Runners' individual learning responses to a biofeedback intervention to reduce tibial acceleration

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Candidate Declaration

I hereby declare that:

1. I have not been enrolled for another award of the University, or other academic or professional organisation, whilst undertaking my research degree.

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.

4. The work undertaken towards the thesis has been conducted in accordance with the SHU Principles of Integrity in Research and the SHU Research Ethics Policy.

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Abstract

Increased peak tibial acceleration has been related to tibial stress fractures. Reducing tibial acceleration could, therefore, help prevent injury. With the use of a single-subject analysis, it was aimed to give an insight into which individual gait strategies participants used and how quickly participants responded to a biofeedback intervention aimed to reduce tibial acceleration.

First, a literature review was performed to identify gaps in the literature and inform primary research studies. Secondly, different methodological approaches were considered and a feedback system was developed based on exploratory studies focussing on the direct learning response, treadmill speed, target, and verbal instruction. A single-subject design was chosen and the minimal detectable difference was calculated to determine the minimum amount of change which was sufficiently greater than the measurement error and day-to-day variability in order to consider the measured change represented a genuine biomechanical difference.

For the group, mean peak tibial acceleration significantly decreased by 26 per cent between the baseline measurements and the one-month follow-ups. Nine out of the eleven participants found a real decrease in mean peak tibial acceleration after a month. Participants needed one to six sessions to automatize running with reduced tibial acceleration. However, they were still able to reduce mean peak tibial acceleration after they automatized running. Further, participants found different shock-absorbing mechanisms comparing measurements taken directly after the intervention to after a month. This suggests participants did not learn a specific solution to be able to reduce tibial acceleration, but were able to switch in between shock-absorbing mechanisms.

This programme of research showed the importance of a single-subject analysis in this area of research. Future directions could focus on in-field, individually tailored, gait retraining to improve the outcomes and be able to help reduce the prevalence of tibial stress fractures in runners.

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Chapter 1: Introduction

1.1 Introduction

This thesis outlines a research programme on the use of biofeedback in reducing tibial acceleration in runners. The different studies within this programme of research focus on improving current methods used to decrease tibial acceleration and on gaining more insight into the individual responses of participants to biofeedback. This chapter outlines the motivation for the work, it further outlines the aims and objectives of the research and, finally, the thesis structure will be discussed.

1.2 Motivation

Tibial stress fractures are common overuse injuries among runners (Bennell, Malcolm, Thomas, Wark, & Brukner, 1995). The tibia is the most commonly injured bone with tibial stress fractures accounting for between 26 per cent to 49 per cent of all stress fractures (Bennell et al., 1995; Brukner, Bradshaw, Khan, White, & Crossley, 1996; Matheson et al., 1987; McBryde, 1985). These injuries can cause significant disruption to training, a reduction in physical fitness, as well as increased psychological distress (Clansey, Hanlon, Wallace, Nevill, & Lake, 2014). Davis et al. (2004) suggested increased tibial acceleration during the loading phase in running to be related to tibial stress fractures and could, therefore, be an important risk factor for this injury. Interventions focusing on decreasing tibial acceleration could, therefore, help to reduce the prevalence of this injury and aid rehabilitation in those injured runners.

Gait retraining is a possible intervention which could help in decreasing tibial acceleration. Gait retraining is a non-invasive technique focusing on the rehabilitation of gait by either muscle strengthening, treadmill training, neurodevelopmental techniques, or intensive mobility exercises (Eng & Fang Tang, 2007). Treadmill training was suggested to be beneficial in both people who suffered a stroke (Teasell et al., 2003) and persons with Parkinson's disease (Herman, Giladi, & Hausdorff, 2009). In addition, when biofeedback was added to treadmill walking or running, strong evidence of a positive benefit in gait retraining was reported (Crowell & Davis, 2011; Teasell, Bhogal, Foley, & Speechley, 2003). Understanding how gait retraining may be used to reduce the risk of overuse injuries is an important step in developing non-invasive treatment plans or prevention strategies to help improve individual outcomes.

Biofeedback makes use of electronic equipment to provide the user with additional biological information, beyond that which is naturally available to them (Agresta & Brown, 2015; James, 1992; Tate & Milner, 2010). Advances in technology have made biofeedback systems more affordable and more accessible to researchers; as a result, there has been an increase in the literature in this area over recent years. Biofeedback was found to be beneficial (Stanton, Ada, Dean, & Preston, 2011; Tate & Milner, 2010) and improve outcomes among several patient groups (Baram, 2013; James, 1992; Richards et al., 2016).

Biofeedback was shown to be effective in runners who tried to reduce tibial acceleration (Bowser, Fellin, Milner, Pohl, & Davis, 2018; Creaby & Franettovich Smith, 2016; Crowell, Milner, Hamill, & Davis, 2010; Wood & Kipp, 2014). In recent studies (Bowser et al., 2018; Creaby & Franettovich Smith, 2016; Crowell et al., 2010; Wood & Kipp, 2014) participants were asked to run on a treadmill while receiving feedback on tibial acceleration. All studies found beneficial effects of feedback in decreasing tibial acceleration within one, or several, sessions. One study (Bowser et al., 2018) found a beneficial effect was retained after a year, but none of the studies focused on the time participants took to modify tibial acceleration in response to real-time feedback within the feedback session. The time participants take to modify tibial acceleration and the strategies they use could be of interest to receive a better insight into how long feedback should be given to participants to allow them to respond accordingly.

The time participants take to modify tibial acceleration might give further insight into how participants learn to reduce tibial acceleration. This time could be quantified in the number of sessions participants needed before they automatized the task of reducing tibial acceleration. A task is automatized when it requires little or no cognitive demand (Fitts & Posner, 1967). One way to measure cognitive loading is through the use of dual-tasks (Neumann, 1984; Richards, van der Esch, van den Noort, & Harlaar, 2018; Wickens, 1989). A dual-task consists of an additional task which has to be executed while performing the intended learned task. If during a dual-task an increase in error is found in the intended learned task it is suggested that the movement was not automatized (Neumann, 1984; Richards et al. 2018; Wickens, 1989). In the current programme of research, automatization of the reduction in tibial acceleration will be tested with the use of a dual-task. Further, learning of reducing tibial acceleration will be described in terms of fast learning and slow learning (Kami et al., 1995) and how many sessions' participants need to automatize the task. Fast learning refers to the learning within a session and slow learning refers to the learning that occurs over several sessions.

The kinematic strategies participants used to change tibial acceleration after six sessions of biofeedback were studied by Clansey et al. (2014). They found that the group adapted in the foot and ankle but no adaptations were made in the knee or hip joint. However, Crowell et al. (2010) observed that in a group of runners that were asked to reduce their tibial acceleration, individual differences existed and responders, as well as non-responders, were found. With participants expected to respond differently to feedback, a typical statistical analysis of group data such as done in the study by Clansey et al. (2014) might have masked individual changes. These individual strategies of runners could give a better insight into the difference between responders and non-responders. By obtaining better insight into how participants respond to the feedback, the feedback interventions could be improved, which could help to further reduce the prevalence of tibial stress fractures.

1.3 Aim and objectives

The aim of this program of research was to investigate the individual responses of participants to a biofeedback intervention aimed to reduce tibial acceleration.

The program of research had the following objectives:

1. Provide a critical review of the literature in the area of biofeedback and gait retraining to establish current knowledge and identify areas that require further research.

2. Consider different methodological approaches in measuring tibial acceleration and gait patterns and develop an appropriate feedback system for laboratory-based use in real-time.

3. Establish the reliability of peak tibial acceleration and selected kinematic and spatiotemporal parameters in describing movement patterns.

4. Investigate the learning response to a biofeedback intervention aimed to reduce tibial shock in a group of runners, with a focus on fast and slow learning responses and task automatization.

5. Establish the kinematic strategies participants used in response to a biofeedback intervention aimed at reducing tibial acceleration.

1.4 Thesis structure

The chapters in this programme of research will be structured as follows:

- In chapter two this area of research will be further introduced with a focus on gait limitations and treatment, motor learning and biofeedback, the use of biofeedback in reducing tibial acceleration, and running patterns and injuries. Further, in chapter two the results of a mapping review, performed during this programme of research, will be discussed.

- Chapter three will consider different methods to measure tibial shock and gait patterns. Followed by a description and justification of the chosen methods. Further, the process of developing the feedback system will be described. Finally, the choice of using a single-subject analysis will be discussed.

- Chapter four examines the reliability of the systems used and defines the minimal detectable difference for the parameters of interest. The minimal detectable difference provides information on the minimum amount of change which is sufficiently greater than the measurement error and day-to-day variability for the variable of interest.

- Chapter five will describe four feasibility studies, aimed at improving the feedback system and the intervention study. The studies will be described in four different subsections: learning response to one feedback session, treadmill speed, intervention target development, and verbal instruction.

- In the sixth chapter, the intervention study will be presented. In this study, participants received six sessions of biofeedback in which they were asked to decrease tibial acceleration. This chapter will focus on whether participants were able to respond to the feedback and if they were, how long it took them before they automatized running with decreased peak tibial acceleration. A further focus will be on the one-month follow-up effect of the intervention. Finally, this chapter will discuss the kinematic strategies participants used to change their gait.

- The final conclusion and discussion in chapter seven will give an overview of this program of research. The limitations and implications of this programme of research will be discussed and recommendations will be given for further research.

Chapter 2: Literature review

2.1 Introduction

This chapter provides a critical review of the literature in the area of biofeedback and gait retraining. The chapter supports objective one of the programme of research, to establish current knowledge and identify areas that require further research. A broader view of the area was chosen, since it was believed other research on biofeedback could inform the current study. This literature research was, therefore, not limited to tibial shock and overuse injuries, but included the whole research area on biofeedback and gait. A mapping review (van Gelder, Barnes, Wheat, & Heller, 2018b) was performed to search the literature in a systematic way, to give an overview of the existing published research and to obtain a better insight into the literature within the research area (Booth, Sutton, & Papaioannou, 2016). Mapping reviews give an overview of the existing published research and can be used to obtain a better insight into the literature within a particular area (Booth et al., 2016). The results can be used to identify gaps in the literature and inform more specific future reviews and/or primary research studies. A mapping review searches the literature in a systematic way, but does not exclude articles based on quality. In the current mapping review, the focus was on the methods used rather than the outcome. This review highlights how many papers were published using particular methods. The method and results of the mapping can be found in Appendix A. The systematised methods used in the mapping review form the foundation of the literature review in this chapter, but a more narrative approach is taken to provide a more comprehensive rationale for the programme of research. This narrative approach was needed to focus on tibial shock and injuries to support this specific programme of research. In this chapter, firstly, a focus will be on gait limitations and their treatment. The following section will focus on the results of the mapping review, with a focus on biofeedback and how this integrates with motor learning. The next section will focus on the use of biofeedback to reduce tibial acceleration and the final section will expand on different running patterns.

2.2 Gait limitations and treatment

2.2.1 Introduction

Before going further into reducing tibial acceleration with the use of biofeedback, in this section, a focus will be on which gait limitations exist and what the different treatment options are for these different limitations to give a broader overview of the field. By exploring different biofeedback systems in different participant groups, it was aimed to get a better understanding of biofeedback systems. Since the development of biofeedback systems is closely related to the gait limitations of participants groups, an overview of gait limitations and possible treatment options will be given first.

2.2.2 Gait limitations

Gait defines the way people or animals move from one place to another by foot, for example by walking, stepping or running. Even though it is a routine task for most people; some people experience limitations in this task (Balaban & Tok, 2014; Bateni & Olney, 2002; Gommans et al., 2016; Kelleher, Spence, Solomonidis, & Apatsidis, 2010; Mueller, Minor, Sahrmann, Schaaf, & Strube, 1994; Svehlik et al., 2009). These gait limitations might hinder people in daily activities, which not only cause an impact on the people themselves but also on their friends and families, since their social interactions can be impaired (Baram & Miller, 2006).

There is a wide variation within gait limitations. Examples of these gait limitations in people with multiple sclerosis are insufficient foot clearance in the swing phase, reduced push-off power (Bregman, Harlaar, Meskers, & de Groot, 2012; Bregman et al., 2010) and a decreased walking speed (Kelleher et al., 2010). These limitations can occur due to muscle weakness, spasticity, sensory disturbances, and general fatigue (Baram & Miller, 2006; Kelleher et al., 2010). The same limitations are experienced by stroke survivors (Balaban & Tok, 2014; De Quervain et al., 1996) and patients with cerebral palsy (Rodda & Graham, 2001) who can also experience increased knee flexion or excessive knee extension during walking, depending on the exact characteristics of the condition. These are just a few examples of the gait limitations which these patient groups can experience.

Gait limitations do not only occur in patient groups, but can also occur in athletes. Injuries such as tibial stress fractures and patellofemoral pain cause disruption of training time, reduction in physical fitness and an increase in personal frustration (Clansey et al., 2014). Higher peak tibial accelerations and vertical force loading rates are associated with tibial stress fractures (Davis et al., 2004; Manson, McKean, & Stanish, 2018). These stress fractures limit gait. Another common overuse injury in runners is patellofemoral pain, which is associated with high-impact loading and abnormal kinematics (Cheung & Davis, 2011). The limitations described above in both patient groups and athletes are just a few of the many gait limitations people can experience and, therefore, interventions to improve functional outcomes and quality of life are much needed.

2.2.3 Treatment options

Various treatment options exist to overcome the negative impacts of gait limitations. Physiotherapy, orthoses, functional electrical stimulation and a variety of surgery options are a few of the possibilities to treat gait impairments in the United Kingdom (National Institute for Health and Care Excellence, 2006, 2016a, 2016b, 2016c, 2016d). In the following paragraphs, these different treatment options will be further explained.

In the United Kingdom, a common way to treat lower-limb musculoskeletal or neurological conditions such as multiple sclerosis, stroke and cerebral palsy is by physical therapy (National Institute for Health and Care Excellence, 2013, 2014, 2016c). Physical therapy could involve fitness training, strength training, repetitive task training, and more specifically, walking therapy (National Institute for Health and Care Excellence, 2013). There is moderate evidence that strength training improves gait in people who suffered a stroke (Teasell et al., 2003) and limited evidence in patients with cerebral palsy (Dodd, Taylor, & Damiano, 2002). Additionally, limited evidence supports treadmill training, an option of walking therapy, mainly due to a lack of high-quality research. Treadmill training, however, was suggested to be beneficial in both people who suffered a stroke (Teasell et al., 2003) and persons with Parkinson's disease (Herman, Giladi, & Hausdorff, 2009). Treadmill training could, therefore, be of benefit to patients; however, more high-quality research is needed.

Ankle-foot orthoses are used to increase stance phase control in patients (National Institute for Health and Care Excellence, 2013, 2016c). They have been used for patients with cerebral palsy and patients who have suffered a stroke. Ankle-foot orthoses have been suggested to help patients with cerebral palsy with equinus deformity, a condition in which there is too much plantarflexion in the foot (National Institute for Health and Care Excellence, 2016a). In people who suffered from a stroke, an ankle-foot orthosis is suggested to help those who experience difficulties with a drop foot in the swing phase (National Institute for Health and Care Excellence, 2013) However, in their review, Teasell et al. (2003) suggested limited evidence for ankle-foot orthoses improving elements of gait in people who suffered a stroke.

Functional electrical stimulation can be used to counteract drop foot in stroke and multiple sclerosis patients. During functional electrical stimulation, small electrical charges are applied to the peripheral nerves of the paralysed muscle (National Institute for Health and Care Excellence, 2013, 2014). This process could improve muscular function and enhance ankle dorsiflexion (National Institute for Health and Care Excellence, 2009). In people who suffered a stroke, there is a modest (Iles & Davidson, 2007) to strong (Teasell et al., 2003) evidence that functional electrical stimulation improves hemiplegic gait.

