coaches must also determine an effective means of prescribing load across training blocks. With two typically available, (% 1RM and RM targets), coaches need a system able to optimise strength adaptations whilst containing prolonged exposure to failure. Study one and previous literature have highlighted the superiority of % 1RM over RM targets for increasing maximum strength (1RM) (Carroll, Bernards, et al., 2019; Suchomel et al., 2021) and it is therefore suggested that practitioners utilise % 1RM when prescribing load.

The multi-faceted nature of most sports often results in non-flexible programming strategies (% 1RM) being sub-optimal when implemented alone. Coaches would therefore benefit from combining % 1RM with a flexible programming strategy (A1-A2, figure 34) to optimise adaptations and account for acute fluctuations in strength, fatigue, and readiness to train (Scott et al., 2016; Suchomel et al., 2021; Weakley, Mann, et al., 2020). Objective methods such as VBT utilise technology that allows coaches to collect quantitative data (e.g., velocity, force, acceleration) that could be used to optimise training prescriptions more effectively than subjective assessments of effort (e.g., RIR or FNLP), potentially eliciting greater strength improvements (Shattock & Tee, 2020). Consequently, S&C coaches should look to combine VBT with periodised % 1RM to maximise strength adaptations and create a long-term programming system that is both well-planned and flexible in nature.

9.2.2 Implementing velocity-based training

9.2.2.1 Generalised vs. individualised zones

VBT is an adaptable tool with a range of applications, from simple in-session feedback and generalised zones to individualised LVP-based autoregulation (study two) (table 6; figure 11; B2, C2, C3, figure 34). Whilst generalised zones are quick and easy to implement, practitioners must consider the individualised nature of load-velocity characteristics (Banyard et al., 2018; Dorrell, Moore, et al., 2020; García-Ramos, Barboza-González, et al., 2019; García-Ramos, Haff, Pestaña-Melero, et al., 2018; Janicijevic et al., 2021). Large between-participant variability and stronger load-velocity relationships when administering individualised vs. pooled LVPs were observed in the free-weight back squat and power clean during study four (figure 24, table 16), potentially due to nuanced differences between individuals with regards to mechanical and neuromuscular characteristics. When thinking about this practically, variability in velocity data could impact the effectiveness of load prescription. For example, 0.5 $m.s^{-1}$ could equate to 80% for one athlete, but 90-95% for another, eliciting very different physiological responses and levels of fatigue. This could be even more pertinent when working in team settings and developing squad- or position-based programmes. Coaches, therefore, should individualise the implementation of VBT where possible to minimise prescriptive error.

Despite the stronger correlations observed in individualised back squat and power clean LVPs, the strength of the pooled profiles (study four) highlights the possibility of implementing group-based data in time-restricted training environments and have previously been shown to elicit greater strength improvements than using non-flexible programming methods alone (% 1RM) (Dorrell, Smith, et al., 2020). Furthermore, coaches from study two indicated that whilst individualised methods such as LVPs are an important part of the velocity-based autoregulation process, generalised zones and normative data were often used where necessary, particularly with big squads. This, coupled with data from Dorrell, Smith, et al. (2020), indicates that any form of velocity-based autoregulation is likely to be more effective than non-flexible programming alone, and coaches should try to develop protocols suited to the nuances of their training environment.

9.2.2.2 Technological considerations within the training environment

VBT is underpinned by technology and the devices practitioners use are crucial to ensure the performance data collected is reliable and valid (B2, figure 34). Reliable data will create confidence in the evaluations made by coaches, ensuring that progress throughout a programme or physical improvements are due to real changes as opposed to error in the measured value. Criterion validity will inform the coach as to whether the data is reflective of performance, for example, how close is the barbell velocity recorded from a device to its actual velocity. Study two identified several devices typically used within practice, including

LPTs (Gymaware or Tendo), IMUs (PUSH), and camera systems (Eliteform), with study three investigating the between-day reliability and criterion validity against 3D motion capture (gold standard). In line with previous literature (Askow et al., 2018; Banyard, Nosaka, Sato, et al., 2017; Dorrell et al., 2019; Weakley et al., 2021), Gymaware LPT was the most reliable and valid device when performing free-weight back squat and power clean exercises and as a result, should be employed where feasible by practitioners.

The reliability and validity (data quality) of technology is deemed integral within the literature, however, the importance of this to practitioners isn't always as obvious. Many coaches identified alternative drivers for buying velocity-based technology during study two. Whilst data quality was considered important, functionality (e.g., usability, portability, or being wireless), end-user interface (e.g., type of feedback or visually pleasing), and available budget were highly influential, supporting previous literature (S. Robertson et al., 2017). Coaches should therefore try to strike a balance between data quality, affordability, and functionality when selecting velocity-based technology.

9.2.2.3 Optimising velocity-based training for the S&C practitioner

There are several considerations for S&C practitioners when optimising VBT within the performance environment. When following the process outlined in figure 34, coaches must decide on the most appropriate velocity metric to use. Typically, coaches measure mean velocity during more strength-based exercises (e.g., back squat, bench press) and peak velocity during more explosive-based exercises (e.g., Olympic lifts or loaded jumps) (study two). Within studies three and four, however, mean velocity was more reliable and valid than peak velocity in the back squat, and comparable to peak velocity in the power clean, suggesting its appropriateness for both strength-based and explosive-based movements

(García-Ramos, Pestaña-Melero, Pérez-Castilla, et al., 2018; Pérez-Castilla, Jiménez-Reyes, et al., 2021). Whilst peak velocity has strong correlations with key force-time events such as take-off velocity (González-Badillo & Marques, 2010; Jiménez-Reyes et al., 2016), the instantaneous nature of peak velocity could create greater error in the data through small perturbations of barbell displacement or acceleration during non-ballistic exercises. To ensure data is comparable across exercises, fully reflective of an individual's neuromuscular capabilities, and is as reliable and valid as possible, it is recommended that mean velocity is used when employing VBT-based practices.

As previously mentioned, velocity-based technology is versatile, permitting immediate velocity feedback during any stage of a training session (B2, figure 34) (Hirsch & Frost, 2021; Mann et al., 2015; Pérez-Castilla, Jiménez-Alonso, et al., 2020; Weakley, Wilson, et al., 2020). Coaches, however, identified technological issues, being consumed by VBT data, and "iPad coaching" as drawbacks to implementing in-session VBT (study two). Coaches appreciated the potential of an objective tool such as VBT but were apprehensive over its implementation due to fears of poor connectivity, device malfunction, extensive troubleshooting, and being consumed by data during the session. Expert S&C coaching requires effective communicative and observational skills, ensuring an athlete-centred approach which helps to maintain control of the room, guarantees personal engagement, builds trust, creates buy-in, and motivates athletes beyond expectation (Foulds et al., 2019; LaPlaca & Schempp, 2020; Massey et al., 2002; Szedlak et al., 2015; Tod et al., 2012). These coaching qualities are likely difficult to implement if distracted by technology and data throughout the entirety of a session and therefore, it is recommended that any immersive VBT approaches such as autoregulation or profiling occur at the start of a session.

9.2.3 Implementing load-velocity profiling

9.2.3.1 Optimising load-velocity profiling for autoregulation

An underpinning application of VBT is load-velocity profiling (C2, figure 34) and was frequently described as a useful tool for testing and monitoring athletes (study two). In fact, VBT is governed by the inverse interaction between load and velocity, with which LVPs provide a practical representation of this relationship and are identified as an integral part of the load autoregulation process (study two) (Balsalobre-Fernández & Torres-Ronda, 2021; Weakley, Mann, et al., 2020). Study four highlighted the strong and reliable relationship between load and velocity, confirming the appropriateness of such a protocol for testing and monitoring purposes. Nevertheless, the configuration of LVPs can depend on environment, with exercises (e.g., bench press, deadlift, back squat), load (% 1RM vs. kg vs. $kg.bm^{-1}$), number of data points (two-point vs. multi-point), and statistical model (linear vs. quadratic) all being manipulated to administer the most suitable protocol to assess athlete load-velocity characteristics (study two) (Bazuelo-Ruiz et al., 2015; García-Ramos, Pestana-Melero, Pérez-Castilla, et al., 2018; Janicijevic et al., 2021; Sayers et al., 2018). Quadrant C2 (figure 34) outlines the nuanced interactions between characteristics of LVPs and must be carefully considered by S&C coaches to optimise profiling.

There is a paucity of literature investigating the efficacy of LVP-based autoregulation, with two options readily available to coaches (figure 13; C2, figure 34). Most peer-reviewed literature employs standardised fluctuations in load (e.g., $\pm$ 5% 1RM) based on changes in velocity (e.g., 0.06 $m.s^{-1}$) (Banyard et al., 2020; Orange, Metcalfe, Robinson, et al., 2020; Shattock & Tee, 2020). Whilst this method seems effective, it again leaves load manipulation open to between-participant variability and sub-optimal prescriptions based on inappropriate physiological stimuli. It is therefore recommended that 1RM prediction be implemented where possible to fully individualise and optimise the prescriptive process as well as ensure longitudinal consistency in the determination of working loads (kg). Interestingly, only two studies to date have investigated the efficacy of LVP-based 1RM prediction strategies within a training intervention (Dorrell, Moore, et al., 2020; Dorrell, Smith, et al., 2020). As articulated by coaches in study two, the scarcity of literature supporting this method could be a result of the time-costly protocols attributed to load-velocity profiling and inaccurate 1RM predictions in free-weight, lower-body exercises (Banyard, Nosaka, & Haff, 2017; Lake et al., 2017; Ruf et al., 2018).