Deep brain stimulation can be performed to treat tremor and dystonia (which is a movement disorder with sustained or repetitive muscle contractions) in patients with multiple sclerosis and cerebral palsy (National Institute for Health and Care Excellence, 2014). Deep brain stimulation is a surgical technique in which a permanent electrode is placed into the brain (National Institute for Health and Care Excellence, 2006, 2016d). As deep brain stimulation includes surgery, complications can occur. These complications include intracranial haemorrhage (0%-10%), stroke (0%-2%), infection (0%-15%), lead erosion without infection (1%-2.5%), lead fracture (0%-15%), lead migration (0%-19%), and death (0%-4.4%) (Bronstein et al., 2011). Bronstein et al. (2011) suggest deep brain stimulation is beneficial, but as it is an invasive treatment it should be performed with care.

Other possible surgery options in cerebral palsy are orthopaedic surgery and selective dorsal rhizotomy. The last being an operation in which some of the sensory nerves are cut which contribute to spasticity in the lower limbs (National Institute for Health and Care Excellence, 2016d). Invasive treatments such as selective dorsal rhizotomy are irreversible and should, therefore, be considered carefully (National Institute for Health and Care Excellence, 2016d). Grunt, Becher and Vermeulen (2011) found spinal abnormalities to be common after selective dorsal rhizotomy, though it was uncertain whether this was related to selective dorsal rhizotomy or due to other factors. Grunt, Becher and Vermeulen (2011) found moderate evidence that selective dorsal rhizotomy had a positive long-term influence on body structure and body function. There was no evidence that selective dorsal rhizotomy had an influence on activity and participation domains of the International Classification of Functioning, Disability and Health (ICF) (Grunt et al., 2011).

The different treatment options described above include invasive and conservative treatments. Invasive treatments, such as deep brain stimulation and selective dorsal rhizotomy, should be performed with care, since complications such as stroke and death could occur. Conservative treatments, such as physiotherapy and ankle-foot orthoses, should, therefore, be considered first. Even though both the use of ankle-foot orthoses and walking therapy reported limited beneficial effects on gait, walking therapy was suggested to benefit both people who suffered a stroke and people with Parkinson's disease, but a lack of high-quality research was reported. In addition, when feedback on muscle activity was added to walking therapy in people who suffered a stroke, strong evidence of a positive benefit in gait retraining was reported, compared to wearing ankle-foot orthoses (Teasell et al., 2003). Crowell and Davis (2011) also suggested gait retraining with biofeedback to be more beneficial in runners and more cost-effective in the long-term than the use of cushioning shoes, foot orthosis and shock reducing insoles in runners. Considering that gait retraining with biofeedback is a conservative treatment and has the potential to be more effective, it is important to focus on improving this treatment option.

2.3 Biofeedback and motor learning

2.3.1 Introduction

Biofeedback provides additional biological information, beyond what is naturally available to the participant (Giggins, Persson, & Caulfield, 2013; Tate & Milner, 2010). This additional information is delivered by electronic equipment (Giggins et al., 2013; Tate & Milner, 2010) and could be on different internal physiological or biomechanical measures. This information could either be familiar or unfamiliar to the participants. Examples are heart rate, muscle activation, joint angles, posture, and external loading. The results are fed back to the participants through a variety of modes: auditory, visual, sensory signals (Giggins et al., 2013), or a combination of these. For over forty years biofeedback has been used to improve healing of or prevention of different diseases or injuries (Giggins et al., 2013). For example, in 1978, 11 participants with lower extremity disabilities were asked to reduce limb load while they received auditory feedback on weight-bearing with the use of a pressure sensor (Miyazaki & Iwakura, 1978). Participants heard a high pitch sound when their weight-bearing was outside a set range and were able to lower their limb load. A similar study was performed in 1980 with patients with dynamic equinus. The patients were asked to walk with a heel landing (Conrad & Bleck, 1980) and heard a sound when they contacted the ground with their heels. With the use of the device participants were able to increase heel strikes by 42 per cent. Both systems were not wireless, but due to advances in technology wireless systems are on the market now (Byl, Zhang, Coo, & Tomizuka, 2015; Sienko, Balkwill, Oddsson, & Wall, 2013; Wood & Kipp, 2014). This together with the use of motion capture systems in studies on biofeedback and gait (Barrios, Crossley, & Davis, 2010) caused a surge in the literature in this area in recent years (van Gelder et al., 2018b - see Appendix A).

Recent research suggests biofeedback to be a promising tool in different patient groups to help improve several gait outcomes (Aruin, Hanke, & Sharma, 2003; Baram & Miller, 2006; Donovan et al., 2016; Giggins et al., 2013; Morris, Matyas, Bach, & Goldie, 1992; Tate & Milner, 2010; van Gelder et al., 2017). For instance, by receiving feedback on their joint kinematics, people who suffered a stroke with genu recurvatum decreased hyperextension by 4.8 degrees, from -4.2 degrees to 0.6 degrees of flexion (Morris et al., 1992). In addition, patients with hemiparesis were able to increase their step width from 0.09 meter to 0.16 meter by receiving auditory feedback on their base of support (Aruin et al., 2003). Children with cerebral palsy who walked with excessive flexion in the knee and hip were able to extend more in both joints. After receiving visual and auditory feedback on their knee and hip angles, peak hip extension improved by 5.1 degrees and peak knee extension by 7.7 degrees (van Gelder et al., 2017). Further, patients with chronic ankle instability were able to decrease plantar pressure in the lateral column of the foot from 133.5 kilopascals to 80.7 kilopascals during treadmill walking while receiving feedback on plantar pressure (Donovan et al., 2016). These are just a few examples of the many positive outcomes biofeedback has had in improving gait in different patient groups.

As well as patient groups, biofeedback has also been found to be effective in changing gait patterns in healthy participants (Davis et al., 2010). Young and older adults were able to reduce trunk sway while they received feedback on this parameter. Older adults reduced their pitch angle from 6.35 degrees to 4.99 degrees while they walked with their eyes open and when they walked with their eyes closed the pitch angle changed from 13.52 degrees to 7.12 degrees. Further, in sporting populations, positive results of feedback on gait have also been reported (Clansey et al., 2014; Crowell & Davis, 2011; Crowell et al., 2010). Runners were able to reduce kinetic risk factors associated with tibial stress fractures by receiving feedback on their peak tibial acceleration over the course of a run. The runners in this study were able to decrease their peak tibial acceleration by 44 per cent (Crowell & Davis, 2011). In a different study, it was found that runners with unilateral patellofemoral pain were able to change their running pattern from a rearfoot to a non-rearfoot strike pattern while receiving feedback on the pressure experienced underneath the heel (Cheung & Davis, 2011). At the baseline measurement, all runners had rearfoot strikes and three months after the intervention two of the three participants had 100 per cent non-rearfoot strikes and the other participant had 93 per cent non-rearfoot strikes (Cheung & Davis, 2011). These results show the positive results of biofeedback are not limited to patient groups with motor dysfunction.

In contrast, some studies have failed to find biofeedback to be an effective tool in improving gait outcomes (Nicolaï, Teijink, & Prins, 2010; Pataky et al., 2009; Tate & Milner, 2010). For example, in a study by Pataky et al. (2009), people with total hip arthroplasty who received visual feedback on foot pressure were unable to significantly change their maximal pressure at the retention tests compared with the baseline values. A possible explanation for the difference in either a positive outcome or no difference between pre- and post-test could be heterogeneity in the study designs of the studies (Stanton et al., 2011; Tate & Milner, 2010). In all studies on biofeedback described above, different parameters were fed back, the way parameters were presented differed, the quality of the studies differed, the number of sessions differed, whether a retention test was performed differed, whether the feedback was delivered in the lab or in the field differed and different outcome measures were reported. All these differences could have an impact on the outcome. Since there are no clear guidelines for feedback it remains uncertain what the best options are to provide biofeedback. A mapping review (van Gelder et al., 2018b - Appendix A) was performed to search the literature in a systematic way to give an overview of the existing published research and to obtain a better insight into the literature within this particular area (Booth et al., 2016). This review highlights how many papers were published using particular methods. The results of the mapping review are discussed in the following sections: feedback parameter, mode of feedback, outcome measures and the design of feedback interventions.

2.3.2 Feedback parameter

Biofeedback is given on different gait parameters and these parameters could be categorised as follows: muscle activity, kinematic, kinetic, spatiotemporal or physiological parameters (van Gelder et al., 2018b - see Appendix A). In a review by Tate and Milner (2010), limited support was found for feedback on muscle activity in improving gait outcome when compared to conventional therapy. Kinematic, kinetic and spatiotemporal biofeedback showed more promising results with moderate to large short-term treatment effects in different patient groups (Tate & Milner, 2010). Feedback on muscle activity might be less effective, since this mode of feedback focuses on knowledge of performance. By giving information on knowledge of performance, instead of knowledge of results, the learning response might be decreased (Winstein, 1991). Knowledge of results refers to the result of the task, while knowledge of performance refers to information about the nature of the movement pattern. For example, in a clinical task in which the participant is asked to rise from a sitting position to a standing position in a given amount of time, knowledge of results could focus on the time it took the participant to rise, while knowledge of performance could focus on the leaning angle of the trunk before rising (Winstein, 1991). Further, motor learning and retention are likely improved when feedback is given on the parameter of interest compared to an intermediate parameter (Wulf, 2013; Wulf & Su, 2007).

Outcomes of the mapping review found a lack of literature which directly compared the different groups of feedback parameters. However, some studies that directly compared some different feedback parameters support the suggestion that feedback on muscle activation results in smaller beneficial effects than feedback on other parameters (Franz, Maletis, & Kram, 2014; Mandel, Nymark, Balmer, Grinnell, & O'Riain, 1990). Franz et al. (2014) found that feedback on ground reaction forces (kinetic parameters) increased propulsive ground reaction forces and gastrocnemius muscle activity during push-off, while feedback on muscle activity had no beneficial effect on the same gait-related outcomes. In another study, feedback on muscle activity of the pretibial and calf muscles had no effect on walking speed, while feedback on ankle angle during heel-off and swing through (kinematic parameter) had a beneficial effect on the same gait-related outcome (Mandel et al., 1990). A direct comparison between kinetic and kinematic parameters has not been reported in gait-related studies, therefore, it remains uncertain which group of variables may offer the best outcomes. A direct comparison between the different groups of parameters is needed to provide more insight into which parameter might be most effective at improving gait-related outcomes.

In the current programme of research, it was chosen to give feedback on peak tibial acceleration. Tibial acceleration was chosen as a feedback parameter, since previous research has found significant reductions in this parameter when feeding back on it. Additionally, giving feedback on tibial acceleration fits within the different learning approaches described above. By giving feedback on tibial acceleration, information is given on knowledge or results opposed to knowledge of performance (Winstein, 1991). Finally, the parameter of interest is tibial shock and tibial acceleration is seen as a proxy measurement of tibial shock in the literature (Sheerin, Reid, & Besier, 2019). And feedback on the parameter of interest could be beneficial over feedback on an intermediate parameter (Chiviacowsky & Wulf, 2002; Wulf & Su, 2007).

2.3.3 Mode of feedback

Biofeedback can be provided to individuals using different modes, including visual, auditory, and sensory (van Gelder et al., 2018b - see Appendix A). Visual feedback takes more time to process by the participant but provides the participant with more information on previous events (Baram & Miller, 2006). Auditory and sensory information is processed faster in the brain compared to visual information and may, therefore, require less conscious attention (Baram & Miller, 2006). However, less detailed information and no history can be provided by using auditory or sensory information. A combination of the three modes, a multisensory integration, has, therefore, previously been suggested to be superior by providing the most information to a participant. The combination provides the participant with more information on previous events by providing visual feedback and it gives immediate feedback by auditory and sensory feedback (Baram & Miller, 2006). Further, multisensory feedback reduces the cognitive load associated with the separate systems due to the distribution of information processing (Sigrist, Rauter, Riener, & Wolf, 2013).

In a systematic review on injured and healthy runners, different modes of feedback were found to be effective in reducing variables related to ground reaction forces, however, no mode of feedback was identified as being superior (Agresta & Brown, 2015). When directly comparing visual, sensory and multisensory feedback, multisensory feedback gave significantly better results (Yen, Landry, & Wu, 2014). In the study by Yen et al. (2014), participants with incomplete spinal cord injuries walked on a treadmill and received either visual feedback, proprioceptive feedback or a combination of those. Visual feedback consisted of visual cues showing the actual and target stride length on a computer and proprioceptive feedback consisted of a resistance applied to the leg (Yen et al., 2014). The combination of both modes led to the best results and the after effect lasted longer. It should be noted that in this study auditory feedback was not considered and, therefore, no direct comparison between all feedback options (visual, sensory, and auditory) was reported. Hirokawa and Matsumura (1989) and Shin and Chung (2017) also found the best gait-related outcomes when using combined visual and auditory feedback, compared to each mode separately. However, it should be noted that different modes of feedback were used for different parameters: visual feedback for step length and auditory feedback for step duration. Based on the results of the mapping review it was concluded that future research on the effectiveness of different modes of feedback is needed to help establish optimum feedback strategies for gait retraining applications within different populations. This suggestion is supported by previous studies (Agresta & Brown, 2015; Sienko, Whitney, Carender, & Wall, 2017).

In conclusion, multisensory feedback is expected to give significantly better results compared to single modes of feedback (Hirokawa & Matsumura, 1989; Shin & Chung, 2017; Yen et al., 2014). Further, the combination of the modes provides the participant with more information (Baram & Miller, 2006) and reduces the cognitive load associated with the separate systems due to the distribution of information processing (Sigrist et al., 2013).

2.3.4 Outcome measures

Most of the studies included in the mapping review measured a wide range of biomechanical parameters, such as plantar pressure (Colborne, Wright, & Naumann, 1994; De León Rodriguez et al., 2013), joint angles (Barrios et al., 2010; Colborne et al., 1994), gait speed (Baram & Miller, 2006; Baram & Lenger, 2012; Colborne et al., 1994) and step length (Baram & Miller, 2006; Baram & Miller, 2007; Colborne et al., 1994). Outcome measures could be chosen since they are seen as a risk factor for a certain injury or a functional outcome for patient groups. The importance of these biomechanical parameters will differ for each individual or patient group, since participants experience different gait limitations. An increase in knee flexion could be meaningful for a participant who walks with excessive knee extension, but not for a participant who walks with excessive knee flexion. Since different outcome measurements will have a different impact on different people, it is not possible to generalise as to which outcome measures are important. It is likely that for every individual a different set of parameters should be chosen. In the current programme of research outcome measures were chosen based on expected changes in the parameter where feedback is given on, tibial acceleration, but also in parameters related to shock-absorbing mechanisms and parameters related to risk injuries. These choices of parameters are further described in section 2.5.

2.3.5 Design of feedback interventions

The design of feedback interventions should be considered to allow for improvement in biofeedback studies. Over half of the previous studies which included biofeedback reported only one feedback session (van Gelder et al., 2018b - see Appendix A). Since beneficial outcomes could be related to the duration of the intervention (Adamovich, Fluet, Tunik, & Merians, 2009; Agresta & Brown, 2015), both the duration and number of sessions required for effective retraining should be explored. These findings are supported by a review by Gordt et al. (2017) on the effects of feedback of wearable sensor data on balance, gait, and functional performance in both healthy and patient populations. These authors concluded that future randomised controlled trials should be designed with adequate intervention periods to enhance learning.

The majority of studies in the mapping review (van Gelder et al., 2018b - see Appendix A) had no retention test or a short-term retention test within a week of the intervention finishing. Establishing the long-term retention of any gait-related changes represents a crucial step in prescribing gait retraining interventions as an effective alternative to existing treatment options (Agresta & Brown, 2015; Gordt et al., 2017; Stanton et al., 2017; Tate & Milner, 2010).