9.2.3.2 The interaction between exercise type and statistical model

When implementing 1RM predictions, coaches must ensure that LVP protocols are configured to optimise the accuracy of the estimations derived from the predictive equations (C2, figure 34). Poor within-participant reliability observed in loads > 85% 1RM in study four (figure 27) and previous literature (Banyard et al., 2018; Orange, Metcalfe, Marshall, et al., 2020; Ruf et al., 2018) could impact the accuracy of 1RM prediction equations if utilising the V_{1RM} as the point of extrapolation, creating error in the model and over- or under-estimating 1RM. This estimation error could cause the physical stress to exceed athlete capacity, risking overreaching or injury (1RM over-estimation); or provide sub-optimal stimuli, diminishing strength adaptations (1RM under-estimation). Consequently, practitioners could identify a load with which velocity is reliable (e.g., 80% 1RM) and use as the point of extrapolation to ensure LVP-based predictions are repeatable, minimise error in load autoregulation, and regularly optimise load prescription (study six).

Once LVP data has been collected, coaches must then determine the most appropriate statistical model to apply to optimise predictions (C2, figure 34). Model determination could be dictated by the exercise being performed e.g., lower vs. upper-body during profiling. Typically, LVPs are analysed using linear regression, assuming that the load-velocity relationship is truly linear. Study four, however, observed comparable correlations when applying both first- and second-order polynomials (table 16), supporting earlier work by Banyard et al. (2018). When performing upper body exercises, coaches could apply linear models and obtain accurate estimations of 1RM (García-Ramos, Barboza-González, et al., 2019; García-Ramos, Haff, Pestaña-Melero, et al., 2018; Janicijevic et al., 2021). When performing free-weight, lower-body exercises, however, coaches must be conscious of the poor systematic biases, SEEs, CVs, TEEs, and MSDs evident when modelling LVP data with linear regression (Banyard, Nosaka, & Haff, 2017; Lake et al., 2017; Ruf et al., 2018), error that is reduced when applying quadratic modelling (Lopes et al., 2022). This preliminary lower-body LVP prediction data suggests that quadratic modelling might be the superior option when performing key exercises such as the back squat or deadlift. S&C practitioners, therefore, need to better understand the relationship between key exercises and statistical models to ensure the most valid combination is employed (study six).

The potential that the load-velocity relationship in free-weight, lower body exercises is curvilinear has further implications for practitioners wanting to implement the more time-efficient, logistically-friendly two-point method. Despite demonstrating promising predictive validity and reliability in upper-body exercises (García-Ramos, Barboza-González, et al., 2019; García-Ramos, Haff, Pestaña-Melero, et al., 2018; Garcia-Ramos & Jaric, 2018; Jaric, 2016), the two-point method has only been used to predict force-velocity parameters in lower-body exercise (loaded SJ and CMJ), with large CV ranges being observed (García-Ramos, Pérez-

Castilla, et al., 2021). Time-costly protocols were described as a major barrier to implementing LVP-based autoregulation in study two, however, if linear regression is an inappropriate model to use for 1RM prediction for lower-body exercises, the two-point method would not be feasible for coaches to implement, and an alternative approach would therefore be required (study six).

9.2.3.3 Implementing ballistic exercise into the load-velocity profile

LVPs are typically performed in non-ballistic exercises (e.g., back squat, bench press) and often begin with loads as light as 20% 1RM (Balsalobre-Fernández & Torres-Ronda, 2021; Weakley, Mann, et al., 2020). Whilst its possible for a coach to use velocity feedback to maximise intent and effort and improve reliability across all loads (Hirsch & Frost, 2021; Weakley, Till, et al., 2019; Weakley, Wilson, et al., 2020), performing lighter loads maximally can be technically challenging due to the period of negative acceleration at the end of the concentric phase which is required to slow down the CoM and prevent projection in to the air (Frost et al., 2008, 2010; Lake et al., 2012; Newton et al., 1996). Lighter loads during other incremental test such as 1RMs are usually performed sub-maximally, however, LVPs require maximal velocity across all reps and loads to ensure reliable data. Interestingly, some coaches combine ballistic and non-ballistic exercise when profiling, administering jumps or throws during lighter loads (e.g., < 60% 1RM) to address this issue (study two). Moreover, this is more representative of practice given 'power training' or explosive, ballistic training is typically performed using loads ≤ 60% 1RM (Cormie et al., 2010; Cormie, McCaulley, et al., 2007; Harris et al., 2008; McBride et al., 2005). The combined method could improve the efficacy and practical representativeness of LVPs ensuring that protocols relate more closely to training practices, and coaches should therefore decide whether including ballistic exercise into a profile is required (C2, figure 34).

Coaches must strive to understand the kinetic and kinematic demands of exercises to ensure appropriate training responses are facilitated and effective testing protocols implemented. Identifying the kinetic and kinematic differences between non-ballistic (back squat) and ballistic (jump squat) exercise could aid practitioners in their decisions to use the combined method (study six) or to simply utilise mean propulsive velocity during non-ballistic protocols were the differences dampened with the removal of the deceleration sub-phase (Frost et al., 2008; Lake et al., 2012). Superior kinetic and kinematic outputs were observed when performing the jump squat vs. the back squat across all loads (0%, 30-60% 1RM), irrespective of the removal of the deceleration sub-phase, likely due to the propulsion sub-phase occurring over a larger range of motion and longer duration, facilitating more work done during the jump squat. These longer periods of acceleration, therefore, result in a greater mechanical output (e.g., force, velocity, work, power, impulse) (Turner et al., 2020) and provide athletes with a better training stimulus and coaches a better reflection of their athletes capabilities. This more valid representation of an individual's mechanical output supports the ideas of coaches (study two) for the inclusion of ballistic exercise in LVPs to ensure a truer reflection of an individual's load-velocity capabilities are represented.

9.2.4 A new approach to LVP-based 1RM prediction

The coaching process (figure 34) outlines a systematic approach to designing an effective programming strategy that will optimise loading through LVPs. Importantly, however, a coach must be confident that the decisions they make, and the method of autoregulation they choose, will result in performance improvements. Study six intended to address this process in the free-weight back squat, an integral training exercise utilised across most programmes, with several unique features evident in developing a novel, valid, and time efficient protocol for predicting 1RM: 1) investigating the validity of predicting 1RM from four submaximal loads for utilisation at the beginning of a training session; 2) utilising a submaximal (80% 1RM) point of prediction – or more specifically, point of interpolation – to then extrapolate to 1RM; 3) combining ballistic and non-ballistic exercise to improve predictive validity in a free-weight, lower-body exercise; 4) comparing quadratic predictive models against the more common linear modelling; 5) utilising multiple sessions to determine repeatability of the model.

The data presented from study six advocates the combination of ballistic and non-ballistic exercise with quadratic modelling to provide valid predictions of 1RM. When compared to linear modelling using the combined method, more accurate estimations of maximum strength were evident, with smaller systematic bias, random error, SEEs, and MSDs (table 21). This indicates that perhaps lower-body velocity data is curvilinear, and that quadratic modelling is the more appropriate statistical model for coaches to use when estimating 1RM. Importantly, similar systematic bias was evident for all models when comparing 4-point vs 7-point protocols (figure 33, table 21). These findings, therefore, suggests that 1RM can be accurately predicted from as few as four loads when using a combined method with quadratic modelling. From a practical perspective, it is possible that coaches could implement such a method during the preparatory stages of a training session, potentially including as part of the athlete warm-up, to autoregulate and manipulate sessional loads quickly and easily in addition to freeing up in-session time for coaching.

Utilising a submaximal load for the point of prediction from LVP data can provide coaches with greater confidence in the validity of the predictive model due to the superior reliability presented at 80% 1RM vs. V_{1RM} in study four and reduce the requirement of administering traditional 1RM assessments, particularly during periods of competition. Whilst VBT should only be complimentary to traditional diagnostic and prescriptive methods, in sports with condensed fixtures and extensive travel requirements, conducting 1RM tests can be detrimental to training priorities, recovery, and neuromuscular capabilities. Therefore, estimating an individual's 80% 1RM as opposed to 100% 1RM could be an attractive option to practitioners in such scenarios.

S&C provision is a supportive mechanism designed to optimise training, mitigate fatigue, and improve physical performance during important competitive periods. With many tools and strategies available to S&C coaches, identifying the most effective ones can be challenging. Autoregulation is an important way of reducing residual fatigue whilst maximising physical output. By implementing velocity-based autoregulatory methods, coaches can maximise adaptation whilst minimising fatigue through reductions in volume, time under tension, and sessional RPE (Banyard et al., 2020; Dorrell, Smith, et al., 2020; Orange, Metcalfe, Robinson, et al., 2020). Utilising sessional LVP-based 1RM predictions from a quick and easy protocol in key training exercises such as the back squat can also help coaches to optimise competition preparation and reduce injury risk. Finally, it is imperative that coaches implement a systematic structure when designing their autoregulatory protocols, with figure 34 being an example of one when using LVPs to autoregulate load. Practitioners should utilise evidence-based data when making such decisions, but must also consider the practical and logistical factors of the training environments they coach in.

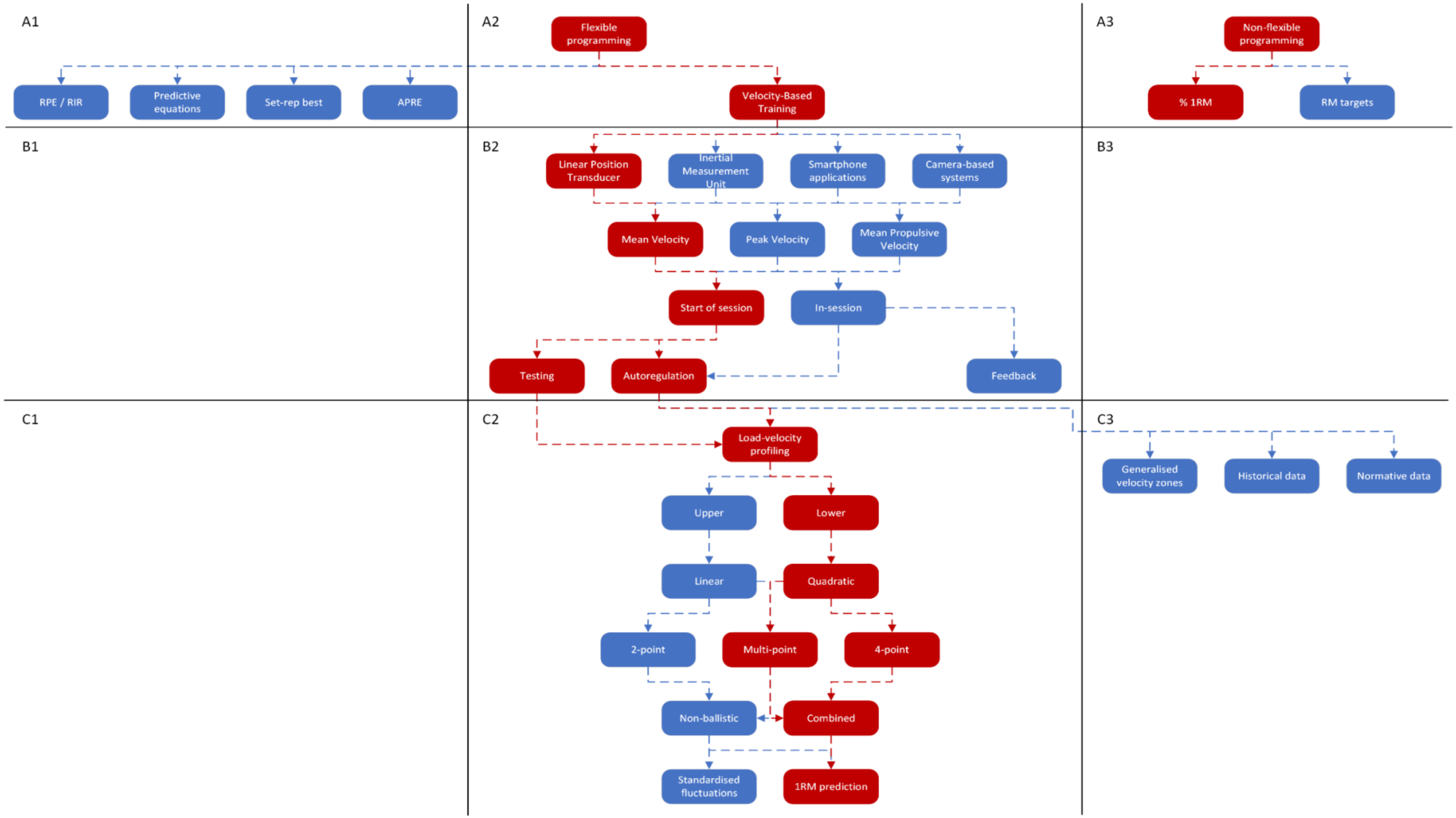

Figure 34. A schematic outlining the decision-making process for developing effective VBT practices. The red squares and arrows indicate the research developed during this PhD and how it impacts the process.

9.3 Strengths and limitations

The research presented in this thesis progresses the knowledge of autoregulation and 1RM prediction. More specifically, it advances current understanding regarding LVP-based protocols for lower-body, free-weight exercise. This PhD adopted a systematic (ARMSS) and pragmatic approach, utilising several different research designs and skills to address the clearly defined research aims and objectives, and present an applied thesis designed to aid coaches and practitioners with programming decisions and flexible prescriptions.

This thesis, however, is not without limitations. Autoregulation is an applied method of manipulating load to optimise prescriptions, accelerate physiological adaptations, and reduce residual fatigue. Whilst the data presented here provides exciting preliminary analysis of the efficacy of a novel LVP-based 1RM prediction model, the effectiveness of this model has not been assessed as part of a training programme. The ARMSS model suggests that once the efficacy of an approach has been determined acutely as outlined in this thesis, it's suitability within a training programme must then be investigated and has been identified as avenues for future research. Moreover, an original objective of this PhD was to evaluate the use of LVPs to manipulate load during a training intervention, however, the impact of a two-year global pandemic meant the aims of the thesis had to shift to meet the restrictions placed upon the world at the time. Nevertheless, this PhD provides a contemporary and practitioner-centred programme of research that contributes to the ever-evolving body of knowledge.

Study 1

Study one provided an important overview of the literature investigating load prescription within S&C but revealed a distinct lack of research evaluating flexible programming methods such as VBT or RIR. As such, only traditional methods (% 1RM and RM targets) met the inclusion criteria at the time of conducting the systematic searches. This study, however, was conducted back in 2017/18, prior to the acceleration of VBT-based literature (e.g., Banyard et al., 2020; Dorrell, Moore, et al., 2020; Dorrell, Smith, et al., 2020; Jiménez-Reyes et al., 2021; Orange, Metcalfe, Robinson, et al., 2020). An updated version of this research, therefore, could provide novel and important insights into the landscape of current prescriptive practices.

The systematic review strictly adhered to the PRISMA guidelines. Nevertheless, the original aim of the study was to be inclusive as possible but maintain academic rigour and robustness. Whilst a meta-analysis might have been more statistically impactful, this was not possible due to the limited data and the range of methods and outcome measures employed across the literature, potentially limiting the interpretation and comparison between the two prescriptive methods. A systematic review was appropriate for the purposes of this PhD, however, as it allowed for an inclusive research design that provided a clear overview of the load prescriptive landscape.

Study 2

This thematic analysis is the first of its kind to better understand the applications, experiences, and opinions of expert coaches with regards to VBT. By using an inductive paradigm, it ensured the data being presented was synthesised in a clear and objective manner. This approach, however, restricted any deeper interpretation and links to current ontological and epistemological viewpoints to identify hidden thoughts, feeling, and opinions. For example, the way in which questions were answered, body language, and tone of voice were not considered. The data provided, however, was descriptive in nature and reflective of participants opinions and experiences, with the aims of the study to evaluate current practice, and thus, deeper reflection into the meanings of answers was not required.

Studies 3 and 4

The participants recruited for these studies required a minimum level of weightlifting experience and competence (must have competed at a minimum of regional level within the 12 months prior to data collection) to ensure the data collected for the power clean was not impacted by technical inability. As a result, sample size was limited to 10 participants. A small sample size, irrespective of three repeat sessions, restricted some of the analyses possible. For example, whilst LOAs were produced for full profiles, identifying systematic bias and random error at each incremental load was not possible due to the small sample size. The participants recruited, however, were competent weightlifters coached by qualified weightlifting coaches and therefore possessed sufficient technical precision and experience to reliably execute the lifts. Moreover, this study was the first of its kind to recruit competitive lifters and investigate LVPs in weightlifting derivatives and therefore sample quantity was sacrificed for sample quality.

As mentioned, these two studies were the first of their kind to investigate load-velocity profiling in a common weightlifting derivative, the power clean. Despite this novel element, the challenges with recruitment and the limited literature investigating free-weight, lower-body exercise meant that the subsequent studies within the thesis only employed the back squat. With LVPs being exercise specific, this prevents generalisation out to other key exercises within a training programme, however, does provide a more generalised understanding of load-velocity characteristics. Nevertheless, the back squat is a fundamental method for developing lower-body strength and therefore warranted such investigations.

Additionally, future research could look to follow a similar series of studies to this doctoral programme when employing weightlifting exercises such as the power clean.

Study 5

The loads assessed during the penultimate study were determined from previous literature investigating optimal loading or maximal mechanical outputs in non-ballistic and ballistic lower-body exercise (Cormie, Mccaulley, et al., 2007; Mundy et al., 2017). The decision to stop the comparison at 60% 1RM was also reflective of the loads that participants would be tasked with jumping with, which for some could have been upwards of 150 kg. Whilst this decision was a justifiable one – based on earlier evidence and the mitigation of injury risk – it did restrict the comparison at heavier loads. Research has suggested that the deceleration sub-phase can impact loads as heavy as 95% 1RM (Martínez-Cava, Morán-Navarro, Hernández-Belmonte, et al., 2019) and therefore, to compare the two exercises in heavier loads could have provided insightful information for coaches to utilise when designing LVP protocols.

Study 6

The final study, which combined the findings of all preceding studies, provided an acute evaluation of the efficacy of predicting 1RM from the newly proposed model. Whilst this is one of the only studies in this area to test the predictive validity against separate LVP data from a second testing session, it does not reflect the accuracy of utilising it over a longer period. Extensive research has investigated the impact neuromuscular fatigue has on different physical characteristics such as strength, force, and velocity (C. A. Moore & Fry, 2007; Morán-Navarro et al., 2017; Weakley, Ramirez-Lopez, et al., 2020), but the sensitivity of this predictive model has not been evaluated longitudinally and would provide important information as to the appropriateness of using this approach throughout full training cycles.

1RM prediction permits the daily autoregulation within the initial stages of a training session or during the warm-up. Conversely, it cannot account for any fluctuations in strength or physiological status that might occur within session (J. M. Moore & Dorrell, 2020). This additional level of autoregulation to ensure within-session fatigue is accounted for throughout a session could be of interest to coaches. It is feasible that the proposed method could be successful in adjusting load by updating the profile, equation, and model with just one load (e.g., 80% 1RM), however this has not been investigated. Furthermore, the omission of loads > 80% 1RM from the model could limit in-session manipulation for heavier loads (e.g., 90% 1RM). Further research is therefore required to investigate these suggestions.

9.4 Future research and practice

The data presented within this thesis provides a significant and novel contribution to the existing literature surrounding VBT, load-velocity profiling, and 1RM prediction. It also provides avenues for future research. The efficacy of the novel LVP-based 1RM prediction model has been verified on an acute level (across two sessions) but requires further investigation across the course of an intervention to better understand its appropriateness within a training environment. In addition, understanding the physiological adaptations associated with the utilisation of autoregulatory methods such as these would provide practitioners with clear mechanistic underpinning to focus their programming on. This would contribute to the ARMSS model through stage six, intervention studies (efficacy trials).