It was further noticed in the mapping review performed in this programme of research (van Gelder et al., 2018b - see Appendix A) that only four of the 173 studies gave feedback in the field, with a further four studies giving a combination of laboratory and field-based training. Though two previous reviews concluded field-based systems should be considered (Richards et al., 2016; Shull et al., 2014), to date the vast majority of published research is confined to laboratory settings. Presenting feedback in the field may facilitate the trend for healthcare to move away from a clinical model to a self-care model supported by technology (McCullagh et al., 2010), and it would also improve the representative design of experiments (Araújo et al., 2007). However, presenting feedback in the field does have some practical implementation issues. For example, visual feedback could be shown on a screen in the laboratory, but this would not be easily possible in the field. Auditory and sensory feedback modes are, therefore, easier to facilitate in field-based settings.

Finally, in the mapping review (van Gelder et al., 2018b - see Appendix A), only fifteen of the included studies used a faded feedback approach within their intervention. By gradually removing feedback over time, it is suggested that participants do not become dependent on the feedback, facilitating improved learning (Winstein, 1991). Therefore, to gain long-term benefits from the feedback intervention, fading the feedback should be considered.

In conclusion, beneficial outcomes could be related to the duration of the intervention (Adamovich et al., 2009; Agresta & Brown, 2015). Establishing the long-term retention of any gait-related changes is important in defining learning effects (Agresta and Brown, 2015; Gordt et al., 2017; Stanton et al., 2017; Tate and Milner, 2010). Further, to improve the representative design of experiments measurement should be performed in the lab (Araújo et al., 2007). And finally, to prevent participants from becoming dependent on the feedback, the feedback should be faded over the sessions (Winstein, 1991). The methods of the current programme of research are formed by the findings of the mapping review described above.

2.3.6 Motor learning

Biofeedback and gait retraining are used to teach participants to change their gait pattern. The use of biofeedback is related to learning. Therefore, a further explanation of how learning will be measured in the current programme of research and how learning can be improved will be given. Learning refers to relatively permanent changes in behaviour acquired through practice. Representational theories, taking a cognitive approach, including Adams' closed-loop model (Adams, 1971) and Schmidt's schema theory (Schmidt, 1975), aim to explain perception and action by internal psychological processes and postulate mental representations (programs or motor schemes) connecting person and the environment (Thon, 2015). Information on the movement (internal sensory feedback) is linked to the movement outcome (knowledge of results), which leads to an improvement in the mental representations of a movement (Thon, 2015). In this context, learning is defined as a strengthening of these mental representations.

Fitts and Posner (1967) proposed a three-stage model of skill acquisition. The three stages are the verbal-cognitive stage, the associative stage, and the autonomous stage. The verbal-cognitive stage includes the time where task goals are established, the movements are still clumsy and inefficient. In this stage, errors are made, but rapid performance gains are found. In the associative stage, fewer errors and refinements of the movement are made. Finally, in the autonomous stage, the movement is almost automatic and very few errors are made. With the movement being habitual, people will be able to perform other tasks alongside the learned movement. In the final stage, minimal performance variability will be found. With the use of the three-stage model of skill acquisition by Fitts and Posner (1967) learning could be quantified with the number of errors that are made, but also in whether the task is automatized and, therefore, whether a person is able to perform the task next to another task. In the current programme of research, it was aimed to define when participants reached the last phase of the three-stage model of motor learning (Fitts & Posner, 1967), in which the task is automatized and requires little or no cognitive demand.

One approach to measure cognitive loading is through the use of dual-tasks (Neumann, 1984; Richards, van der Esch, van den Noort, & Harlaar, 2018; Wickens, 1989). A dual-task consists of an additional task which has to be executed while performing the intended learned task. The cognitive loading, a participant experiences, can then be measured by the increase in the error of the intended learned task, in this programme of research, reducing tibial acceleration. An increase in error during a dual-task suggests that the movement was not automatized (Neumann, 1984; Richards et al. 2018; Wickens, 1989). Further, the dual-task paradigm better represents field-based settings. During running in the field a person will have to process other information alongside their learned task, suggesting there will be increased cognitive loading. It is, therefore, of importance that the skill is learned, so the cognitive demand is lower and the task can be transferred from the laboratory to field-based settings. Previous research in biofeedback in gait (Richards et al., 2018) has used dual-tasks at the beginning and the end of a biofeedback intervention to investigate the additional cognitive demand when learning a new gait pattern. Richards et al. (2018) used to dual-task to define whether participants had reached the third stage of the three-stage model of motor learning in accordance with Fitts & Posner (1967). In the current programme of research a dual-task will be performed in every session to gain an insight into how automatization of the task occurs over the biofeedback sessions.

As well as automatization of the task, motor learning can be considered in terms of fast and slow learning responses. Fast learning refers to the learning within a session and slow learning refers to the learning that occurs over several sessions, leading to progressive improvements and long-term retention of the task to be learned (Kami et al., 1995). Going from fast to slow learning is associated with a shift in patterns of brain activity associated with motor skill acquisition (Lohse, Wadden, Boyd, & Hodges, 2014). Fast learning on a short time-scale (less than one day) is associated with cortico-cerebellar activity in the brain, while slow learning over a longer time scale (more than one day) is associated with cortico-striatal activity (Lohse et al., 2014). To find permanent changes in behaviour the slow learning response should be reached. The current research will therefore, investigate both participants' fast and slow learning responses.

As described in section 2.3.2, learning can be improved by giving information on knowledge of results opposed to knowledge of performance (Winstein, 1991) and on the parameter of interest over an intermediate parameter (Chiviacowsky & Wulf, 2002; Wulf & Su, 2007). Further, based on a study by Schmidt et al. (1989), in which participants got feedback on learning a series of arm movements in a fixed time, practice results were better for continuous feedback, but learning results were better for summarised feedback. With summarised feedback, a mean result is given for a chosen number of measurements. A risk of over-reliance and lack of evaluation of intrinsic feedback can be reduced by giving summary feedback (Schmidt et al., 1989). Intrinsic feedback refers to feedback generated from within the context of the action itself, while extrinsic feedback refers to feedback which is generated in a context external to the action. A study by Janelle et al. (1997) further explored the concept of over-reliance and not only compared summary feedback to continuous feedback, but also included self-controlled feedback. During a self-controlled feedback schedule, participants ask for feedback when they think feedback is needed. It was noticed that self-controlled feedback enhanced learning compared to any of the other feedback schedules. Additionally, Janelle et al. (1997) concluded that participants asked for more feedback in the beginning and that this naturally faded. In two studies by Chiviacowsky and Wulf (2002, 2005) it was further found that in the measurements including self-controlled feedback, the feedback was mainly asked after a correct execution of the task. In the studies by Janelle et al. (1997) and Chiviacowsky and Wulf (2002, 2005) the task involved throwing a ball to a target and participants were given feedback on whether they did or did not hit the target. The results of Janelle et al. (1997) and Chiviacowsky and Wulf (2002, 2005) imply that self-controlled feedback would lead to better motor learning results compared to continuous or summary feedback. However, it should be noted that these results are limited to tasks in which there was a long time between outcomes. Running is a continuous action; it is, therefore, difficult to give self-controlled feedback, since there is a delay between asking for and giving the feedback. When using a self-controlled feedback approach during running, participants would likely be several steps ahead of the moment they requested the feedback, by the time feedback would be delivered to them. They will, therefore, be unable to link the feedback given to the step the feedback was asked for. Therefore, for a running study, summary feedback might be the most beneficial approach. Research which has used continuous and summary feedback will be further described in the following section on the use of biofeedback in reducing tibial acceleration.

2.4 The use of biofeedback in reducing tibial acceleration

2.4.1 Introduction

Biofeedback has been shown to be effective in runners who tried to reduce tibial acceleration (Bowser et al., 2018; Clansey et al., 2014; Creaby & Franettovich Smith, 2016; Crowell & Davis, 2011; Crowell et al., 2010; Gray, Sweeney, Creaby, & Smith, 2012; Wood & Kipp, 2014; Zhang, Chan, Au, An, Shull, et al., 2019; Zhang, Chan, Au, An, & Cheung, 2019). Increased tibial acceleration has been related to tibial stress fractures (Davis et al., 2004; Manson, McKean, & Stanish, 2018). Interventions focusing on decreasing tibial acceleration could, therefore, help to reduce the prevalence of this injury and aid rehabilitation in the running population. Since the duration of an intervention could influence the outcome (Adamovich et al., 2009; Agresta & Brown, 2015), single sessions of feedback on peak tibial acceleration will be discussed separately from feedback interventions with several sessions.

2.4.2 A single session of biofeedback

In recent studies (Creaby & Smith, 2016; Crowell et al., 2010; Gray, Sweeney, Creaby, & Smith, 2012; Wood & Kipp, 2014) participants were able to reduce mean peak tibial acceleration with a single session of biofeedback. In the study of Crowell et al. (2010), five participants ran on a treadmill for ten minutes at a self-selected pace, ranging from 2.4 to 2.6 m/s, while receiving visual feedback. Target acceleration was set at approximately 50 per cent of peak tibial acceleration. Participants decreased mean peak tibial acceleration from 9.0 g at the baseline measurement to 6.3 g at the post-measurement, a decrease of 30 per cent. Gray et al.'s (2010) study compared the visual feedback method, consistent with that of Crowell et al. (2010), to verbal feedback. Eight runners, received two feedback sessions a week apart, in which they ran for 10 minutes at a speed of 3 m/s, while they received either visual or verbal feedback. Verbal feedback consisted of a clinician providing them with verbal commands. A significant effect was found for the visual feedback condition, comparing the feedback trial (peak tibial acceleration = 3.26 g ± 1.20 g) to the baseline measurement (peak tibial acceleration = 3.89 g ± 1.54 g), but no significant effects were found comparing both the effects of visual (peak tibial acceleration = 3.20 g ± 0.67 g) and verbal (peak tibial acceleration = 3.60 g ± 1.49 g) feedback during the retention measurement to the baseline measurements (peak tibial acceleration, visual = 3.89 g ± 1.54 g; verbal = 4.41 g ± 1.64 g). On the contrary, Creaby and Franettovich Smith (2016) found significant beneficial effects of both visual and verbal feedback comparing the measurement taken during the feedback (peak tibial acceleration, visual = 3.82 g; verbal = 4.37 g), during the retention direct after the feedback (peak tibial acceleration, visual = 4.33 g; verbal = 4.13 g), and during the retention after a week (peak tibial acceleration, visual = 4.21 g; verbal = 4.48 g) to the baseline measurements (peak tibial acceleration, visual = 5.34 g;

verbal = 5.74 g). The methods in the study of Creaby and Frannettovich Smith (2016) were similar to Gray et al. (2010), twenty-two runners received 10 minutes of either visual or verbal feedback while running at a treadmill at a speed of 3 m/s. The difference between the studies was that in the study of Gray et al. (2010) participants received both feedback conditions with a week apart, while in the study of Creaby and Frannetovich, two groups were formed, with each group receiving either visual or verbal feedback. Both studies of Gray et al. (2010) and Creaby and Frannettovich (2016) did not find a significant difference between a group which received biofeedback compared to a group who got clinician-guided feedback (Creaby & Franettovich Smith, 2016). However, both groups received different forms of feedback. The visual feedback group received continuous visual feedback, whereas the clinician-guided feedback group received intermittent auditory feedback. As described in section 2.3.6, continuous feedback might be less effective than intermittent feedback (Schmidt et al., 1989). Further, both the clinician guided and biofeedback groups only received one feedback session. This might not be enough to produce a beneficial effect on the intervention (Adamovich et al., 2009; Agresta & Brown, 2015) and further sessions might be required. An increase in the number of sessions might, therefore, show a divergence in the effectiveness of the two approaches.

Wood and Kipp (2014) published the only study in which auditory feedback was given on mean peak tibial acceleration. Nine participants were asked to run at a comfortable, fast, jog pace (3.1 m/s ± 2.5 m/s), while they received two times, five minutes of auditory feedback. The target was set at 10 to 15 per cent of the baseline measurement. The numerical difference between the target and peak tibial acceleration was scaled to the pitch of a beep and participants were asked to run without any beeps or keep the pitch as low as possible. A significant decrease in mean peak tibial acceleration was found, comparing the retention measurement (mean peak tibial acceleration = 5.4 g ± 0.7g) to the baseline measurement (mean peak tibial acceleration = 5.9 g ± 0.7g). Both visual (Creaby & Franettovich Smith, 2016; Crowell et al., 2010) and auditory (Wood & Kipp, 2014) feedback have shown to be beneficial, with decreases in mean peak tibial acceleration during biofeedback sessions. However, larger decreases were seen when visual feedback was given (21 per cent and 30 per cent), compared to when auditory feedback was given (8 per cent). However, these results should be interpreted with care since different methods were used in the studies. Participants in the study of Wood and Kipp (2014) ran at faster speeds, which could have influenced their capability to reduce tibial acceleration. At higher speeds, the variability in the different joint angles of runners decreases (Valizadeh, Khaleghi, & Abbasi, 2018) and, therefore, it is likely that fewer solutions to reduce tibial acceleration can be found.

The largest decrease in mean peak tibial acceleration of a single session of feedback was found in a study by Crowell et al. (2010). In this study the baseline measurement tibial acceleration was 9 g and participants found a decrease of 30 per cent. The other studies had baseline measurements of mean peak tibial acceleration variating between 3.89 g and 5.9 g and decreased 8 to 21 per cent in mean peak tibial acceleration, comparing the baseline measurement to the post measurement. The higher percentage reduction in mean peak tibial acceleration achieved in the study by Crowell et al. (2010) is likely due to their participants' higher baseline measurements of tibial acceleration. A flooring effect could have occurred in the other studies. Therefore, it is likely that a higher peak tibial acceleration at baseline could allow for a higher percentage decrease in mean peak tibial acceleration, this should be noted when comparing percentage change between studies.

Based on these results (Creaby & Franettovich Smith, 2016; Crowell et al., 2010; Wood & Kipp, 2014) one session of biofeedback can reduce mean peak tibial acceleration. Reductions in mean peak tibial acceleration differed between 8 per cent and 30 per cent. Visual biofeedback seemed to be more beneficial compared to auditory feedback for a single session.

2.4.3 Biofeedback intervention

Beneficial effects were found for five feedback intervention studies on tibial acceleration (Bowser et al., 2018; Clansey et al., 2014; Crowell & Davis, 2011; Zhang, Chan, Au, An, Shull, et al., 2019; Zhang, Chan, Au, An, & Cheung, 2019). In the study by Crowell and Davis (2011), ten participants received feedback on tibial acceleration while running at a self-selected speed on a treadmill. Participants were able to reduce peak tibial acceleration from 8.1 g at the baseline measurement to 4.5 g at the one-month retention measurement. Feedback was given visually, a target was set at 50 per cent of the baseline measurement and the feedback was faded over eight feedback sessions. Crowell and Davis (2011) found an average of 44 per cent decrease in mean peak tibial acceleration in their participants from the baseline measurement to the one-month follow-up measurement. The methods used by Crowell and Davis (2011) were also applied by Bowser et al. (2018), these methods included participants being selected based on having a higher tibial acceleration, eight visual feedback sessions, feedback target set at 50 per cent, and fading of the feedback. Bowser et al. (2018) reported a decrease of 41 per cent after a month (6.24 g) and 38 per cent after a year after the intervention (5.56 g), compared to the baseline measurement (10.57 g) for 19 participants. Zhang, Chan, Au, An, Shull, et al. (2019) and Zhang, Chan, Au, An, & Cheung (2019) used a similar protocol to Crowell and Davis (2011) and Bowser et al. (2018), but the target was set at 80% of the mean peak tibial acceleration measured in the pre-training assessment. In their studies, reductions in mean peak tibial acceleration of 28.5 per cent (Zhang, Chan, Au, An, & Cheung, 2019) and 37.3 per cent (Zhang, Chan, Au, An, Shull, et al., 2019) were found comparing the post-measurement taken within one week after the intervention to the baseline measurement. They further found the reduction in mean peak tibial acceleration to be transferable to outdoor level running (Zhang, Chan, Au, An, & Cheung, 2019). Participants were able to find a significant reduction in mean peak tibial acceleration comparing pre- and post-measurements during laboratory- (reduction of 28.5 per cent) and field-based measurements (reduction of 11.7 per cent), while participants only received feedback in the laboratory. Further, participants were able to find reductions of 35 to 37 per cent across running speeds varying ten per cent around their self-selected running speed, while feedback was only given while participants ran at their self-selected speed (Zhang, Chan, Au, An, Shull, et al., 2019). These reductions across running speeds were not only found in the leg where feedback was given on, but also in the untrained leg with reductions varying between 22 and 30 per cent depending on the running speed (Zhang, Chan, Au, An, Shull, et al., 2019). These results suggest that the learned task is transferable to other tasks, such as level running in the field and running at different speeds.