In addition to exploring the efficacy of the 1RM prediction model within an intervention-based research design, understanding the barriers to administering such a model and then investigating its effectiveness within an applied setting (case study research) is required to complete the final two stages of the ARMSS model (Bishop, 2008). Stage seven should be applied by revisiting qualitative research as conducted in study two but should be done so by presenting the 1RM prediction model for coaches to identify potential barriers to implementation. Stage eight would then implement this model within an applied sport setting to see if the robustness can withstand the multi-faceted and sometimes chaotic environment of applied sport (Bishop, 2008). S&C training studies typically take place across 4-12 weeks (Banyard et al., 2020; Dorrell, Smith, et al., 2020; Orange, Metcalfe, Robinson, et al., 2020), providing a relatively small snapshot as to the effectiveness of different approaches. To fully analyse effectiveness, season-long, longitudinal research designs could be implemented.

The structure of this PhD and ARMSS model could be utilised to investigate the efficacy of LVP-based 1RM prediction models across other important, free-weight exercises such as bench press, deadlift, or weightlifting variations. Moreover, the application of VBT within weightlifting-based training methods is vastly under-researched. The underpinning requirement to accelerate the bar during these derivatives indicates the potential appropriateness of utilising VBT for autoregulation and feedback purposes. LVPs are exercise-specific, and therefore, require individual analyses to understand the validity of the model to predict 1RM. The outcomes of this PhD, however, provides an important foundation from which further research in this area can be scaffolded from.

One of the main applications and benefits of VBT that emerged from study two was providing athletes with live feedback to drive intent, motivation, and competition. This is a relatively under-researched area, with only a few studies specifically utilising velocity-based technology or protocols to provide audible or visual feedback (Hirsch & Frost, 2021; Nagata et al., 2020;

Pérez-Castilla, Jiménez-Alonso, et al., 2020; Randell et al., 2011a; Weakley, Till, et al., 2019; Weakley, Wilson, et al., 2020). Future research should therefore explore the efficacy of such an approach, to identify the effects of utilising VBT for feedback on physiological adaptations, mechanical outputs and psychophysical elements such as motivation.

An important assumption of load-velocity profiling is the stability of velocity at specific % 1RM, irrespective of changes in strength. Research suggests that even with a significant increase in 1RM, the velocities at submaximal and maximal loads remain the same (Banyard et al., 2020; Davies et al., 2020; González-Badillo & Sánchez-Medina, 2010; Hernández-Belmonte et al., 2020; Pérez-Castilla & García-Ramos, 2020). Whilst this data is promising, this has only been explored pre-post intervention, and therefore requires investigation over a longer period. By understanding this, practitioners could be more confident in implementing such approaches as the one proposed in this thesis.

In addition to research, the information from this thesis provides future avenues for practice. Study two highlighted fears and apprehension with regards to implementing some of the more complex VBT strategies. Whilst time is often at a premium within professional sport, coach education through workshops, webinars, and conference presentations could provide practitioners with simple strategies for maximising VBT within their environments and improve their confidence in doing so.

Time-consuming protocols were big deterrents to implementing LVPs for coaches. Time-efficient methods such as the two-point or the new four-point from this thesis could save time for practitioners, making implementation more feasible. Practically, however, this still does take time. The idea of using the models presented within this research but adapting to accurately predict 1RM from a single load could be effective for practitioners, making maximum load estimation and autoregulation even more streamlined. This would, however, require preliminary research to test this hypothesis.

VBT is emerging as a progressive application within S&C, with new ideas and approaches frequently being developed. In addition, accessibility to new and creative technologies is becoming more possible. The versatility, attractive price tag, and ease of use should encourage coaches to experiment with VBT, identify where it can complement their current practices and add value to their programmes. Coaches should work along the VBT continuum (figure 7) to determine the most effective strategies for their athletes. Finally, coaches should develop a system such as the one in figure 34 to best inform their decision-making processes.

9.5 Summary and conclusions

Load-velocity profiling is an effective method for predicting an individual's maximum strength, permitting the autoregulation of load (study six) and should complement more traditional prescriptive methods (e.g., % 1RM). In practice, however, LVPs can prove time costly, stagnate sessional flow, and negatively impact subsequent prescriptions through inaccurate estimations (study two). Additionally, VBT can often distract coaches through technological troubleshooting, data saturation, and "iPad coaching" (study two). If adopting velocity-based strategies, practitioners should utilise the Gymaware LPT where possible, however must, as a minimum, understand the limitations of any device integrated into their practices (study three). Profiling athletes in the free-weight back squat is a valid and reliable performance diagnostic, however, should be limited to submaximal loads, mean velocity, and second-order polynomials where possible ($\leq$ 90% 1RM) (studies four and six). Additionally, to maximise mechanical output and predictive validity, lighter loads ($\leq$ 60% 1RM) should be administered using ballistic exercise (studies five and six). Combining ballistic and non-ballistic exercise, submaximal load prediction followed by extrapolation, quadratic modelling of LVP data, and limiting to only four loads (data points), practitioners are presented with a valid, reliable, time efficient autoregulatory strategy that can be utilised during the initial stages of a session to maintain presence and attention during coaching. Importantly, predicting 1RM on a sessional or weekly basis can help to regulate residual fatigue, optimise loading strategies, maximise adaptations, and ensure more effective performance and competitive preparation.

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Chapter 11.0: Appendices

11.1 Appendix A

Supplementary materials from Review

Modified Downs and Black methodological assessment checklist

Reporting		Score
1.	Is the hypothesis/aim/objective of the study clearly described?	0 – 1
2.	Are the main outcomes to be measured clearly described in the Introduction or Methods section?	0 – 1
3.	Are the characteristics of the participants included in the study clearly described?	0 – 1
4.	Are the interventions of interest clearly described?	0 – 1
5.	Are the distributions of principal confounders in each group of participants to be compared clearly described?	0 – 1
6.	Are the main findings of the study clearly described?	0 – 1
7.	Does the study provide estimates of the random variability in the data for the main outcomes?	0 – 1
8.	Have all important adverse events that may be a consequence of the intervention been reported?	0 – 1
9.	Have the characteristics of participants lost to follow-up been described?	0 – 1
10.	Have actual probability values been reported (e.g. 0.035 rather than <0.05) for the main outcomes except where the probability value is less than 0.001?	0 – 1
External validity		
11.	Were the subjects asked to participate in the study representative of the entire population from which they were recruited?	0 – 1
12.	Were those subjects who were prepared to participate representative of the entire population from which they were recruited?	0 – 1
13.	Were the staff, places, and facilities where the participants were treated, representative of the treatment the majority of participants receive?	0 – 1
Internal validity - bias		
14.	Was an attempt made to blind study participants to the intervention they have received?	0 – 1
15.	Was an attempt made to blind those measuring the main outcomes of the intervention?	0 – 1
16.	If any of the results of the study were based on “data dredging”, was this made clear?	0 – 1
17.	In trials and cohort studies, do the analyses adjust for different lengths of follow-up of participants, or in case-control studies, is the time period between the intervention and outcome the same for cases and controls?	0 – 1
18.	Were the statistical tests used to assess the main outcomes appropriate?	0 – 1
19.	Was compliance with the intervention/s reliable?	0 – 1
20.	Were the main outcome measures used accurate (valid and reliable)?	0 – 1
Internal validity – confounding (selection bias)		
21.	Were the participants in different intervention groups (trials and cohort studies) or were the cases and controls (case-control studies) recruited from the same population?	0 – 1
22.	Were study participants in different intervention groups (trials and cohort studies) or were the cases and controls (case-control studies) recruited over the same period of time?	0 – 1

23.	Were study participants randomised to intervention groups?	0 – 1
24.	Was the randomised intervention assignment concealed from both participants and health care staff until recruitment was complete and irrevocable?	0 – 1
25.	Was there adequate adjustment for confounding in the analyses from which the main findings were drawn?	0 – 1
26.	Were losses of participants to follow-up taken into account?	0 – 1
27.	Did the study have sufficient power to detect a clinically important effect where the probability value for a difference being due to change is less than 5%?	0 – 1
28.	Were exercise sessions supervised?	0 – 1
29.	Was exercise adhered to?	0 – 1

11.2 Appendix B

Interview guide

<u>Interview guide</u>

Things to cover at the start of the interview:

- *Thanks very much for agreeing to do the interview*
- *It's being recorded – but speak openly, freely and honestly*
- *All data will be anonymised for publication and only the research team and those doing the transcripts will have access*
- *Let them know that I will try to as little talking as possible so if I'm quiet, it's because I'm listening and wanting to let you open up, I haven't disappeared.*
- *Asking about the general time in coaching, their opinions and use of technology, load prescription and velocity-based training*
- *If unsure of any questions, please let me know and I'll rephrase.*
- *Any questions?*

Introductions:
How long have you been involved in S&C and how did you first get in to coaching?
Qualifications (accreditations etc.)
Previous roles
Most interesting / defining role?
So, you've worked with several top, professional clubs / athletes, so with that in mind, how would you define 'elite'?
How would you describe your coaching philosophy?

Ok, so I now I'd like to focus more specifically on load prescription if that's ok?

Can you tell me about the methods you typically employ to prescribe load?
How has this evolved from when you first started coaching?
Do you feel there are any specific advantages / disadvantages to the methods you use?

Tell me about your use of technology within your programming and coaching?
So, would you say technology is important to you as a coach?

What technology do you typically use? For what and why?
Tell me about the thought process and deciding factors on choosing your technology
Probe into things such as reliability, validity, cost, usability
What do you feel are the advantages of using technology?
And disadvantages?

Use this point to transition in to VBT tech (if they haven't already mentioned it). If they have, ask specifically what they use, how often and how they made their decisions on the choice of VBT tech?

Tell me about how you utilise VBT into your coaching practice…

- Are there any specific methods you use and what does that look like?

- Why did you decide to implement VBT?
- Will you tell me how you decided on these methods? (probe into things such as research, social media, practitioners, tech companies etc.)
- What do you feel are the advantages of VBT?
- What do you feel are the disadvantages?
    - Try to get them to answer from a practical, programming and data usability perspective.
- Are there specific VBT approaches that you would like to implement but currently are not able to? Why is that?
    - What are some of the things that are preventing you? What are the barriers?

11.3 Appendix C

Braun and Clarke thematic analysis model (Braun & Clarke, 2006)

Phase	Description of the process
1. Familiarising yourself with the data	Transcribing data (if necessary), reading and re-reading the data, noting down initial ideas.
2. Generating initial codes	Coding interesting features of the data in a systematic fashion across the entire data set, collating data relevant to each code.
3. Searching for themes	Collating codes into potential themes, gathering all data relevant to each potential theme.
4. Reviewing themes	Checking if the themes work in relation to the coded extracts (Level 1) and the entire data set (Level 2), generating a thematic 'map' of the analysis.
5. Defining and naming themes	Ongoing analysis to refine the specifics of each theme, and the overall story the analysis tells, generating clear definitions and names for each theme.
6. Producing the report	The final opportunity for analysis. Selection of vivid, compelling extract examples, final analysis of selected extracts, relating back of the analysis to the research question and literature, producing a scholarly report of the analysis.

Tracey's eight "big tent" criteria (Tracy, 2010)

Criteria for quality (end goal)	Various means, practices, and methods through which to achieve
Worthy Topic	The topic of the research is: • Relevant • Timely • Significant • Interesting
Rich Rigor	The study uses sufficient, abundant, appropriate, and complex: • Theoretical constructs • Data and time in the field • Sample(s) • Context(s) • Data collection and analysis processes
Sincerity	The study is characterised by: • Self-reflexivity about subjective values, biases, and inclinations of the researcher(s) • Transparency about the methods and challenges
Credibility	The research is marked by: • Thick description, concrete detail, explication of tacit (non-textual) knowledge, and showing rather than telling • Triangulation or crystallization • Multivocality • Member reflections

Resonance	The research influences, affects, or moves particular readers or a variety of audiences through: • Aesthetic, evocative representation • Naturalistic generalizations • Transferable findings
Significant contribution	The research provides a significant contribution: • Conceptually/theoretically • Practically • Morally • Methodologically • Heuristically
Ethical	The research considers: • Procedural ethics (such as human subjects) • Situational and culturally specific ethics • Relational ethics • Exiting ethics (leaving the scene and sharing the research)
Meaningful coherence	The study: • Achieves what it purports to be about • Uses methods and procedures that fit its stated goals • Meaningfully interconnects literature, research questions/foci, findings, and interpretations with each other

11.4 Appendix D

Reliability data for kinetic and kinematic variables

Coefficient of Variation (95% Confidence Intervals) for all dependent variables

Exercise	Load (% 1RM)	Mean Concentric Force	Mean Propulsion Force	Mean Concentric Velocity	Mean Propulsion Velocity	Mean Concentric Power	Mean Propulsion Power	Mean Net Impulse
Back squat	0%	0.1 (0.1, 0.2)	3.0 (2.2, 4.6)	2.2 (1.6, 3.4)	3.1 (2.3, 4.9)	2.1 (1.6, 3.3)	2.7 (2.0, 4.2)	3.1 (2.3, 4.8)
	30%	0.1 (0.1, 0.2)	4.3 (3.1, 6.7)	1.9 (1.4, 2.9)	2.0 (1.5, 3.1)	1.8 (1.3, 2.8)	2.7 (2.0, 4.2)	2.0 (1.4, 3.1)
	40%	0.1 (0.1, 0.2)	3.2 (2.3, 4.9)	1.6 (1.1, 2.4)	2.2 (1.7, 3.5)	1.5 (1.1, 2.4)	2.4 (1.8, 3.7)	2.2 (1.7, 3.5)
	50%	0.1 (0.1, 0.2)	3.2 (2.4, 5.0)	2.6 (1.9, 4.0)	3.3 (2.4, 5.2)	2.6 (1.9, 4.0)	3.4 (2.5, 5.3)	3.2 (2.4, 5.0)
	60%	0.1 (0.0, 0.1)	3.9 (2.8, 6.2)	3.6 (2.6, 5.7)	3.3 (2.4, 6.7)	3.6 (2.6, 5.7)	4.3 (3.1, 7.2)	3.2 (2.3, 5.1)
Squat Jump	0%	0.2 (0.1, 0.3)	2.9 (2.1, 4.5)	2.3 (1.7, 3.6)	2.2 (1.6, 3.4)	2.2 (1.6, 3.5)	4.0 (2.9, 6.2)	2.0 (1.5, 3.1)
	30%	0.2 (0.1, 0.3)	2.3 (1.7, 3.5)	1.5 (1.1, 2.4)	1.1 (0.8, 1.7)	1.5 (1.1, 2.3)	1.8 (1.4, 2.9)	1.0 (0.8, 1.6)
	40%	0.1 (0.1, 0.2)	2.9 (2.1, 4.5)	1.8 (1.3, 2.8)	1.6 (1.2, 2.5)	2.7 (2.0, 4.2)	3.8 (2.8, 5.9)	1.1 (0.8, 1.6)
	50%	0.2 (0.1, 0.2)	3.6 (2.7, 5.6)	2.3 (1.7, 3.5)	2.2 (1.6, 3.4)	2.3 (1.7, 3.5)	3.0 (2.2, 4.6)	2.0 (1.5, 3.2)
	60%	0.1 (0.1, 0.2)	3.2 (2.4, 5.0)	3.5 (2.6, 5.4)	2.5 (1.8, 3.9)	3.4 (2.5, 5.3)	4.2 (3.1, 6.6)	2.1 (1.6, 3.3)

Exercise	Load (% 1RM)	Concentric Duration	Propulsion Duration	Concentric Displacement	Propulsion Displacement	Concentric Work	Propulsion Work
Back squat	0%	2.1 (1.6, 3.3)	4.3 (3.1, 6.7)	3.4 (2.5, 5.3)	1.9 (1.4, 2.9)	3.4 (2.5, 5.3)	5.0 (3.7, 7.9)
	30%	1.6 (1.2, 2.5)	3.4 (2.5, 5.3)	2.1 (1.5, 3.3)	2.6 (1.9, 4.1)	2.1 (1.5, 3.2)	2.5 (1.9, 4.0)
	40%	1.3 (1.0, 2.0)	2.3 (1.7, 3.5)	2.0 (1.5, 3.1)	1.8 (1.3, 2.8)	2.0 (1.5, 3.1)	2.4 (1.8, 3.7)
	50%	3.3 (2.4, 5.1)	3.9 (2.9, 6.2)	3.5 (2.6, 5.5)	3.8 (2.8, 6.0)	3.5 (2.6, 5.4)	3.8 (2.8, 6.0)
	60%	2.8 (2.0, 4.4)	3.6 (2.6, 5.7)	3.8 (2.7, 6.0)	3.8 (2.7, 7.8)	2.8 (2.1, 4.5)	3.2 (2.3, 5.2)
Squat Jump	0%	1.4 (1.0, 2.2)	2.8 (2.1, 4.4)	2.8 (2.1, 4.4)	2.4 (1.7, 3.7)	3.4 (2.0, 4.2)	5.0 (2.1, 4.4)
	30%	1.6 (1.2, 2.6)	2.3 (1.7, 3.5)	2.2 (1.6, 3.5)	1.5 (1.1, 2.3)	2.2 (1.6, 3.4)	2.2 (1.6, 3.4)
	40%	2.9 (2.1, 4.5)	4.1 (3.0, 6.4)	1.7 (1.3, 2.7)	2.1 (1.5, 3.2)	1.7 (1.3, 2.6)	1.7 (1.2, 2.6)
	50%	3.0 (2.2, 4.7)	3.7 (2.7, 5.8)	2.9 (2.1, 4.5)	3.0 (2.2, 4.6)	2.8 (2.1, 4.3)	2.9 (2.1, 4.5)
	60%	3.7 (2.7, 5.9)	4.6 (3.3, 7.3)	3.5 (2.5, 5.4)	3.2 (2.4, 5.1)	3.4 (2.5, 5.3)	3.3 (2.4, 5.1)

1RM 1 repetition maximum

Intraclass Correlation Coefficient (95% confidence intervals) for all dependent variables

Exercise	Load (% 1RM)	Mean Concentric Force	Mean Propulsion Force	Mean Concentric Velocity	Mean Propulsion Velocity	Mean Concentric Power	Mean Propulsion Power	Mean Net Impulse
Back squat	0%	1.00 (1.00, 1.00)	0.97 (0.93, 0.99)	0.93 (0.81, 0.97)	0.87 (0.68, 0.95)	0.97 (0.91, 0.99)	0.96 (0.89, 0.99)	0.94 (0.83, 0.98)
	30%	1.00 (1.00, 1.00)	0.95 (0.87, 0.98)	0.92 (0.78, 0.97)	0.94 (0.84, 0.98)	0.98 (0.95, 0.99)	0.96 (0.90, 0.99)	0.98 (0.94, 0.99)
	40%	1.00 (1.00, 1.00)	0.96 (0.88, 0.98)	0.92 (0.79, 0.97)	0.94 (0.83, 0.98)	0.98 (0.95, 0.99)	0.96 (0.88, 0.98)	0.97 (0.90, 0.99)
	50%	1.00 (1.00, 1.00)	0.93 (0.81, 0.97)	0.88 (0.68, 0.95)	0.87 (0.68, 0.95)	0.96 (0.89, 0.99)	0.94 (0.84, 0.98)	0.93 (0.81, 0.98)
	60%	1.00 (1.00, 1.00)	0.95 (0.86, 0.98)	0.83 (0.56, 0.94)	0.86 (0.64, 0.95)	0.94 (0.82, 0.98)	0.92 (0.78, 0.97)	0.94 (0.83, 0.98)
Squat Jump	0%	1.00 (1.00, 1.00)	0.97 (0.90, 0.99)	0.91 (0.77, 0.97)	0.94 (0.84, 0.98)	0.96 (0.90, 0.99)	0.93 (0.82, 0.98)	0.98 (0.93, 0.99)
	30%	1.00 (1.00, 1.00)	0.98 (0.94, 0.99)	0.93 (0.82, 0.98)	0.98 (0.94, 0.99)	0.99 (0.97, 1.00)	0.98 (0.96, 0.99)	0.99 (0.98, 1.00)
	40%	1.00 (1.00, 1.00)	0.97 (0.90, 0.99)	0.85 (0.63, 0.95)	0.95 (0.87, 0.98)	0.96 (0.88, 0.98)	0.93 (0.80, 0.97)	0.99 (0.98, 1.00)
	50%	1.00 (1.00, 1.00)	0.93 (0.82, 0.98)	0.85 (0.62, 0.95)	0.89 (0.71, 0.96)	0.97 (0.92, 0.99)	0.96 (0.88, 0.98)	0.97 (0.92, 0.99)
	60%	1.00 (1.00, 1.00)	0.93 (0.81, 0.97)	0.73 (0.38, 0.90)	0.86 (0.65, 0.95)	0.93 (0.82, 0.98)	0.91(0.75, 0.97)	0.97 (0.90, 0.99)