Clansey et al. (2014) used different methods compared to Crowell and Davis (2011). Clansey et al. (2014) used a traffic-light symbol, in which the mean peak tibial acceleration was calculated over the previous five steps. If this mean was above 75 per cent of the baseline mean peak values, a red light was shown, if it was between 50 per cent and 75 per cent an orange light was shown, and if it was below 50 per cent a green light was shown. Feedback was given, while participants ran at 3.7 m/s on a treadmill. Clansey et al. (2014) further compared their results to a control group for which no significant difference was found, comparing a baseline measurement to a retention measurement taken a month after running six sessions on a treadmill without feedback. Further, they concluded that the feedback did not negatively affect the running economy (Clansey et al., 2014). Clansey et al. (2014) found a 22 per cent decrease in mean peak tibial acceleration, with participants reducing mean peak tibial acceleration from 10.67 g to 8.30 g. This difference in percentage decrease between the study of Clansey et al. (2014) and the studies described before (Bowser et al., 2018; Crowell & Davis, 2011) could exist due to differences in the methods between the different studies. Even though Clansey et al. (2014) did give summary feedback, they did not fade the feedback, as Crowell and Davis (2011) and Bowser et al. (2018) did.

In conclusion, based on the results of previous research, compared to summery feedback (Clansey et al., 2014), continuous, faded feedback (Bowser et al., 2018; Crowell & Davis, 2011) appeared to more beneficial at a one-month follow-up measurement. Further, the reduction of mean peak tibial acceleration is transferable to other tasks, such as running in the field and running at different speeds (Zhang, Chan, Au, An, & Cheung, 2019). Finally, previous studies (Bowser et al., 2018; Adam Charles Clansey et al., 2014; Crowell & Davis, 2011; Zhang, Chan, Au, An, Shull, et al., 2019; Zhang, Chan, Au, An, & Cheung, 2019) have found beneficial effects of biofeedback interventions aimed at reducing tibial acceleration, with reductions variating between 22 per cent and 44 per cent.

2.4.4 Kinematic response

The kinematic responses of runners to a biofeedback intervention to reduce tibial acceleration were explored in one study by Clansey et al. (2014). Clansey et al. (2014) investigated the kinematic strategies participants used to reduce tibial acceleration after six sessions of biofeedback and found that most adaptations were made in the foot (foot strike angle: pre = 12.78° ± 9.00°, one-month post = 7.16° ± 11.60°) and ankle (ankle dorsiflexion: pre = 3.69° ± 5.59°, one-month post = -2.74° ± 10.09°). Further, a reduction in heel velocity at initial contact (pre = 0.36 m/s ± 0.27 m/s, post = 0.19 m/s ± 0.14 m/s) was found comparing the baseline measurement to the post-test. The adaptations made in the ankle consisted of runners changing from a rearfoot contact to a midfoot contact, accompanied by a more plantarflexed ankle (Clansey et al., 2014). Clansey et al. (2014) found no significant adaptations were made in the knee (knee flexion angle: pre = 12.80° ± 7.05°, one-month post = 11.46° ± 5.30°) or hip joint (hip flexion angle: pre = 39.66° ± 14.55°, one-month post = 37.64° ± 5.95°) for a group of runners. The reason for mean peak tibial being decreased with a change in foot strike angle might be related to the force vector being increased from the ankle joint axis of rotation, which could increase the impact of energy that is absorbed in the ankle joint (Derrick, Hamill, & Caldwell, 1998). This mechanism will allow muscles to act eccentrically, which will improve the impact-attenuation during running (Derrick et al., 1998). Further, by landing with a more plantarflexed foot, the ankle will be able to dorsiflex more after the impact and therefore the period of time required to change a runners' downward velocity could be increased (Bishop, Fiolkowski, Conrad, Brunt, & Horodyski, 2006).

2.4.5 Individual response to a biofeedback session

Crowell et al. (2010) observed that in a group of runners that were asked to reduce their tibial acceleration, individual differences existed and responders, as well as non-responders, were found. Even within the responders, differences were found in reductions of peak tibial acceleration, variating from 17% to 60%. With participants expected to respond differently to feedback, a typical statistical analysis of group data such as done in the study by Clansey et al. (2014) might have masked individual changes. These individual strategies of runners could give a better insight into the difference between responders and non-responders. By obtaining better insight into how participants respond to the feedback, the feedback interventions could be improved, which could help to further reduce participants tibial acceleration and therefore possibly the prevalence of tibial stress fractures. The expected changes in the running gait pattern and how these changes might relate to injuries will further be explained in the next section.

2.5 Running patterns and injuries

2.5.1 Introduction

In the studies following in this programme of research, a specific focus was on reducing tibial acceleration during running with the use of biofeedback. As found in a study by Clansey et al. (2014) a change in foot strike angle might be expected after a biofeedback intervention aimed at reducing tibial acceleration. The following sections will further explore this adaptation, but will also describe possible other adaptations that might be found when participants receive biofeedback on mean peak tibial acceleration. Further, these changes will be related to possible injuries.

2.5.2 Change in foot contact pattern and reduction in heel velocity

Previous research by Clansey et al. (2014) reported that a reduction in tibial acceleration was accompanied by group changes in foot strike angle, with participants moving from a rearfoot to midfoot strike pattern, and a significant increase in ankle plantarflexion. No significant changes were found in neither hip nor knee kinematics at initial contact (Clansey et al., 2014). As well as finding ankle mechanical adaptations, Clansey et al. (2014) found participants' reduced their heel velocity at initial contact. Reduced heel velocity at initial contact was predicted to have a strong association with reductions in impact loading (Gerritsen, van den Bogert, & Nigg, 1995). A reduction in heel velocity is an outcome of a kinematic strategy.

A change in the foot contact pattern is likely to change other biomechanical parameters as well. In their systematic review with meta-analysis, Almeida, Davis and Lopes (2015) found significant differences between forefoot and rearfoot strikers, at initial contact, for foot and knee angles. A forefoot strike resulted in increased plantarflexion (mean difference = 16.06°) and knee flexion at initial contact (mean difference = 3.08°) compared to rearfoot strikers. It was further reported that forefoot strikers had decreased vertical loading rates (mean difference = 23.93 bodyweight/s) compared to rearfoot strikers (Almeida et al., 2015). Forefoot strikers (9.88 g ± 2.51 g) also experienced significant lower tibial acceleration values compared to rearfoot (12.24 g ± 3.59 g) and midfoot strikers (11.82 g ± 2.68 g) during a marathon (Ruder, Jamison, Tenforde, Mulloy, & Davis, 2019). In their review, Goss and Gross (2012) found similar results to Almeida et al. (2015), they further found greater angular work at the ankle and decreased angular work at the knee in forefoot contact compared to rearfoot contact. Increased work at the knee could result in higher patellofemoral and tibiofemoral compressive forces, which could lead to increased knee injury risk. In contrast, increased ankle work by eccentric control of the triceps surea might cause Achilles tendinopathy and calf muscle strains. So where rearfoot strikers might be more prone to knee injuries, forefoot strikers might be prone to calf injuries (Goss & Gross, 2012). Next to a difference in the sort of injury, rearfoot strikers are twice as likely to sustain repetitive stress injuries than forefoot strikers (Daoud et al., 2012). It should further be noted that a forefoot contact pattern has been associated with a shorter stride length, but an increased stride frequency (Goss & Gross, 2012). An increased frequency will result in more impacts per unit of time and distance and an increased amount of impact could cause overuse injuries (Goss & Gross, 2012).

Even though Clansey et al. (2014) found participants moving from a rearfoot to midfoot strike pattern, and significantly increasing ankle plantarflexion, they did not find increased knee flexion at initial contact as would be expected based on the reviews of Almeida et al. (2015) and Goss and Gross (2012). This could mean that either just a change in the ankle joint was sufficient to reduce mean peak tibial acceleration or that participants found other strategies which cancelled out changes found in the knee joint. For example, a decrease in knee flexion angle at initial contact with an increase in knee excursion during the stance phase could also reduce the impact by functioning as a shock attenuating mechanism (Milner, Hamill and Davis, 2007). As well as a change in foot strike pattern, other shock-absorbing strategies exist, these other shock-absorbing strategies will be further explained in the following section.

2.5.3 Shock-absorbing running techniques

As described in section 2.5.2 a change from rearfoot strike to forefoot strike is likely to result in increased plantarflexion and knee flexion at initial contact, shorter stride length, increased stride frequency (cadence) and a decrease in knee flexion excursion (Almeida et al., 2015; Goss & Gross, 2012). However, an increase in knee excursion during the stance phase could also reduce the impact by functioning as a shock attenuating mechanism (Milner, Hamill and Davis, 2007). Other shock-attenuating mechanisms include increased ankle eversion excursion (Hreljac, Marshall and Hume, 2000; Almeida, Davis and Lopes, 2015) or hip adduction excursion (Novacheck, 1998), and a decreased landing distance, also known as the foot displacement relative to the pelvis (Diss, Doyle, Moore, Mellalieu, & Bruton, 2018; Lieberman, Warrener, Wang, & Castillo, 2015). These shock-attenuating mechanisms are based on either prolonging the period of time required to change a runners' downward velocity to zero or by reducing the amount of change in velocity (Goss & Gross, 2012). Prolonging the time required to change a runners' downward velocity could be achieved by increasing the range of motion or joint angle excursion (Bishop et al., 2006). Reducing the amount of change in velocity could be accomplished by reducing the vertical height from which the body's centre of mass falls (Heiderscheit, Chumanov, Michalski, Wille, & Ryan, 2011). This will lead to a more gliding style as opposed to bouncing up and down. This could be achieved by a reduction in the range of motion or joint angle excursion, but an increase in joint angle at initial contact. Since this intervention aimed at reducing tibial shock, the variables associated with shock-attenuating mechanisms were included in the current study to be able to establish the kinematic strategies participants used. These parameters included: foot strike angle, ankle dorsiflexion at initial contact, knee flexion at initial contact, knee flexion excursion, hip flexion at initial contact, hip adduction excursion, ankle eversion excursion, cadence, landing distance, and heel velocity at initial contact.

Changing a running pattern to reduce tibial acceleration might reduce the prevalence of tibial stress fractures, but could put more load on other structures. As described in section 2.5.2, rearfoot strikers might be more prone to knee injuries, while forefoot strikers might be prone to calf injuries (Daoud et al., 2012; Goss & Gross, 2012). The following sections will describe which biomechanics are related to tibial stress fractures, since that is the parameter of interest, but also the biomechanics related to other injuries, since a change in gait pattern might affect these other parameters related to injuries. However, before focussing on the biomechanics an insight will be given on how overuse injuries can occur.

2.5.4 Overuse injuries

Overuse injuries are common in runners. They include Achilles tendinitis, chondromalacia patellae, plantar fasciitis, medial tibial stress (shin splints), and stress fractures (Hreljac, 2004; Hreljac, Marshall, & Hume, 2000). Overuse injuries result from stress applications within an inadequate time. When stress is applied to tissue with sufficient time between the loading and below the tensile limit, the structure will be positively remodelled. A theoretical fatigue curve, which shows the relationship between injury and the frequency of applied stress and the level of stress, can be found in Figure 2.1. When the structure is subjected to a stress level and frequency above the fatigue curve an injury would be obtained, while an injury can be avoided when staying underneath the curve. The curve, however, is not fixed, the curve is dynamic and can shift upwards when an optimal number of repetitions in combination with an optimal stress level can be found which would strengthen the structure. The opposite can be true as well, when the level of stress is lowered the curve can shift downwards which would weaken the structure, which could, in turn, increase the likelihood of overuse injuries. As well as the frequency of the stress that is applied, the type of stress is important (Hreljac, 2004). Impact force is one of the most important forces acting upon the body;

it has a short duration with a relatively high magnitude. Impact forces in running vary in magnitude from 1.5 to 5 times the body weights and last between 10 to 30 milliseconds (Nigg, Denoth, & Neukomm, 1981). Several authors have, therefore, suggested that impact forces are associated with overuse injuries (Hreljac, 2004; Zadpoor & Nikooyan, 2011).

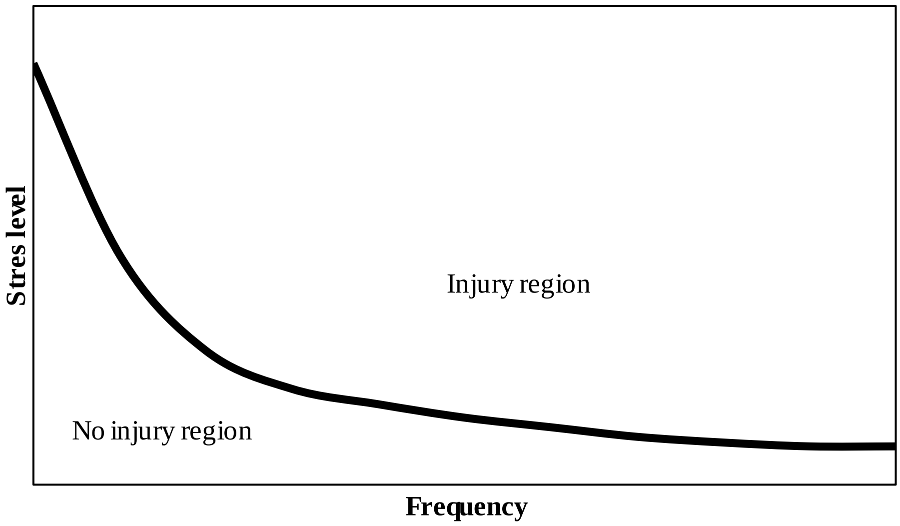

Figure 2.1 Fatigue curve, showing the theoretical relationship between stress application and frequency, adapted from Hreljac (2004).

The cause of overuse injuries is likely to be multifactorial and diverse (Hreljac, 2004). Extrinsic factors influencing injuries include footwear, running surface, weekly mileage, gender, training adaptation, and injury history (Hreljac, 2004; Willems et al., 2006). Most overuse injuries could be attributed to training errors. An injury will occur when the runner went over the fatigue curve. This curve differs from individual to individual and it is likely that there is an underlying anatomical or biomechanical feature that prevents some runners to train as intensely as compared to other runners (Hreljac, 2004). Intrinsic factors include: longitudinal arches (pes cavus), ankle range of motion, leg length discrepancies, lower extremity alignment abnormalities (Hreljac, 2004), injury history, decreased muscle strength, muscle fatigue, and inflexibility (Willems et al., 2006). However, different studies found contradictory results (Hreljac, 2004). Further, static measurements were less associated with injury risk compared to dynamic measurements (Kaufman, Brodine, Shaffer, Johnson, & Cullison, 1999), that in combination with impact forces being of importance and the likelihood of underlying biomechanical differences between runners causing overuse injuries, the focus will be on the relation between biomechanics and injuries in the following paragraphs.