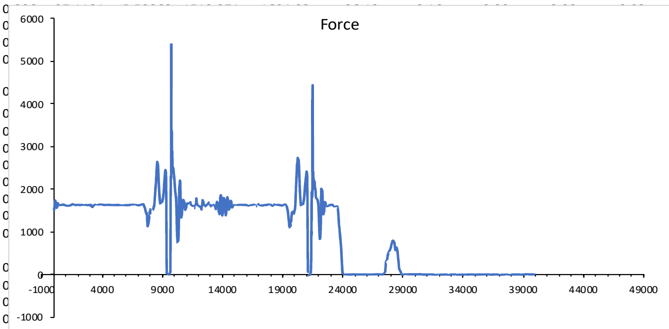
Exercise	Load (% 1RM)	Concentric Duration	Propulsion Duration	Concentric Displacement	Propulsion Displacement	Concentric Work	Propulsion Work
Back squat	0%	0.91 (0.77, 0.97)	0.92 (0.79, 0.97)	0.87 (0.66, 0.95)	0.96 (0.90, 0.99)	0.96 (0.88, 0.98)	0.92 (0.79, 0.97)
	30%	0.95 (0.87, 0.98)	0.94 (0.84, 0.98)	0.93 (0.81, 0.98)	0.92 (0.80, 0.97)	0.98 (0.95, 0.99)	0.98 (0.94, 0.99)
	40%	0.96 (0.90, 0.99)	0.96 (0.89, 0.99)	0.92 (0.79, 0.97)	0.97 (0.91, 0.99)	0.98 (0.95, 0.99)	0.98 (0.94, 0.99)
	50%	0.88 (0.69, 0.96)	0.90 (0.74, 0.96)	0.72 (0.37, 0.89)	0.81 (0.53, 0.93)	0.94 (0.84, 0.98)	0.94 (0.82, 0.98)
	60%	0.92 (0.78, 0.97)	0.92 (0.77, 0.97)	0.74 (0.39, 0.91)	0.87 (0.65, 0.95)	0.97 (0.90, 0.99)	0.96 (0.88, 0.99)
Squat Jump	0%	0.95 (0.86, 0.98)	0.95 (0.85, 0.98)	0.92 (0.80, 0.97)	0.95 (0.86, 0.98)	0.96 (0.90, 0.99)	0.92 (0.89, 0.99)
	30%	0.87 (0.67, 0.95)	0.88 (0.69, 0.96)	0.91 (0.76, 0.97)	0.98 (0.93, 0.99)	0.98 (0.95, 0.99)	0.98 (0.95, 0.99)
	40%	0.79 (0.50, 0.92)	0.75 (0.42, 0.91)	0.94 (0.84, 0.98)	0.95 (0.87, 0.98)	0.99 (0.97, 1.00)	0.99 (0.97, 1.00)
	50%	0.80 (0.52, 0.93)	0.80 (0.51, 0.92)	0.84 (0.60, 0.94)	0.91 (0.75, 0.97)	0.97 (0.90, 0.99)	0.97 (0.90, 0.99)
	60%	0.75 (0.40, 0.91)	0.71 (0.33, 0.89)	0.72 (0.36, 0.89)	0.86 (0.65, 0.95)	0.95 (0.86, 0.98)	0.95 (0.87, 0.98)

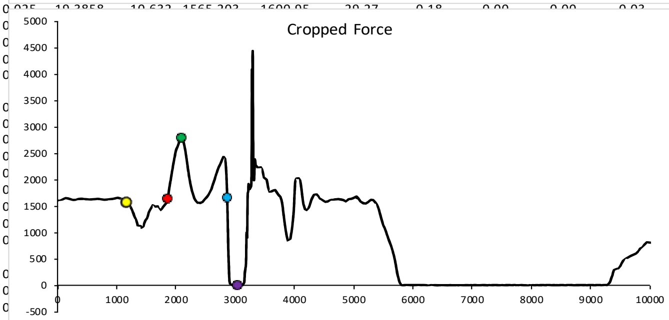
1RM 1 repetition maximum

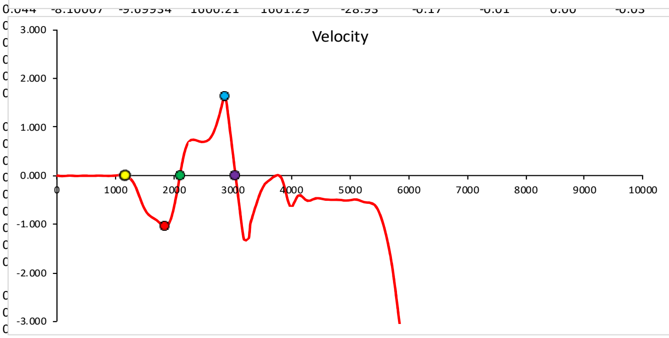
11.5 Appendix E

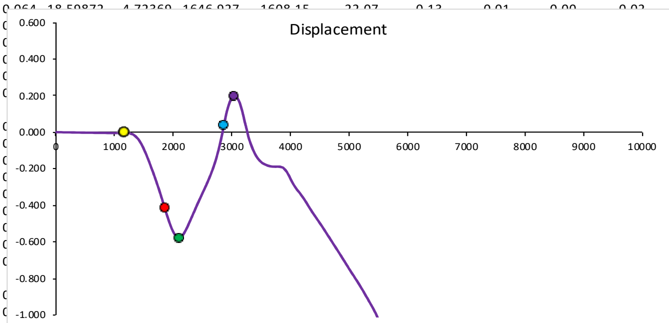
Example force plate analysis sheet

Row	Time	Fx	Fy	Fz	Cropped Fz	Net Fz	Az	Vz	Sz	Jz	Power
1	0	-39.7738	-7.36555	1501.739	1603.69	-26.53	-0.16	0.00	0.00	-0.03	0.00
2	0.001	-38.9933	-7.05494	1507.565	1605.40	-24.82	-0.15	0.00	0.00	-0.03	-0.24
3	0.002	-38.521	-6.74386	1507.224	1604.37	-25.85	-0.16	0.00	0.00	-0.02	-0.49
4	0.003	-38.8393	-6.4334	1507.57	1606.43	-23.79	-0.14	0.00	0.00	-0.02	-0.72
5	0.004	-36.9559	-6.2777	1510.999	1606.43	-23.79	-0.14	0.00	0.00	-0.03	-0.95
6	0.005	-37.112	-6.12263	1513.055	1603.69	-26.53	-0.16	0.00	0.00	-0.03	-1.20
7											-1.46
8											-1.69
9											-1.95
10											-2.23
11											-2.49
12											-2.75
13											-3.01
14											-3.27
15											-3.56
16											-3.83
17											-4.10
18											-4.36
19											-4.61
20											-4.87
21											-5.13
22											-5.40
23											-5.67
24											-5.93
25											-6.20
26	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-6.48
27											-6.77
28											-7.05
29											-7.35
30											-7.65
31											-7.93
32											-8.21
33											-8.49
34											-8.79
35											-9.09
36											-9.39
37											-9.68
38											-9.97
39											-10.25
40											-10.53
41											-10.82
42											-11.10
43											-11.39
44											-11.67
45	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-11.96
46											-12.24
47											-12.52
48											-12.79
49											-13.06
50											-13.34
51											-13.64
52											-13.92
53											-14.18
54											-14.44
55											-14.70
56											-14.96
57											-15.23
58											-15.48
59											-15.74
60											-16.00
61											-16.24
62											-16.49
63											-16.71
64											-16.91
65	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-17.14
66											-17.35
67											-17.54
68											-17.74
69											-17.93
70											-18.13
71											-18.31
72											-18.47
73											-18.64
74											-18.78
75											-18.94
76											-19.09
77											-19.24
78											-19.36
79											-19.50
80											-19.61
81											-19.71
82											-19.80
83											-19.93
84	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-20.02
85	0.084	39.46316	-6.43277	1745.781	1624.94	-5.28	-0.03	-0.01	0.00	-0.01	-20.11
86	0.085	40.09363	-6.58784	1747.499	1624.95	-5.27	-0.03	-0.01	0.00	-0.01	-20.17
87	0.086	40.87818	-6.43214	1749.558	1624.95	-5.27	-0.03	-0.01	0.00	-0.01	-20.22
88	0.087	40.87413	-5.1889	1752.651	1624.60	-5.62	-0.03	-0.01	0.00	-0.01	-20.27
89	0.088	41.97492	-6.74291	1753.685	1624.26	-5.96	-0.04	-0.01	0.00	0.00	-20.32
90	0.089	42.60539	-6.12137	1755.747	1627.69	-2.53	-0.02	-0.01	0.00	0.00	-20.39
91	0.09	43.38791	-6.58768	1758.152	1627.69	-2.53	-0.02	-0.01	0.00	0.00	-20.41
92	0.091	44.48668	-6.27691	1758.495	1628.37	-1.85	-0.01	-0.01	0.00	0.00	-20.44
93	0.092	44.6448	-5.18842	1758.843	1628.72	-1.50	-0.01	-0.01	0.00	0.00	-20.46
94	0.093	45.90169	-4.10041	1759.875	1630.08	-0.14	0.00	-0.01	0.00	0.00	-20.48
95	0.094	45.43137	-3.78917	1759.878	1630.77	0.55	0.00	-0.01	0.00	0.00	-20.48
96	0.095	45.74963	-3.4784	1761.593	1631.46	1.24	0.01	-0.01	0.00	0.00	-20.48
97	0.096	46.84031	-2.54561	1760.913	1628.72	-1.50	-0.01	-0.01	0.00	0.00	-20.46
98	0.097	46.37201	-1.61267	1760.915	1632.49	2.27	0.01	-0.01	0.00	0.00	-20.48
99	0.098	46.53013	-0.83559	1760.574	1633.17	2.95	0.02	-0.01	0.00	0.00	-20.46
100	0.099	45.73952	-0.5245	1761.954	1635.57	5.35	0.03	-0.01	0.00	0.01	-20.44
101	0.1	47.785	-0.21358	1760.242	1634.89	4.67	0.03	-0.01	0.00	0.01	-20.39