2.5.5 Biomechanics related to tibial stress fractures

Stress fractures are common injuries in runners (Milner, Davis, & Hamill, 2006; Milner, Ferber, Pollard, Hamill, & Davis, 2006). They need sufficient recovery time, lasting 6-12 weeks, which makes them the most serious overuse injuries in terms of recovery time (Harmon, 2003; Milner, Davis, et al., 2006; Tuan, Wu, & Sennett, 2004). The tibia is the most commonly injured bone with tibial stress fractures accounting for between 26 per cent to 49 per cent of all stress fractures (Bennell et al., 1995; Brukner et al., 1996; Matheson et al., 1987; McBryde, 1985).

As described in section 2.5.4 overuse injuries, such as tibial stress fractures, result from stress applications within an inadequate time. When stress is applied to tissue with sufficient time between the loading and below the tensile limit, the structure will be positively remodelled. However, when the structure is subjected to a stress level and frequency above the fatigue curve an injury would be obtained. The impact during running could increase the stress on the bone. To monitor tibial stress fractures in runners, a direct *in-vivo* bone strain measurement would be ideal, but since this method would involve surgery, it is too invasive and impractical (Burr et al., 1996). Tibial acceleration is, therefore, commonly used as a proxy measurement for the impact forces experienced at the tibia, based on Newton's second law (F=m*a) (Sheerin, Reid and Besier, 2019). The relationship between tibial acceleration and bone strain is, however, unclear. A bone strain is not only dependent on the external ground reaction force, which originates from initial contact, but contracting muscles also apply forces on the bone, which could both increase and decrease bone strain (Matijevich, Branscombe, Scott, & Zelik, 2019). However, in prospective studies by Davis, Milner and Hamill (2004) and Manson, McKean and Stanish (2018), increased peak tibial acceleration during the loading phase in running was suggested to be related to tibial stress fractures and could, therefore, be an important risk factor for injury. Other risk factors which were related to tibial stress fractures included instantaneous and average loading rates. However, no significant relation was found between peak ground reaction force and tibial stress fractures (Davis et al., 2004; Manson et al., 2018). In a retrospective study by Milner et al. (2006) and a systematic review by Zadpoor and Nikooyan (2011), similar results were found. Further, Milner et al. (2006) found for every 1 g increase in mean peak tibial acceleration the likelihood of a history of tibial acceleration increased by a factor 1.361. They further concluded that tibial stress fractures are more related to loading rates and less to the impact peak or the posterior loading rates during braking. Since ground reaction forces represent the net forces working on the centre of mass, tibial acceleration gives a better estimate of impact loading on the bone compared to ground reaction forces. Tibial acceleration might, therefore, be a more sensitive discriminator for runners with a higher risk for tibial stress fractures (Milner, Ferber, et al., 2006; Shorten & Winslow, 1992).

Another retrospective study (Pohl, Mullineaux, Milner, Hamill, & Davis, 2008) did not find peak tibial acceleration or vertical loading rate that discriminated between runners with or without tibial stress fractures. Instead, they found large effects sizes for increased peak hip adduction, absolute free moment (moment during stance about a vertical axis due to friction between the foot and the ground), and rearfoot eversion. Further having a number of risk factors increases the odds of a subject falling into the tibial stress fracture group, highlighting the multifactorial nature of the injury (Pohl et al., 2008). Milner, Davis and Hamill (2006) also found an increase in free moment to be related to runners who sustained a tibial stress fracture and Milner, Hamill, and Davis (2007) found knee stiffness to be increased in runners who sustained a tibial stress fracture.

Different parameters appeared to be related to tibial stress fractures. However, increased peak tibial acceleration was found to be related in two prospective studies and concluded to be a proxy measurement of tibial shock in the literature. Therefore, in this programme of research, axial tibial acceleration was used as a measure of tibial shock and related to tibial stress fractures.

2.5.6 Biomechanics related to other injuries

In this section, examples will be given of parameters which are related to injuries other than tibial stress fractures. Changing a running pattern to reduce tibial acceleration might reduce the prevalence of tibial stress fractures, but could put more load on other structures. Even though there is a large role for kinetics in running injuries, in the current section only kinematic parameters related to injuries will be discussed since there was no possibility of measuring ground reaction forces during this programme of research. Several kinematic parameters have been related to injuries. Increased peak eversion during stance was already related to tibial stress fractures in runners (Pohl et al., 2008). However, it is also associated with other overuse injuries (Hreljac, 2004). In their review, Hreljac (2004) concluded that not only the magnitude of the eversion was of importance but also the timing. In running eversion (sub-movement of pronation) typically occurs during the absorption phase (Novacheck, 1998). The transverse tarsal joint 'unlocks' during pronation allowing it to function as a shock absorber by increasing the flexibility. The peak pronation occurs around forty per cent of stance, after which the foot then supinates and becomes neutral at seventy per cent of the stance phase. The transverse tarsal joint then locks to create a more rigid foot to act as a lever for push-off, when the generation phase is reached (Novacheck, 1998). Therefore, eversion (sub-movement of pronation) is not only a problem when it is increased or decreased during the impact; injuries could further be associated with over eversion after mid stance, where the foot should be neutral (Hreljac, 2004). In a review by Chuter and Janse de Jonge (2012), which included prospective studies, excessive foot eversion was suggested to increase risk of exercise-related lower leg pain in physical education students and medial tibial stress syndrome in military recruits. However, in runners, no association was found between excessive eversion and risk of general lower limb injury, Achilles tendinopathy, patellofemoral pain, or iliotibial band friction syndrome. They further suggested excessive eversion could have a protective effect against the development of tibial and femoral stress fractures. However, this was based on studies in which eversion was measured in military recruits and during walking (Chuter & Janse de Jonge, 2012) and as shown these results might differ from runners.

Other parameters that have been linked to different injuries including knee injuries and iliotibial band syndrome are peak hip adduction and hip internal rotation in both retrospective and prospective studies (Agresta & Brown, 2015; Goss & Gross, 2012; Noehren, Pohl, Sanchez, Cunningham, & Lattermann, 2012). But as with eversion, hip adduction is expected to absorb the shock (Novacheck, 1998), however, when excessive hip adduction is experienced it may result in greater compressive stresses on the patellofemoral joint. Both hip adduction and internal rotation can contribute to greater stress within the tibia (Noehren et al., 2012).

As concluded before by Hreljac (2004) the cause of overuse injuries is likely to be multifactorial and diverse. Therefore, the results above should be interpreted with care. However, to gain an understanding on how a change in gait pattern, to reduce mean peak tibial acceleration, could potentially influence other gait parameters related to injuries, excessive peak eversion and hip adduction were included to the parameters of interest in this programme of research. Though there are other risk factors that are related to injuries, these were beyond the scope of the programme of research. The decision to focus on excessive peak eversion and hip adduction was made as they are associated with over overuse injuries in running (Chuter & Janse de Jonge, 2012; Noehren et al., 2012) and the current programme of research used these as a marker for the potential development of injuries from changing gait patterns.

2.5.7 Definition of the parameters of interest

Because there is a discrepancy in the literature on the definition of gait parameters, this section will outline how the parameters of interest will be defined in the current programme of research. Initial contact is defined as the moment the foot contacts the ground and it defines the start and the end of a gait cycle (Novacheck, 1998).

Kinematics is used to describe the movement in angles. In this programme of research, the angles will be described in three different planes in which angles are mostly studied. These include: the sagittal plane, the frontal plane and the transverse plane. The sagittal or longitudinal plane is a plane that goes through the body from the front to the back and divides the body between the left and right side. In this plane, the flexion and extension angles in the hip and knee joints and plantar- and dorsiflexion angles in the ankle joint are determined (Figure 2.2). The frontal or coronal plane is a plane that goes through the body from left to right and divides the body in front and back. In this plane abduction and adduction in the hip and knee joints and ankle inversion and eversion can be determined. The transverse plane is a horizontal plane that divides the body to a bottom and upper section. In this plane the internal and external rotation in the hip and knee joint and the progression angle (toe-in vs. toe-out) in the ankle joint are determined. The movements in the frontal and transverse planes are small in magnitude in comparison to the sagittal plane (Novacheck, 1998).

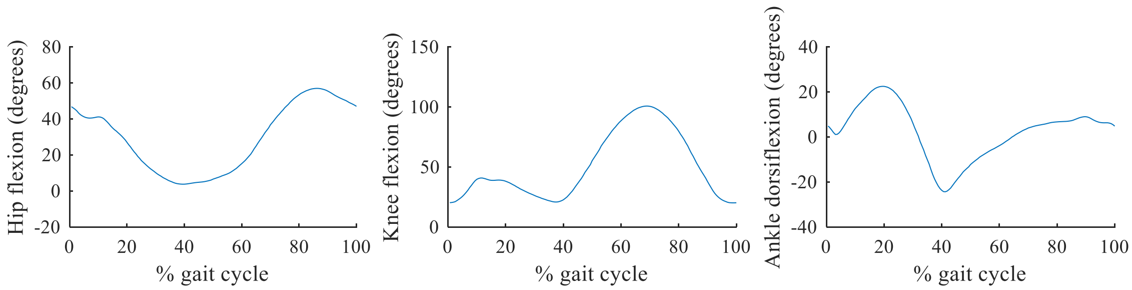

Figure 2.2 Hip flexion (left), knee flexion (middle) and ankle dorsiflexion (right) patterns in the sagittal plane. Figures display the mean of the baseline session of participant 4 of the intervention study.

The ankle biomechanics are discussed here in a separate section because of the complexity of the joint. The ankle joint is made up of the lower leg and the foot, and with the lower leg having two bones but the foot having twenty-six bones, complexity is added to the representation of the ankle joint. The ankle joint itself is made up of three different joints: the subtalar (talocalcaneal), tibiotalar (talocrural), and transverse-tarsal (talocalcaneonavicular) joint (Brockett & Chapman, 2016). By combining the motions across the different joints, three-dimensional movements can be described as supination and pronation (Brockett & Chapman, 2016; Novacheck, 1998). Supination is a combination of plantarflexion, inversion and toeing-in of the foot, causing the sole of the foot to face medially. Pronation is the combination of dorsiflexion, eversion and toeing-out, causing the sole of the foot to face laterally. So where plantar-/dorsiflexion occurs in the sagittal plane, toeing in/out in the transverse plane and inversion-eversion in the frontal plane, pronation and supination are triplanar movements (Brockett & Chapman, 2016; Novacheck, 1998). It should be noted that in the literature pronation and eversion and supination and inversion are sometimes used interchangeably, but in this programme of research inversion/eversion are frontal plane motions of the ankle (the talocalcaneal, tibiotalar, and transverse-tarsal joint), whereas pronation/supination are triplanar motions of the foot/ankle complex.

2.6 Chapter summary

In this chapter, several gait limitations and treatment options were discussed to give a broader view of the field. Biofeedback is one of the less invasive options and has been beneficial in different participant groups. One of these participant groups includes runners. Tibial stress fractures are a common injury in runners. Increased peak tibial acceleration has been related to this injury and, therefore, reducing tibial acceleration could help to prevent the injury. Several studies have found beneficial effects of feedback on tibial acceleration, but none of these studies focused on the time participants took to modify tibial acceleration in response to real-time feedback within the feedback session. The time participants take to modify tibial acceleration and the strategies they use could be of interest to receive a better insight into how long feedback should be given to participants to allow them to respond accordingly.

One previous study focused on the strategy participants used to reduce tibial acceleration with feedback and found that runners went from a forefoot contact to a midfoot contact, accompanied by a more plantarflexed ankle angle, no differences were found in the knee or hip joint. A forefoot strike compared to a rearfoot strike was expected to result in increased plantarflexion and knee flexion at initial contact, decreased vertical loading rates, greater angular work at the ankle and decreased angular work at the knee. Other shock-attenuating mechanisms include increased knee flexion excursion, ankle eversion excursion, or hip adduction excursion, and a decreased landing distance. Finally, kinematics were discussed in relation to overuse injuries. The cause of overuse injuries is likely to be multifactorial and diverse. Excessive eversion or mistiming of the eversion, excessive peak hip adduction and hip internal rotation might be related to different overuse injuries.

Chapter 3: Methodology

3.1 Introduction

This chapter describes the development of the feedback system. Additionally, this chapter considers different methodological approaches in measuring tibial acceleration and gait human gait patterns. A motion capture system and accelerometers were used to measure participants' gait mechanics, consequently, different methodological approaches needed consideration as described in objective two. These considerations included the use of different sensors, data processing, and filtering. All of these methodological considerations are explored and justified in this chapter. Finally, since individual responses to the intervention were of interest, the choice of a single-subject analysis will be discussed.

3.2 Measurement of tibial acceleration

3.2.1 Sensors

In this programme of research, accelerometers were used to estimate the impact loading of the tibia at initial contact. As described in section 2.5.5, increased repetitive loading of the tibia at initial contact has been associated with tibial stress fracture risk. An accelerometer directly attached to the bone would give the most accurate estimate of tibial acceleration (Lafortune, Henning, & Valiant, 1995). However, bone mounted accelerometers are invasive and impractical. Skin mounted accelerometers are an alternative and their use has become commonplace within routine lab analysis. Skin mounted accelerometers have been found to overestimate tibial acceleration by up to 6.4 g, due to movement and resonance of the sensor (Lafortune et al., 1995). However, the signal of the skin mounted accelerometer may represent bone mounted sensors more accurately with the use of appropriate filtering (Lafortune et al., 1995), lighter accelerometers (Ziegert & Lewis, 1979), and correct sensor placement, (Norris, Anderson, & Kenny, 2014). In the current study, two different skin mounted accelerometers were used, one sensor regarded as the gold standard for measuring tibial acceleration, and a wireless sensor.

Gold standard sensor

Tibial acceleration in the laboratory was measured using a uniaxial accelerometer (PCB Piezotronics, Stevenage, UK, Model: 352C22), with its sensitive axis visually aligned with the long axis of the right tibia. This sensor is regarded as a gold standard for measuring tibial acceleration (Brayne, Barnes, Heller, & Wheat, 2015). The accelerometer was mounted on a small piece of thermoplastic (total mass: 1.65 g), which was attached with double-sided tape to the wireless accelerometer manufactured by RunScribe (Figure 3.1). Both sensors together were then attached to the anteromedial aspect of the right tibia, five centimetres above the medial malleolus and wrapped in cohesive bandage, as described by Barnes, Wheat and Milner (2011). This placement was chosen to maximise the coupling between the sensor and the bone and to minimise soft tissue movement. The measurements in the lab were done with both sensors, to be able to define the reliability of the wireless sensors. The accelerometer was connected via a cable to a PCB signal conditioner (PCB Piezotronics, Stevenage, UK, model: 480E09; gain = 10) and sampled at 1000 Hz.

Figure 3.1 Placement of both sensors on the anteromedial aspect of the right tibia, five centimetres above the medial malleolus.

Wireless sensor

A wireless accelerometer was used to measure tibial acceleration in the field. This was necessary to be able to identify participants with a high tibial acceleration for inclusion in the intervention study. Compared to the gold standard sensor, wireless sensors are low in cost, easy to use and waterproof (Brayne et al., 2015). This makes them more suitable for the measurement of tibial acceleration in the field. The tri-axial, wireless accelerometer was part of an inertial measurement unit (RunScribe version 2, Scribe Labs, California, USA), which also contained a magnetometer and a rate gyroscope, with a total mass of 9.55 g. The wireless sensor was attached to the anteromedial aspect of the right tibia, five centimetres above the medial malleolus (Barnes et al., 2011). The sensor was attached with double-sided tape and overwrapped with cohesive bandage. The wireless sensor started recording when a threshold of 3 g was reached and stopped recording when the signal stayed underneath the threshold for approximately 15 seconds. The signal was sampled at 500 Hz.

3.2.2 Filtering

The acceleration signal was filtered to improve the signal to noise ratio. Whilst filtering can help remove noise from the data, it can also cause unwanted side effects, such as an altered signal, resulting in delayed and reduced peaks (Widmann, Schröger, & Maess, 2015). Concerning the acceleration data, the high-frequency components (10-20 Hz) represent the deceleration of the lower limb, and low frequencies (4-8 Hz) are associated with voluntary leg movement during the contact phase (Sheerin et al., 2019; Shorten & Winslow, 1992). Depending on the sensor used, a resonant frequency (likely to be above 60 Hz) might also be present in the time domain (Sheerin et al., 2019; Shorten & Winslow, 1992).

Power spectral density was calculated to analyse the signal in the frequency domain for the baseline measurement for each participant. Based on visual inspection of the power spectral density a bandpass-filter of 8-60 Hz was chosen, since the low frequency associated with voluntary leg movement were found to be below 8 Hz and resonant frequencies were found to be above 60 Hz. Data were filtered using a Hamming finite impulse response (FIR) filter. FIR filters offer pertinent advantages over more commonly used infinite impulse response filters (such as Butterworth), including a narrow transition band and a steep filter roll-off (Widmann et al., 2015). Since a sharp roll-off was needed to be able to filter out the low frequencies (under 8 Hz), but include the frequencies of interest (10-20Hz), an order of 400 was used. The order was defined by analysing the magnitude response in the frequency domain of the digital filter through visual inspection.

3.2.3 Data processing

Defining the peaks within the tibial acceleration signal

The data collected with the accelerometers was converted from volts into acceleration of gravity (g). After applying the 400^{th} order Hamming band-pass filter with lower and upper cut-off frequencies of 8 and 60 Hz, respectively, in Matlab (Mathworks, R2016a), the mean was subtracted from the data to standardize between measurements and the peaks of the signal were determined. Peaks were determined with the function: "find peaks", with a minimum peak height of 1.5 g and a minimum of 500 ms between peaks. Peaks which were three standard deviations above or below the mean were deleted for the gold standard sensor to exclude missteps. Missteps in the laboratory, while participants were running on a treadmill, could occur due to for example kicking the front of the treadmill. Data were visually checked to ensure the correct peaks were identified.

Defining running in the data measured by the wireless sensor

The wireless accelerometer was used to measure participants in the field during a five-kilometre time trial. Because participants walked around with the sensor before and after the five-kilometre time trial, the threshold could have been reached prior to the run starting and the signal may not have gone under the threshold directly after the run finished. Therefore, to find the peaks where participants were running, the following algorithm was written: within the first 100 steps, the last point was found at which the time difference between two peaks was longer than the mean of the time difference between the first 100 peaks and 3 standard deviations. This point should be the last point a step was more likely to be walking then running. The same calculations were used to find the end of the run, but instead of using the first 100 steps, the final 100 steps were used. The time calculated by the algorithm was in agreement with the time recorded by the event (Appendix B).

The chosen five-kilometre course (for more information, see Appendix C) can be crowded, which might not only force participants to start later it also might force some participants to walk certain narrow sections. To enable comparisons with the laboratory data, in which participants run continuously, walking steps were removed. The steps were removed with the following algorithm: time between every peak was calculated and sorted from shortest to longest; the mean of the 500 shortest times between peaks was taken; these 500 steps were considered to be running, steps that took longer than this mean and four standard deviations were considered to be walking and removed from the data.

Clipped data in wireless sensor

The wireless accelerometer measures up to 16 g, meaning the signals above 16 g were clipped and returned as missing data. To fill these gaps, all missing data were set to 16 g. This is likely to underestimate the true value of peak acceleration for affected participants. However, the purpose of this data was to identify participants with an increased tibial shock rather than accurately measure it. Therefore, having gap-filled data meant participants experienced a high tibial shock and should, therefore, be included in the intervention study.

3.2.4 Comparison data wireless sensor to gold standard sensor

Introduction

To assess the validity of the wireless sensor in measuring field-based peak tibial acceleration, the agreement between the wireless accelerometer and the gold standard accelerometer was calculated.

Methods

11 participants (2 female, 9 male; 43 ± 10 years; stature: 1.74 ± 0.07 m; body mass: 74 ± 11 kg) completed the measurement, following institutional ethical approval (Appendix D). The data used in the current section were measured as a part of the intervention study (chapter 5). While the feedback intervention existed of six sessions, in the current section, the data of both sensors of the baseline measurement of the first session were compared. This baseline measurement consisted of two minutes of running after a six-minute warm-up. The treadmill speed was set to 95 per cent of participants' five-kilometre time-trial (section 5.3).

Tibial acceleration was measured using a gold standard, uniaxial, accelerometer (PCB Piezotronics, Stevenage, UK, Model: 352C22) and a wireless sensor (RunScribe version 2, Scribe Labs, California, USA), with its sensitive axes visually aligned with the long axis of the right tibia. The gold standard accelerometer was mounted on a small piece of thermoplastic (total mass: 1.65 g), which was attached with double-sided tape to the wireless accelerometer. Both sensors together were then attached to the anteromedial aspect of the right tibia, five centimetres above the medial malleolus and wrapped in cohesive bandage, as described by Barnes, Wheat and Milner (2011). The gold standard accelerometer was connected via a cable to a PCB signal conditioner (PCB Piezotronics, Stevenage, UK, model: 480E09; gain = 10) and sampled at 1000 Hz. The wireless accelerometer samples at 500 Hz.

The raw signal from the accelerometers was exported to Matlab (Mathworks, R2016a) and filtered with a 400th order, finite impulse response, Hamming, band-pass filter with lower and upper cut-off frequencies of 8 and 60 Hz, respectively (section 3.2.2). After filtering, the mean of the signal was subtracted from the data to standardize the data and the peaks of the signal were determined (section 3.2.3). The final 20 steps of each measurement were used for comparison, so a total of 220 peaks for each accelerometer were compared (Bates, Dufek & Davis, 1992).

Because the wireless accelerometer started recording when participants' accelerations went above 3 g, the recorded signal was longer, i.e. it included both the warm-up plus the two minutes of the baseline measurement, compared to the measurement done with the gold standard sensor. To gain reassurance the data collected from both sensors were recorded at the same time, data of the wireless sensor was synchronised to the data recorded with the gold standard sensor. All peaks of the gold standard sensor were cross-correlated with the final peaks (the same amount of peaks as the gold standard sensor plus 50 peaks) of the wireless sensor. The delay with the highest cross-correlation was used as an offset of the trace of the signal of the wireless sensor against the gold standard sensor to ensure synchronisation.

To assess the reliability between the sensors, the intraclass correlation coefficient (ICC(2,1)) estimates and their 95% confidence intervals were calculated using SPSS version 24 (SPSS Inc, Chicago, IL), based on a single rater, absolute agreement, two-way random-effects model. A single rater measurement was chosen since a single measurement will be the basis of the actual measurement (Koo & Li, 2016). Further, an absolute agreement was chosen instead of consistency since there was an interest in the absolute difference of the measurements and not the relative (Field, 2014; Koo & Li, 2016; Weir, 2005). A two-way model was chosen since every subject was rated by every sensor (McGraw & Wong, 1996). Finally, a random-effects model was chosen, because measurements taken were a sample from the population and, therefore, generalizable to other participants as well (Field, 2014). Values less than 0.5, between 0.5 and 0.75, between 0.75 and 0.9, and greater than 0.9 indicated respectively poor, moderate, good and excellent reliability (Koo & Li, 2016).

The ICC is prone to several constraints. These constraints include calculating relative reliability and not absolute reliability and being prone to heteroscedasticity, meaning that a high correlation may still mean an unacceptable measurement error. Therefore, a paired samples *t*-test, a Bland-Altman plot, calculation of the limits of agreement (LOA) and the correlation between the absolute difference and the mean of the two methods were calculated as well.

Results

The wireless accelerometer had good agreement with the gold standard sensor, with 95% confidence intervals ranging from poor to excellent agreement (ICC = 0.802, 95% CI = 0.45-0.91) across participants.

Based on the paired-samples *t*-test a significant difference was found between the two sensors ($p<0.001$), with the wireless sensor being 0.87 g higher on average than the gold standard sensor. The Bland-Altman plot can be found in Figure 3.2, the mean ± 95% limits of agreement were calculated to be 0.86 ± 2.15 g. The correlation between the absolute difference and the means of the two methods was r = -0.08 and non-significant ($p=0.233$). From these results, it could be concluded that the data were homoscedastic.

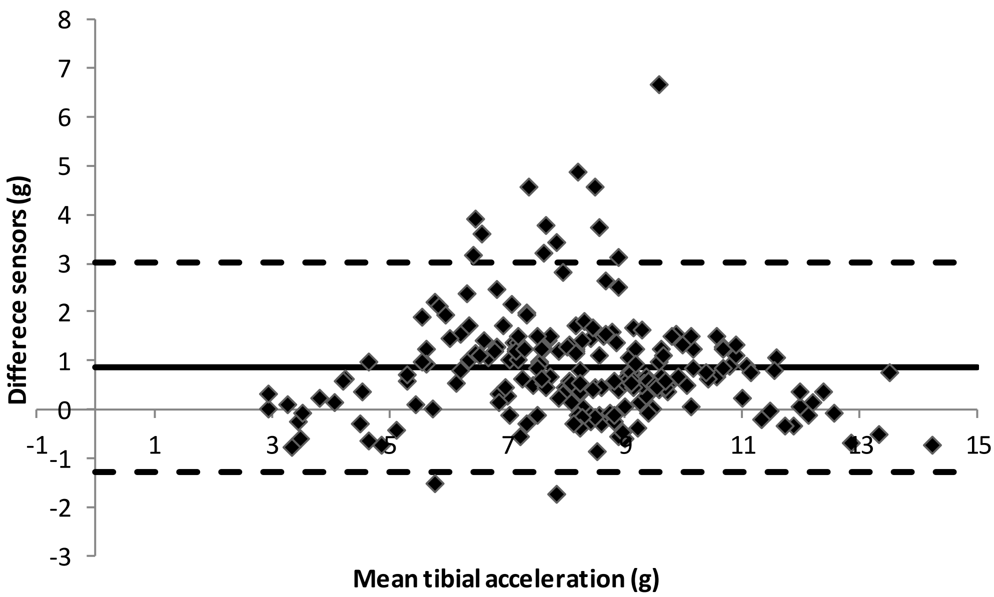

Figure 3.2 Bland-Altman plot and limit of agreement for the mean tibial acceleration for both sensors.

Discussion

A good agreement was found between the sensors based on the intraclass correlation coefficient. However, a systematic error was found between the sensors, with the wireless sensor being higher on average. Brayne et al. (2015) did a similar test, with similar sensors. Brayne et al. (2015) found the wireless accelerometer (RunScribe version 1.0) had a good to excellent agreement with the reference accelerometer at different running speeds (2.5 m/s: ICC = 0.92, 95% CI = 0.76-0.97; 3.5 m/s: ICC = 0.90, 95% CI = 0.71-0.97; 4.5 m/s: ICC = 0.89, 95% CI = 0.66-0.97), showing accuracy to within 1.20–1.65 g based on the 95% confidence intervals of the limits of agreement. Even though Brayne et al. (2015) also reported the means of the wireless sensor to be higher compared to the gold standard sensor, they did not find it affected the ICC as was the case in the current study. Where Brayne at al. (2015) found a difference between the sensors of 0.24 - 0.36 g (increasing with speed) the current study found a difference of 0.87 g, based on the mean limits of agreement. Differences between the current study and the study by Brayne et al. (2015) included a difference in filtering and the synchronising of the sensors. It should further be noted that participants that were included in the current study were included based on increased tibial acceleration, while participants in the study by Brayne et al. (2015) were included based on being rearfoot runners. Finally, in the current study participants were asked to run at 95 per cent of their five-kilometre speed trial, while in the study by Brayne et al. (2015) participants were asked to run at different speeds.

The difference in filtering and synchronising of the sensors could have caused the different findings between the studies. Where in the current study the data were filtered with a 400th order Hamming band-pass filter with lower and upper cut-off frequencies of 8 and 60 Hz, respectively, the data in the study of Brayne et al. (2015) was filtered with a band-pass, second order Butterworth filter with cut-off frequencies of 2 and 75 Hz. Low frequencies (4-8 Hz) are associated with voluntary leg movement during the contact phase (Sheerin et al., 2019; Shorten & Winslow, 1992). By filtering out these lower frequencies a larger difference between the sensors could be found, since the lower frequencies components showed increased power in the frequency domain and therefore are likely to have a large contribution in the time domain. With this contribution gone in the current study, by filtering the lower frequencies out, a larger difference between the sensors might have been found compared to the study of Brayne et al. (2015). A different explanation for the difference in findings between the current study and the study of Brayne et al. (2015) could be the difference in synchronization. In the study of Brayne et al. (2015) both sensors were synchronized by the participant stamping their foot before starting a run, while in the current study an algorithm was used, which might be less accurate. Compared to the study of Brayne et al. (2014) a systematic error was found in the data (which was confirmed by the *t*-test). The data measured with the wireless sensor were used for selecting participants and, therefore, the absolute value of the measurement was not of importance since participants with a high tibial acceleration were selected.

3.3 Measurement of selected kinematic and spatiotemporal parameters

3.3.1 System

Objective five of this programme of research was to establish the kinematic strategies participants used to adapt their gait patterns in response to biofeedback on tibial acceleration. A motion capture system was used to measure kinematic gait patterns. Kinematic data were collected using a 14-camera optoelectronic motion capture system (12 x Raptor model and 2 x Eagle model, Motion Analysis Corporation, Santa Rosa, CA, USA, due to one camera being repaired, the first measurements were with 13 cameras) sampling at either 240 or 250 Hz (between the measurement days the sampling frequency was changed by another researcher which was unnoticed during the measurement). The cameras were placed around the treadmill with a capture volume of 2.25 m, a width of 0.75 m, and a height of 1.5 m, which included the legs and pelvis of the participants. The system was calibrated in two steps. First, the global, right-handed coordinate system was defined using a rigid L-frame with four markers at known locations. Second, the individual cameras were calibrated with the use of a three-marker wand (length 500 mm). The averages of the 3D residuals were under 0.4 mm for each calibration. The positive x-axis was directed mediolateral, pointing perpendicular to the treadmill; the positive y-axis was directed anterior, while the positive z-axis was directed upwards.

3.3.2 Marker set and joint coordinate systems

A marker set was chosen and joint coordinate systems were defined to be able to measure gait patterns. To be able to measure the parameters of interest the right leg and pelvis were chosen. The right leg was chosen, since this was the leg of where tibial acceleration was measured. The marker set was defined in accordance with Cappozzo et al. (1995). A minimum of three non-collinear markers was placed on each segment. Retro-reflective, spherical markers (12.5 mm diameter) were placed on the following anatomical landmarks of the foot, shank, thigh and pelvis (Figure 3.3): anterior superior iliac spines, posterior superior iliac spines, medial and lateral femoral condyles, medial and lateral malleoli, back of the calcaneus (heel) at the same height as the other foot markers, and the first and fifth distal metatarsal heads. The foot markers were placed on the shoe. Four non-collinear tracking markers on moulded thermoplastic shells were secured on the lateral distal aspects of both thigh and shank segments (Manal, McClay, Stanhope, Richards, & Galinat, 2000). These cluster markers were made in accordance with Cappozzo et al. (1997). The cluster marker shells were attached with double-sided tape and wrapped with cohesive bandage. The area where the cluster markers were placed was sprayed with adhesive spray for a better attachment (Milner, 2008). All markers were placed by the same researcher for all measurements.

After participant preparation, a static measurement was recorded in which participants were asked to stand in the anatomical position. Next, a measurement to enable calculation of the functional hip joint was recorded. Participants were asked to perform ten cycles of flexion-extension, abduction-adduction and circumduction movements of the hip with a limited range of motion, since this was demonstrated to be the most accurate for estimating the hip joint centre (Begon, Monnet, & Lacouture, 2007). During the movement trials, medial and lateral femoral epicondyles, and medial and lateral malleoli markers were removed, leaving the remaining markers for tracking.