Crop Fz from:	18200
Rep length:	4000
Weighing time:	1000
Weight:	1630.22
SD:	11.68
Mass:	166.18
Weight - 5SD:	1571.83
Weight + 5SD:	1688.61
Peak force:	2785.08
Peak force row:	2096
Down min force:	1080.26
Down min force row:	1431
Max QS force:	1659.80
Initial change in force:	-
Start row:	1158
Start force:	1575.45
Velocity @start force:	0.00
Disp @start force:	0.00
Min velocity row:	1857
Min velocity:	-1.05
Disp @min velocity:	-0.41
Force @min velocity:	1627.00
Min displacement row:	2099
Min displacement:	-0.58
Velocity @ min displacement:	0.00
Force @ min displacement:	2784.05
Max velocity row:	2865
Max velocity:	1.62
Disp @max velocity:	0.04
Force @max velocity:	1662.58
Max displacement row:	3049
Max displacement:	0.20
Velocity @max disp:	-0.01
Force @max disp:	3.74
Concentric mean force:	1984.17
Concentric mean velocity:	0.80
Concentric mean power:	1589.60
Concentric time:	0.77
Concentric work:	1217.63
Concentric impulse:	270.90
System Mass	166.18
Concentric mean force	1630.79
Concentric mean net force	0.57
Concentric peak force	2784.05
Concentric peak net force	1153.83
Eccentric mean force	1629.34
Eccentric mean net force	-0.88
Mean propulsive force	1984.17
Mean net propulsive force	353.95
Peak propulsive force	2784.05
Peak net propulsive force	1153.83
Mean unloading force	1380.80
Mean net unloading force	-249.42
Mean braking force	2345.31
Mean net braking force	715.09
Concentric phase (mean velocity)	0.81
Concentric phase (peak velocity)	1.62
Eccentric phase (mean velocity)	-0.61
Eccentric phase (peak velocity)	-1.05
Mean propulsive velocity	0.80
Peak propulsive velocity	1.62
Mean unloading velocity	-0.59
Peak unloading velocity	-1.05
Mean braking velocity	-0.67
Peak braking velocity	-1.05
Concentric impulse	-0.85
Eccentric impulse	-0.22
Propulsive impulse	270.90
Unloading impulse	-174.57
Braking Impulse	174.35
Concentric power	1330.13
Eccentric power	-991.32
Mean propulsive power	1589.60
Mean unloading power	-826.35
Mean braking power	-1469.50
Concentric duration	0.95
Eccentric duration	0.94
Propulsive duration	0.77
Unloading duration	0.70
Braking duration	0.24
Concentric range of motion	0.77
Eccentric range of motion	0.58
Propulsive range of motion	0.61
Unloading range of motion	0.41
Braking range of motion	0.16
Concentric work	1263.62
Eccentric work	932.84
Propulsive work	1217.63
Unloading work	577.62
Braking work	355.62
Mean decelerative force	165.85
Mean net decelerative force	-1464.37
Peak decelerative force	1662.58
Peak net decelerative force	32.36
Mean decelerative velocity	0.88
Peak decelerative velocity	1.62
Decelerative impulse	-271.74
Mean decelerative power	261.81
Decelerative duration	0.18
Decelerative range of motion	0.16
Decelerative work	48.17

11.6 Appendix F

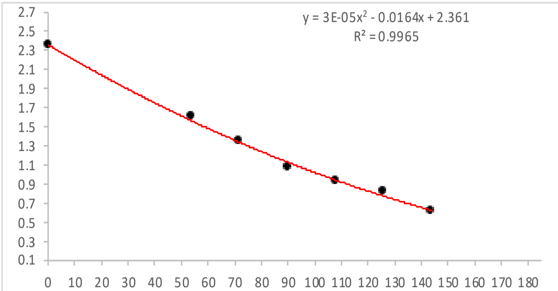
Example 1RM prediction sheet

Absolute load	Velocity (y)	Percentage of 1RM (x)
144	0.62	80
126	0.81	70
108	0.93	60
90	1.07	50
72	1.34	40
54	1.61	30
0	2.35	0

a	b	c	
0.00003034	-0.01641914	2.36096352	
b^2-4ac	0.00005830	0.00005466	0.00006194
-b-SQRT(D)	0.00878355	0.00902580	0.00854875
2a	0.00006068	0.00006068	0.00006068
Error	0.030		

Participant lifted		
Vel	Load	Percentage VEL
0.62	144	144.75
0.59		148.74
0.65		140.88

Lift	1RM	1RM - predicted	
Squat 1	180	-0.94	kg
		-0.52	%



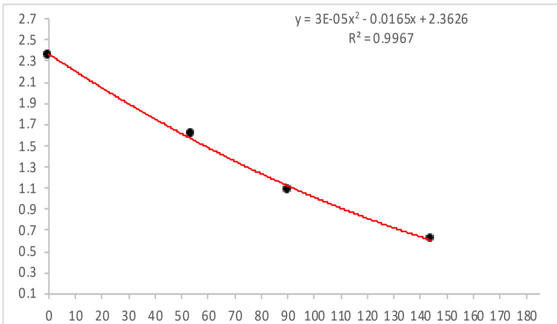
% 1RM	Actual load	Vel-error	Vel+error	Percentage diff
70	126.66	130.15	123.27	
72.5	131.18	134.80	127.67	
75	135.70	139.45	132.08	
77.5	140.23	144.09	136.48	
80	144.75	148.74	140.88	
82.5	149.27	153.39	145.28	
85	153.80	158.04	149.69	
87.5	158.32	162.69	154.09	
90	162.84	167.34	158.49	
92.5	167.37	171.98	162.89	
95	171.89	176.63	167.30	
97.5	176.41	181.28	171.70	
100	180.94	185.93	176.10	-5.43

Absolute load	Velocity (y)	Percentage of 1RM (x)
144	0.62	80
90	1.07	50
54	1.61	30
0	2.35	0

a	b	c	
0.00002984	-0.01648584	2.36264706	
b^2-4ac	0.00006381	0.00006023	0.00006739
-b-SQRT(D)	0.00849756	0.00872488	0.00827652
2a	0.00005967	0.00005967	0.00005967
Error	0.030		

Participant lifted		
Vel	Load	Percentage VEL
0.62	144	142.41
0.59		146.22
0.65		138.70

Lift	1RM	1RM - predicted	
Squat 1	180	1.99	kg
		1.11	%



% 1RM	Actual load	Vel-error	Vel+error	Percentage diff
70	124.61	127.94	121.37	
72.5	129.06	132.51	125.70	
75	133.51	137.08	130.03	
77.5	137.96	141.65	134.37	
80	142.41	146.22	138.70	
82.5	146.86	150.79	143.04	
85	151.31	155.36	147.37	
87.5	155.76	159.92	151.71	
90	160.21	164.49	156.04	
92.5	164.66	169.06	160.38	
95	169.11	173.63	164.71	
97.5	173.56	178.20	169.04	
100	178.01	182.77	173.38	-5.28

11.7 Appendix G

Example participant information sheet

Sheffield Hallam University | Academy of Sport and Physical Activity

Participant Information Sheet

Predicting 1RM from load-velocity data

Lead Researchers: Steve Thompson
The aim of this document is to provide you with as much information regarding the uses of the data being collected on you.

Sheffield Hallam University undertakes research as part of its function for the community under its legal status. Data protection allows us to use personal data for research with appropriate safeguards in place under the legal basis of public tasks that are in the public interest. A full statement of your rights can be found at https://www.shu.ac.uk/about-this-website/privacy-policy/privacy-notices/privacy-notice-for-research. However, all University research is reviewed to ensure that participants are treated appropriately, and their rights respected. This study was approved by UREC with Converis number ER13605026. Further information at https://www.shu.ac.uk/research/ethics-integrity-and-practice

What are we asking you to do?
If happy to participate, you will be asked to visit the S&C lab at Sheffield Hallam University a total of three times, each separated by 48-96 hours. During this time, we would kindly ask you to refrain from any other physical activity. The visits will look as follows:

The first visit will consist of participant information and anthropometric data being collected (age, body mass, stature, rack height) alongside relevant participant consent forms being completed. You will then undertake a standardised individualised warm up protocol. Once all preliminary preparation is complete, you will be taken through an incremental 1RM protocol to determine the loads for the subsequent two sessions:

- 5 reps @ 50% 1RM
- 3 reps @ 70% 1RM
- 2 reps @ 80% 1RM
- 1 rep @ 90% 1RM
- 1 rep @ 95% 1RM
- 1 rep @ 100% 1RM
- Following a successful completion of the 100% 1RM, you will work with the lead investigator to increase the load (by approximately 0.5-5kg per rep) to find a true 1RM.