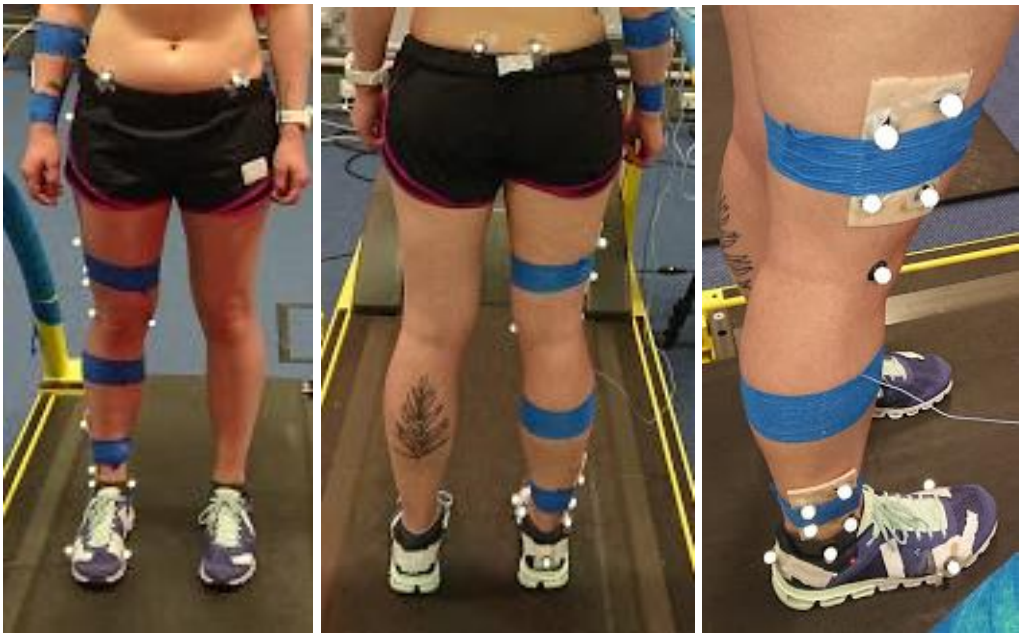

Figure 3.3 Marker set applied to a participant. Left to right: front, back, side.

3.3.3 Data analysis

The data recorded with the motion capture system were first processed in Cortex software (version 5.3, Motion Analysis Corporation, Santa Rosa, CA, USA). The software was used to track and export the raw marker coordinate data. Gaps in the data were filled with the use of the other three other markers when they were present. Alternatively, gaps were filled with the use of a cubic spline, when two or more markers were missing. The exported data were filtered in Visual 3D software (C-Motion Inc., Germantown, USA) with a low-pass, fourth order, zero-phase-shift, Butterworth filter with a cut-off frequency of 14 Hz or 18 Hz (for more information on filtering see section 3.3.4). The filtered signal was used to calculate three-dimensional hip, knee and ankle joint coordinate system angles (Grood & Suntay, 1983) as further described in Appendix E. Joint angles and filtered marker data were exported from Visual 3D (C-Motion Inc., Germantown, USA) and parameters of interest were extracted using Matlab (Mathworks, R2016a).

3.3.4 Filtering

The motion capture data were filtered to remove noise of skin marker movement from the human movement data. Human movement, which is of interest, occurs mainly in the low frequencies, while skin marker movement occurs mainly in the higher frequencies (Milner, 2008). Because of these differences in lower and higher frequencies, the motion capture data were filtered with a low-pass, fourth order, zero-phase-shift, Butterworth filter with a cut-off frequency of 18 Hz. Fourth order, zero-phase shift, Butterworth filters have proven to be suitable for motion capture data (Winter, 2009; Winter, Sidwall, & Hobson, 1974). To define the cut-off frequency for this filter a residual analysis was used instead of the spectral analysis. A spectral analysis is less suitable when the cut-off frequency of the filter is not infinitely sharp, a Butterworth filter has a wider transition zone compared to the FIR filter used in section 3.2.2 and is, therefore, more convenient. The residual analysis compensates for the shortcomings of the filter having a wide transition zone. Where the filter for the acceleration data requires a narrow transition band and a steep filter roll-off to be able to filter out the low frequencies (under 8 Hz), but include the frequencies of interest (10-20Hz), this narrow transition band is not needed for kinematic data. A residual analysis compares the difference between the filtered and unfiltered signals over a wide range of cut-off frequencies. By using this analysis the characteristics of the filter in the transition region are considered in the process as well and are, therefore, more suitable than a spectral analysis (Winter, 2009).

The residual analysis was performed on each running measurement for each participant and each session to define the optimum cut-off frequency (Winter, 2009). The residual analysis was based on the residual analysis of Wells and Winter (1980) and performed in Matlab (Mathworks, R2016a). The calculations can be found in Appendix F. If the marker data were used for displacement calculations, a cut-off frequency of 18 Hz was used, however, when the marker data were used to calculate accelerations based on the markers, the cut-off frequency was set at 14Hz.

3.3.5 Define initial foot contact

Initial contact is the point in where ground reaction force is transferred to the lower extremity and participants were therefore expected to change their gait pattern around this moment. In this programme of research initial contact was defined based on the foot markers as described in a method by Maiwald et al. (2009). In their study, they compared different algorithms to define initial contact based on kinematic data. The foot contact algorithm was recommended when analysing running gait, with a mean difference of one millisecond between the true events from force plate data and the algorithm estimates. In this foot contact algorithm, Maiwald et al. (2009) determined initial foot contact from the vertical acceleration of a target foot marker. In the current study, there were the following three foot markers: heel (calcaneus), first metatarsal head, and fifth metatarsal head. To be able to accommodate the algorithm with different foot strike patterns (forefoot, midfoot, rearfoot), first, the vertical position of the foot markers was compared to the vertical position of the static trial. When the position of the marker during the running measurement was lower than the position of that same marker in the static trial a local minimum of that marker was found in the running measurement. When the vertical position of the marker in the running measurement did not go below the vertical position of that same marker in the static trial, the marker was excluded from the next equation. The frames of the local minima of the three markers were compared and the marker that had a minimum first was taken as a target marker and an approximate time of initial contact. A narrow time interval around this approximate time of initial contact was defined to determine the peak acceleration of that marker, 50 milliseconds before and 100 milliseconds after the approximate time of initial contact (Maiwald et al., 2009). After applying this algorithm, peaks were manually checked and it was noticed that for some participants (mainly landing on the forefoot) the approximate interval had to be changed to 100 milliseconds or even 200 milliseconds instead of 50 milliseconds before the approximate time of initial contact. The final algorithm was checked for all participants to ensure it was accurately detecting initial contact.

3.4 Biofeedback system

A multisensory feedback system was developed to provide the participants with biofeedback. Multisensory feedback was chosen over the separate modes of feedback since it has previously been suggested to be superior to single modes of feedback, see section 2.3.3 for more information. Multisensory feedback not only provide the most information (Baram & Miller, 2006), it also reduces the cognitive load associated with the separate systems due to the distribution of information processing (Sigrist et al., 2013).

The system was developed using the PCB Piezotronics accelerometer described in section 3.2.1. The accelerometer was connected via a cable to a PCB signal conditioner (PCB Piezotronics, Stevenage, UK, model: 480E09; gain = 10) and sampled at 1000 Hz. The signal from the accelerometer was processed in a custom-written LabVIEW™ (National Instruments, Austin, TX, USA) program, filtered at 50 Hz with a 4th order, low-pass, Butterworth filter, after which the offset was removed (Barnes et al., 2011). This signal was visually displayed on a screen, together with the target line (Figure 3.4). If participants failed to reach the identified target, they heard a sound and felt a vibration scaled to the error, with a higher-pitched sound and more intense vibration corresponding to an increased value above the target. The vibration was applied on the wrist by a vibration motor (Precision Microdrives, London, UK, model: 307-103). The wrist was chosen since feasibility studies showed a vibration on the legs was not felt by participants whereas a vibration on the wrist was. The vibration motor was connected to the same PCB signal conditioner as the accelerometer to drive the vibration.

Figure 3.4: Participant receiving feedback on tibial acceleration. The screen shows the tibial acceleration signal (white peaks) together with the target (green line).

3.5 Single-subject analysis

Previous research on tibial acceleration found that participant groups were able to reduce tibial acceleration in response to a gait retraining intervention (Clansey et al., 2014; Creaby & Franettovich Smith, 2016; Crowell & Davis, 2011; Crowell et al., 2010). However, individual differences exist, Crowell et al. (2010) observed responders as well as non-responders to tibial acceleration feedback. Therefore, there is an interest in how different participants change their running pattern according to biofeedback. Additionally, an understanding of the differences between responders and non-responders to biofeedback could further improve the intervention.

For a group of participants who received biofeedback on tibial acceleration, Clansey et al. (2014) reported changes in foot strike angle, a shift from a rearfoot to midfoot strike pattern, and a significant increase in ankle plantarflexion. In their research, no changes were found in either the hip or knee joint angles. However, these group results could mask individual results. As seen before in the study by Crowell et al. (2010), not all participants respond to the feedback, even though the overall group does. Further, when asked during the feasibility studies (section 5.5) participants described different strategies to change their running pattern. These different strategies can cancel each other out when calculating the mean over a group and, therefore, demonstrate no difference. Dufek et al. (1995) and Bates, James and Dufek (2004) argue in their research that the average person or average result does not always exist. This is based on several studies demonstrating the group statistics were not representative of any of the individual subject results. These studies are examples of a mathematical (statistical) cancellation effect, due to aggregation of the same task using different performance strategies. Aggregation masks individual performance strategies across a group of subjects and alters results in false support of the null-hypotheses (Bates et al., 2004).

A single-subject analysis can be used to characterise unique learning strategies (Bates, 1996), focusing on characterising movement within an individual, rather than in a group. It is important to note that a single-subject analysis is an experimental technique that aims for an in-depth examination of individual movement characteristics. It focuses on common movement characteristics between participants. It should, therefore, not be compared to case studies (Bates et al., 2004). In a single-subject analysis, each step is seen as trial data, instead of each participant. Therefore, different steps within a session will be compared to different steps from another session. In addition, each step in a single-subject analysis is considered to be independent. This assumption of independence was evaluated using short-range autocorrelation (Bates, 1996). Bates, James and Dufek (2004) proposed several analysis techniques, including: non-parametric Mann-Whitney U test, Bootstrap/randomization, Model Statistics or the use of a one-way analysis of variance (ANOVA). Crowell et al. (2010) and van Gelder et al. (2018a), suggested a repeated measurement ANOVA, proposing that the assumption of no autocorrelations within the data, made by Bates (1996), to be incorrect. Even though short-range correlations were not found in gait, long-range auto-correlations were found

(Hausdorff, Peng, Ladin, Wei, & Goldberger, 1995). It is, therefore, proposed that the data should be regarded as dependent.

The analysis techniques used in a single-subject analysis, as mentioned above, are mainly based on calculating the ratio of the variance between sessions to the variance between individuals. In case of a single-subject analysis, this is the variation of different steps within a session. What is not taken into account in a single-subject analysis is that the between-day variance can be increased with the use of certain measurement systems, for example, due to reapplying markers or an accelerometer, compared to within-day measurements (Alenezi, Herrington, Jones, & Jones, 2016). How this variability induced by reapplying markers or an accelerometer affects the group statistics compared to the single-subject analysis is described in an example below with a one-way ANOVA. Formulas can be found in Appendix G.

In a group analysis the between-group variability (MS_M) is based on the variance explained by the fact the data comes from different groups (different sessions). The variance for both the group analysis as well single-subject analysis is affected by reapplying the markers/accelerometer between sessions. The within-session variability (MS_R) is based on the variation caused by extraneous factors or individual differences. In a group analysis the variance will increase by reapplying the markers/accelerometers to different participants. However, in a single-subject analysis the markers and accelerometer are not reapplied within a session and, therefore, the variance will be smaller compared to group statistics. This means that in a single-subject analysis the MS_R is likely to be smaller and, therefore, the F-statistic is likely to be higher (see formula displayed in Appendix G). With a higher F-statistic, it is more likely to find a statistical difference between the sessions. Therefore, reapplying of the markers/accelerometer has a much greater effect in a single-subject analysis and should be accounted for.

The minimal detectable difference can be calculated to determine the minimum amount of change which was sufficiently greater than the measurement error in order to consider that the measured change represented a genuine biomechanical difference (Weir, 2005). The minimal detectable difference is a value based on the standard error of measurement (SEM), which is seen as an indicator of absolute reliability (Atkinson & Nevill, 1998; Weir, 2005). By creating 95% confidence intervals around the SEM, the confidence intervals can be used to differentiate between "real" changes and those that might be due to error (Atkinson & Nevill, 1998; Weir, 2005). The SEM is an estimation of the expected random variation when no real change has taken place. However, it should be noted that Atkinson and Nevill (1998) and Weir (2005) advised calculating the SEM with the use of the mean-squared error term of a repeated measures analyses of variance (ANOVA), instead of calculating it by its more reported formula:

$$\text{SEM}=\text{SD}\sqrt{1-ICC} \tag{1}$$

in which SD is the standard deviation of the scores of all subjects. By using the mean-squared error term of a repeated measures ANOVA, the variance between participants is excluded from the calculation. In the current programme of research, the minimal detectable difference will be used to define a "real" difference between sessions, when single-subject comparisons will be made.

3.6 Chapter summary

The aim of this chapter was to consider different methodological approaches. First, there was an elaboration on the use of two different accelerometers (PCB Piezotronics and the Runscribe). Axial tibial acceleration was used as a measure of tibial shock, both being related to tibial stress fractures (Davis et al., 2004). The use of a motion capture system was described to define gait patterns. Further, a multisensory feedback system was developed for participants to reduce tibial acceleration. Next to seeing the acceleration signal and the target on a screen, participants felt a vibration on the wrist and heard a high pitch sound scaled to the error.

Finally, the rationale for choosing a single-subject analysis was discussed. With responders as well as non-responders to an acceleration biofeedback intervention (Clansey et al., 2014), group statistics were expected to mask individual strategies. Therefore, a single-subject analysis was selected to characterise the learning effects (Bates, 1996). Further, instead of using a traditional p-value approach, a minimal detectable difference was calculated. Traditional p-value based analysis does not provide information on the cause of the change. A significant change could occur due to a change in the performance as well as due to a measurement error, therefore, the minimal detectable difference will be calculated. The minimal detectable difference determines the minimum amount of change which was sufficiently greater than the measurement error and day-to-day variability in order to consider that the measured change represented a genuine biomechanical difference.

The methodological considerations in this chapter informed the methods for the following chapters. In the next chapter, the reliability of the systems will be further explored.

Chapter 4: Reliability and minimum detectable difference in acceleration, kinematic and spatiotemporal data during treadmill running

4.1 Introduction

To determine the effect of an intervention, it is essential to ensure the data are reliable. Therefore, the third objective of this programme of research was to establish the reliability of peak tibial acceleration, kinematic and spatiotemporal data in describing movement parameters. Reliability in this context refers to the consistency of a measurement or the ratio of the true score variance to the total variance of the observed measurement (Weir, 2005). The total variance of the observed measurement consists of the true variance and error variance. Sources of true variance in the measurement of peak tibial acceleration, kinematic and spatiotemporal parameters during gait could include natural variation in gait, while sources of error variance could include: skin movement, application and reapplication of sensors and markers, and the ability of the system to make accurate measurements (Ferber, McClay Davis, Williams, & Laughton, 2002; McGinley, Baker, Wolfe, & Morris, 2009; Weir, 2005). Regardless of these possible sources of variance in gait, previous studies have found good to excellent reliability using intraclass correlation coefficients (ICC) for both acceleration data (Barnes, 2011) as well as kinematic data (Alenezi et al., 2016; Ferber et al., 2002). However, there are differences in the methods used in these studies to those used in the current programme of research. For example, in the studies by Alenezi et al. (2016) and Ferber et al. (2002), the reliability of different parameters was assessed compared to the current study. Further, the different studies used not-only different marker and camera set-ups, they also used different filters. These differences in methods could influence the measurement error and, therefore, the results found in those studies could not be generalized to the current study.