A Gymaware and force plate will be used throughout to measure force and velocity parameters.

Sessions 2 and 3

Sessions 2 and 3 will be identical in procedures. You will attend the laboratory and will undertake a full load-velocity profile in the free-weight back squat. For the lighter loads (0-60% 1RM), a loaded squat jump will also be performed. Loads will be determined by the 1RM data collected during session 1. Participants will be asked to perform the following rep and load ranges:

- 3 x reps @ unloaded
- 3 x reps @ 30% 1RM
- 3 x reps @ 40% 1RM
- 2 x reps @ 50% 1RM
- 2 x reps @ 60% 1RM
- 2 x reps @ 70% 1RM
- 1 x rep @ 80% 1RM
- 1 x rep @ 90% 1RM
- 1 x rep @ 100% 1RM

Force-velocity and load-velocity data will be collected simultaneously via a combination of force-plate and Gymaware. You will be asked to perform each repetition with maximal intent and velocity during the concentric portion of the lift.

Covid-19 related requirements

For this research to take place in the current climate, the following precautions and directions must be followed by both researcher and participant:

- Only researcher and one participant will be present in the room during the testing session
- Researcher will wear face mask and protective gloves throughout
- 2 m social distancing will be maintained throughout
- A clear researcher zone and participant zone will be marked out prior to your arrival for when testing begins, there will be a 4 m distance between these zones
- Only participant will touch the barbell and wooden dowel
- Only researcher will touch all other equipment
- All equipment used will be sterilised and cleaned down before and after each testing session
- Doors will be opened by researcher and left open throughout testing. Windows and doors will be opened to enhance ventilation
- All participant consent forms will be completed remotely via google forms using participant personal smart device
- Additional rest will be provided where necessary

Why have you been asked to partake?

You have been asked to be a part due to the fact you meet the following criteria:

- Healthy adult (18-40 years old) - free from cardiovascular, metabolic and respiratory disease and free from any injury - this will be determined via a pre-screening medical questionnaire.
- Competent at back squat (must be able to squat to full depth)
- Agree to not train during testing week(s)
- Strength levels = 1.5 x body weight for back squat
- Resistance Trained 2 x week for previous 12 months

What are the risks and how will they be minimised?

Undertaking maximum strength training can be fatiguing and potentially risk injury. To minimise these risks, you will undertake a full dynamic warm up; you will have no current injuries; you will have a minimum strength level of 1.5 x body mass; and will have trained consistently in the back squat for at least 12 months. Your technique will also be assessed in visit 1. These criteria will ensure you have the suitable characteristics to undertake maximal testing procedures.

A UKSCA accredited S&C coach will be present through all testing procedures to ensure safety and rigour. The research project has been approved by the Sheffield Hallam Ethics committee and meets all the necessary health and safety requirements.

Why do we want to use your data?
We are looking to investigate two different approaches to predict your maximal intensity (1RM). By undertaking this research, we will be able to make recommendations on the most appropriate ways in which to do this. This will also provide a allow coaches to confidently prescribe based upon maximal intensity, but without the need to undertake direct measurements on a regular basis.

What will happen to the data?
The data will be stored securely and anonymously on a password protected computer in line with the data protection act 1998. You will be able to ask to see any of your data at any point. The researcher running this study will be the only person to have access to the data. The data will be used to create a research publication and a poster presentation. All data will be always kept anonymous and will be stored for a minimum of five years.

Can I withdraw from the study?
You can of course withdraw from the study at any time. The study is completely voluntary and therefore you do not have to take part if you don't want to.

What if I have further questions?
If you have any further questions, please do not hesitate to contact any members of the research team below.

Contact Information
Steve Thompson (07801 997099) s.w.thompson@shu.ac.uk

<table>
<tr>
<td>You should contact the Data Protection Officer if:
• you have a query about how your data is used by the University
• you would like to report a data security breach (e.g. if you think your personal data has been lost or disclosed inappropriately)
• you would like to complain about how the University has used your personal data

DPO@shu.ac.uk</td>
<td>You should contact the Head of Research Ethics (Professor Ann Macaskill) if:
• you have concerns with how the research was undertaken or how you were treated

• a.macaskill@shu.ac.uk</td>
</tr>
<tr>
<td colspan="2">Postal address: Sheffield Hallam University, Howard Street, Sheffield S1 1WBT Telephone: 0114 225 5555</td>
</tr>
</table>

11.8 Appendix H

Example informed consent form

PARTICIPANT CONSENT FORM

Predicting 1RM from load-velocity data

Please answer the following questions by ticking the response that applies

		YES	NO
1.	I have read the Information Sheet for this study and have had details of the study explained to me.	☐	☐
2.	My questions about the study have been answered to my satisfaction and I understand that I may ask further questions at any point.	☐	☐
3.	I understand that I am free to withdraw from the study within the time limits outlined in the Information Sheet, without giving a reason for my withdrawal or to decline to answer any particular questions in the study without any consequences to my future treatment by the researcher.	☐	☐
4.	I agree to provide information to the researchers under the conditions of confidentiality set out in the Information Sheet.	☐	☐
5.	I wish to participate in the study under the conditions set out in the Information Sheet.	☐	☐
6.	I consent to the information collected for the purposes of this research study, once anonymised (so that I cannot be identified), to be used for any other research purposes.	☐	☐

Participant's Signature: ____ Date: ____________

Participant's Name (Printed): _______________________________________

Contact details: ____

____

Researcher's Name (Printed): Steve Thompson

Researcher's Signature:

Researcher's contact details:

Steve Thompson
s.w.thompson@shu.ac.uk
07801997099

11.9 Appendix I

pre-screening medical questionnaire

PRE-PARTICIPATION HEALTH SCREEN QUESTIONNAIRE

Sheffield Hallam University | Academy of Sport and Physical Activity

Name…………………………………....... Male/Female Date of Birth ……………..…..

As a volunteer participating in a study, it is important that you are currently in good health and have had no significant medical problems in the past. This is to ensure your own continuing well-being

Please complete this questionnaire before taking part:

1. At present, do you have any health problem for which you are:

(a)	on medication, prescribed or otherwise	Yes	☐	No	☐
(b)	attending your general practitioner	Yes	☐	No	☐
(c)	on a hospital waiting list...	Yes	☐	No	☐
(d)	currently suspending your normal physical activity	Yes	☐	No	☐

2. In the past two years, have you had any illness or injury which required you to:

(a)	consult your GP	Yes	☐	No	☐
(b)	attend a hospital outpatient department	Yes	☐	No	☐
(c)	be admitted to hospital	Yes	☐	No	☐

3. Have you ever had any of the following:

(a)	Convulsions/epilepsy	Yes	☐	No	☐
(b)	Respiratory conditions / Asthma	Yes	☐	No	☐
(c)	Eczema	Yes	☐	No	☐
(d)	Diabetes	Yes	☐	No	☐
(e)	A blood disorder	Yes	☐	No	☐
(f)	Head injury	Yes	☐	No	☐
(g)	Digestive problems	Yes	☐	No	☐
(h)	Heart problems/chest pains…………………………..	Yes	☐	No	☐
(i)	Problems with muscles, bones or joints	Yes	☐	No	☐
(j)	Disturbance of balance/coordination	Yes	☐	No	☐
(k)	Numbness in hands or feet	Yes	☐	No	☐

(l)	Disturbance of vision	Yes		No
(m)	Ear/hearing problems	Yes		No
(n)	Thyroid problems	Yes		No
(o)	Kidney or liver problems	Yes		No
(p)	Problems with blood pressure	Yes		No

If YES to any question, please describe briefly if you wish (e.g. to confirm problem was/is short-lived, insignificant or well controlled.)

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4. Smoking, physical activity and family history

(a)	Are you a current or recent (within the last six months) smoker?	Yes		No
(b)	Are you physically active (30 minutes of moderate intensity, physical activity on at least 3 days each week for at least 3 months)?	Yes		No
(c)	Has any, otherwise healthy, member of your family under the age of 35 died suddenly during or soon after exercise?	Yes		No

5. <u>Allergy Information</u>

(a)	Are you allergic to any food products?	Yes		No
(b)	Are you allergic to any medicines?	Yes		No
(c)	Are you allergic to plasters?	Yes		No
(d)	Are you allergic to latex?	Yes		No

If YES to any of the above, please provide additional information on the allergy

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6. <u>Additional questions for female participants</u>

(a)	Are your periods normal/regular?	Yes		No
(b)	Are you on "the pill"?	Yes		No
(c)	Could you be pregnant?	Yes		No
(d)	Are you taking hormone replacement therapy (HRT)?	Yes		No

7. <u>As far as you are aware is there anything that might prevent you from successfully completing, or have a problem that could be made worse by your involvement in this study?</u>

Yes ☐ No ☐

If yes, please provide details.

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8. <u>Please provide contact details of a suitable person for us to contact in the event of any incident or emergency.</u>

Name…….

Telephone Number……………………………………………………………………

Relationship to Participant ………………………………………………………………………..................

11.10 Appendix J

Recruitment posters

Sheffield Hallam University | Department of Sport and Physical Activity

Research Participants needed!!

Researchers at Sheffield Hallam University are investigating the application of velocity-based training (VBT) within strength and conditioning. The aim is to speak directly to S&C coaches to learn about their experiences of utilizing VBT technology, methods and research within their coaching practices.

You are eligible if you…

…currently work in elite or professional sport as an S&C practitioner

…utilize VBT in your coaching in some way

…are available for an online interview lasting approximately 30 to 90 minutes

If you are eligible and willing to take part, please contact:

Steve Thompson (principal investigator)
s.w.thompson@shu.ac.uk
@steve381 (twitter)

The application of velocity-based training: a thematic analysis