The intraclass correlation coefficient (ICC) gives a relative measure of reliability. The relative measurement of reliability can be large even though there is a large absolute difference between two measurements. Therefore, the ICC should be reported together with an absolute measurement of error. Both Atkinson and Nevill (1998) and Weir (2005) suggested the standard error of measurement (SEM) as a measure for absolute error. The SEM is an estimation of the expected random variation when no real change has taken place. The SEM and a degree of confidence, often 95%, can be used to estimate the minimal detectable difference (MDD) (Atkinson & Nevill, 1998; Weir, 2005). The MDD value provides information on the minimum amount of change which is sufficiently greater than the measurement error for the variable of interest. The MDD gives the value which is minimally needed for a measurement to be considered "real" (Atkinson & Nevill, 1998; Weir, 2005). This chapter establishes the reliability of peak tibial acceleration and selected kinematic and spatiotemporal parameters in describing movement patterns.

Based on previous research (Ferber et al., 2002; Kadaba et al., 1989), the within-session reliability was hypothesised to be larger compared to the between-session variability. In the current study within- and between-session reliability will be explored. In the intervention study kinematic and spatiotemporal data will only be compared between-days, but acceleration data will be compared within- and between-days. While skin movement, the ability of the system to make an accurate measurement, and natural variation in running, will affect both between- and within-session variability the application and reapplication of sensors and markers will only affect the between-session variability (Ferber et al., 2002; McGinley et al., 2009; Weir, 2005). The difference in within- and between-session reliability will, therefore, provide further information about movement variability and the reapplication of the accelerometer (Ferber et al., 2002). Focusing on the kinematic variables, angular excursion values were expected to be more reliable compared to peak values (Ferber et al., 2002). Similarly, angles measured in the sagittal plane were expected to be more reliable compared to angles measured in the coronal plane (Ferber et al., 2002; Kadaba et al., 1989).

4.2 Methods

4.2.1 Participants

Following institutional ethical approval (Appendix H), eight participants were included for the calculations of reliability (5 female, 3 male; 30 ± 3 years; stature: 1.67 ± 0.08 m; body mass: 66.3 ± 8.0 kg). All participants ran at least once a week for five kilometres or more. All participants were injury-free, provided signed informed consent and were asked not to do any exercise on the day of testing or do any race in the two days before testing. This was due to participants possibly getting fatigued and therefore affecting their gait patterns (Sheerin et al., 2019).

4.2.2 Study design and equipment

Within- and between-session reliability were tested for peak tibial acceleration. Only between-session reliability was tested for kinematic and spatiotemporal data, since these data were only compared between sessions. All participants came to the lab twice, separated by approximately one week. On both occasions, participants ran on a treadmill, at 95 per cent of their five-kilometre time trial speed (Appendix C), as was used in the intervention study in chapter 6. By letting participants run at the same speed as they would run during a five-kilometre time trial a more representative design (Araújo, Davids, & Passos, 2007; Brunswik, 1956) could be created compared to letting participants run at a fixed speed. However, some participants were able to run under a 20-minute five-kilometre pace. Therefore, these participants were unlikely to sustain their five-kilometre pace for the longest feedback session, which lasted 20 minutes, as the speed they could maintain would decrease over 20 minutes when running at 100% effort (Riegel, 1980). The decision was, therefore, made to set the treadmill speed at 95 per cent of each participant's five-kilometre time trial pace. This allowed all participants to maintain a constant speed while allowing them to run equally close to their five-kilometre pace. Maintaining a relatively high speed is crucial to create a representative design, since the speed participants run is related to tibial acceleration (Sheerin et al., 2019).

Right lower extremity kinematics were assessed using an optoelectronic motion capture system (Motion Analysis Corp., Santa Rosa, CA), for more information see section 3.3. Retro-reflective, spherical markers were placed on anatomical landmarks of the pelvis, thigh, shank and foot and clusters of four makers were applied on the thigh and shank of the participants to define the segments (for more information see section 3.3.2). The markers were applied by the same investigator at both sessions to improve consistency of placement.

A gold standard accelerometer (PCB Piezotronics, Stevenage, UK, Model: 352C22) was placed on a wireless accelerometer (RunScribe version 2, Scribe Labs, California, USA) with double-sided tape. Both sensors were then attached by the same investigator at both sessions to the anteromedial aspect of the tibia, five centimetres above the medial malleolus and wrapped around with cohesive bandage as described by Barnes, Wheat and Milner (2011). Only the reliability of the gold standard accelerometer was assessed. The accelerometer was connected via a cable to a PCB signal conditioner (PCB Piezotronics, Stevenage, UK, model: 480E09; gain = 10) and sampled at 1000 Hz (for more information see section 3.2.1)

After recording a static trial and a functional hip joint trial, participants completed a six-minute warm-up of on the treadmill followed by a two-minute data collection. During the warm-up participants were asked to bring the speed up to the treadmill speed they were asked to run on during the measurement.

4.2.3 Outcome measures and data analysis

The acceleration signal was filtered with a 400th order Hamming band-pass filter with lower and upper cut-off frequencies of 8 and 60 Hz, respectively (for more information on the sensor and filters see section 3.2). The mean was removed and peak tibial acceleration was calculated. Peaks which were three standard deviations above or below the mean were ignored (section 3.2.3). For each participant, the mean of the last 20 steps of each measurement was used (Bates et al., 1992). For the within-session comparison, the last 20 steps of the first minute and the second minute of the data collection were compared.

The data recorded with the motion capture system were first processed in Cortex software (version 5.3, Motion Analysis Corporation, Santa Rosa, CA, USA), for more information see section 3.3.1. The data were exported to Visual 3D (C-Motion Inc., Germantown, USA) where they were filtered with a low-pass, fourth order zero-phase-shift, Butterworth filter with a cut-off frequency of 14 Hz or 18 Hz (for more information on filtering see section 3.3.4). Joint coordinate systems were defined (Grood & Suntay, 1983) as described in Appendix E and as described in section 3.3.2 joint angles were calculated in Visual 3D (C-Motion Inc., Germantown, USA). Joint angles and filtered marker data were exported and parameters of interest were extracted using Matlab (Mathworks, R2016a). This included joint angles, foot strike angle and spatiotemporal parameters at initial contact. Initial contact was defined based on a study by Maiwald et al. (2009) and is further explained in section 3.3.5. The mean of the final 20 steps of each measurement was used to calculate dependent variables (Bates et al., 1992).

The dependent variables were related to different shock attenuating variables or risk factors for injuries as described in section 2.5. Hip flexion, knee flexion, and ankle dorsiflexion angle were calculated at initial contact. Peak hip adduction and peak ankle eversion were calculated during stance. Knee flexion, hip adduction, and ankle eversion joint angular excursion values were calculated. The joint angular excursion was defined as the angular displacement between initial contact and the peak value during the stance phase of each step. Foot strike angle was calculated by subtracting the foot angle while standing from the foot angle at initial contact of each step during the running measurements, such that values of 0° correspond with a flat foot (Altman & Davis, 2012). The foot angle was defined as the angle between the vector between the heel and the first metatarsal head and the anteroposterior axis in the lab coordinate system. A rearfoot strike was defined as foot strike angle ≥ 8.0°, a midfoot strike as foot strike angle ≥ - 1.6° and < 8.0°, and a forefoot strike as foot strike angle ≤ -1.6° (Altman & Davis, 2012). Landing distance was calculated as the horizontal distance between the sacrum (the virtual midpoint between the left and right posterior superior iliac spine markers) and the heel marker at initial contact (Gullstrand, Halvorsen, Tinmark, Eriksson, & Nilsson, 2009). Since the upper body was not included in the marker-set used in this study, the whole-body centre of mass position could not be determined. The sacrum will be posterior to the centre of mass, however, it should be consistent and, therefore, the relative change should still be correct. Therefore, the sacrum was used as a proxy for the centre of mass (Gullstrand et al., 2009). Cadence was calculated as the inverse of stride time, which was defined as the time between two initial contacts. Heel marker vertical velocity was determined at initial contact. Velocity was calculated by differentiation of the position of the heel marker.

To assess reliability, first, the intra-class correlation coefficient ICC (2,1) estimates and their 95% confidence intervals were calculated using SPSS version 24 (SPSS Inc, Chicago, IL) based on a single measurement, absolute agreement, two-way random-effects model. Values less than 0.5, between 0.5 and 0.75, between 0.75 and 0.9, and greater than 0.9 indicated respectively poor, moderate, good and excellent reliability (Koo & Li, 2016). 95% confidence intervals of the ICCs were calculated because of the susceptibility of ICC to differences in between-participant variance (Atkinson & Nevill, 1998; Weir, 2005).

To analyse the variance of the measurement, a Bland-Altman plot was calculated including the limits of agreement (LOA). To test whether there was a systematic error in the data, a paired-samples *t*-test was performed. To test for heteroscedasticity, the correlation between the absolute difference and the mean of the two methods were calculated. In the case of homoscedastic data, the minimal detectable change was calculated, based on the standard error of measurement. The SEM was calculated as the square root of the mean squared error term of a repeated measure ANOVA. The minimal detectable difference was calculated using the following equation (Weir, 2005; Wilken et al., 2012):

$$MDD = SEM \ * \ 1.96 \ * \ \sqrt{2} \qquad (2)$$

In the case of heteroscedastic data similar calculations were performed to calculate the MDD, however, the data were log-transformed. Data are heteroscedastic if the amount of random error increases with increasing measured values. The antilog was taken of the square root of the mean-squared error term of the ANOVA performed on the log-transformed data (Weir, 2005). To cover 95% of the observations the antilog taken of the square root of the mean-squared error term of the ANOVA was expressed to the power of 1.96 (Atkinson & Nevill, 1998).

4.3 Results

4.3.1 Tibial acceleration

Excellent between- and within-session agreement was found for mean peak tibial acceleration with moderate to excellent (95% CI = 0.654-0.983) and good to excellent (95% CI = 0.810-0.991) 95% confident intervals, respectively. For both tibial acceleration comparisons (between-session comparison and within-session comparison) the data were found to be heteroscedastic and, therefore, a ratio value was calculated instead of an absolute difference (Table 4.1). The limits of agreement for the between-session comparison for mean peak tibial acceleration were 0.18 g ± 1.71 g, while for the within-session comparison the limits of agreement were 0.19 g ± 1.29 g (Appendix I).

4.3.2 Kinematics and spatiotemporal parameters

Based on the ICC estimates an excellent agreement between-days was found for most variables with exceptions of: hip flexion at initial contact (ICC = 0.80, 95% CI =0.33-0.95), peak hip adduction (ICC = 0.76, 95% CI = 0.16-0.95), knee flexion at initial contact (ICC = 0.54, 95% CI = -0.19-0.89), and peak eversion excursion (ICC = -0.03, 95% CI = -0.77-0.67) for which good, good, moderate, and poor agreement were reported, respectively. Based on the paired-samples *t*-test a systematic difference was found between the two measurements of landing distance, but none of the other parameters. Knee flexion at initial contact and knee flexion excursion were found to be heteroscedastic, while the other variables were homoscedastic (Table 4.1, Appendix I). Large percentage differences were found for ankle dorsiflexion at initial contact (10%), hip adduction excursion (17%) and peak ankle eversion (10%).

Table 4.1 The intraclass correlation coefficient and 95% confidence intervals, mean absolute and relative difference, paired-samples t-test, limits of agreement, Pearson's correlation between the absolute difference and the mean of the two methods, and either the ratio value or the minimal detectable difference.

Variable	Ses 1 Mean (SD)	Ses 2 Mean (SD)	ICC (95% interval)	Mean diff abs (%)	*t*-test (p)	Limits of Agr	corr r (p)	MD/ Rat
Pk tibial acc (g)	5.81 (2.18)	5.63 (1.90)	0.92 (0.65-0.98)	0.18 (3%)	0.58	0.18 ± 1.71	0.48 (0.22)	21%
Pk tibial acc W (g)	5.81 (2.18)	5.62 (2.12)	0.96 (0.81-0.99)	0.19 (3%)	0.44	0.19 ± 1.29	0.53 (0.17)	16%
Foot contact ang (°)	13.33 (12.09)	13.07 (11.74)	0.98 (0.88-0.99)	0.3 (1%)	0.80	0.26 ± 5.49	0.07 (0.87)	3.9
Ank dorsflex IC (°)	4.17 (9.27)	3.78 (10.89)	0.92 (0.65-0.98)	0.4 (10%)	0.81	0.38 ± 8.39	0.22 (0.60)	5.9
Knee flexion IC (°)	21.05 (4.25)	20.08 (2.38)	0.54 (-0.19-0.89)	1.0 (5%)	0.44	0.98 ± 6.55	0.90 (0.00)	23%
Knee flexion ex (°)	25.27 (3.44)	25.47 (4.22)	0.90 (0.59-0.98)	0.2 (1%)	0.75	-0.20 ± 3.50	0.56 (0.15)	10%
Hip flexion IC (°)	38.40 (7.77)	36.37 (6.03)	0.80 (0.33-0.95)	2.0 (6%)	0.22	2.04 ± 8.38	-0.11 (0.80)	5.9
Hip adduction ex (°)	4.24 (2.87)	3.63 (3.30)	0.94 (0.71-0.99)	0.6 (17%)	0.11	0.61 ± 1.87	0.30 (0.47)	1.3
Ank eversion ex (°)	12.83 (3.76)	12.87 (4.14)	0.96 (0.83-0.99)	0.1 (0%)	0.96	-0.04 ± 4.51	-0.43 (0.28)	3.2
Landing distance (m)	0.24 (0.05)	0.25 (0.05)	0.98 (0.51-0.99)	0.01 (4%)	**0.01**	-0.01 ± 0.01	0.29 (0.49)	0.01
Cadence (steps/s)	1.46 (0.05)	1.46 (0.07)	0.94 (0.73-0.99)	0.00 (0%)	0.65	-0.00 ± 0.04	-0.07 (0.86)	0.02
Heel veloc IC (m/s)	0.47 (0.29)	0.48 (0.27)	0.99 (0.97-0.99)	0.01 (2%)	0.41	-0.01 ± 0.06	-0.08 (0.85)	0.05
Pk hip adduction (°)	14.54 (7.04)	14.51 (5.26)	0.76 (0.16-0.95)	0.0 (0.2%)	0.99	0.03 ± 8.81	0.43 (0.29)	6.2
Pk ank eversion (°)	11.64 (3.94)	12.94 (3.93)	-0.03 (-0.77-0.67)	1.3 (10%)	0.54	-1.30 ±11.03	-0.18 (0.67)	7.8

Ses = session, SD = standard deiavtion, ICC = intraclass correlation coefficient, diff = difference, abs = absolute, p = p-value, Agr = agreement, corr = Pearson's correlation, r = Pearson's r, MD/rat = minimal detactable difference / ratio, Pk = peak, acc = acceleration, W = within, ang = angle, Ank = ankle, dorsflex = dorsiflexion, IC = initial contact, ex = excursion, veloc = velocity, **Bold** = significant, p<0.05

4.4 Discussion

The aim of the current chapter was to establish the reliability of the dependent variables used in the current programme of research. The results demonstrated excellent reliability for tibial acceleration (ICC = 0.92 - 0.96) and spatiotemporal parameters (ICC = 0.94-0.99) and variable levels of reliability for kinematic parameters (ICC = -0.03 - 0.98) according to the classifications of Koo and Li (2016).

Moderate to excellent between-days reliability (ICC = 0.92, 95% CI = 0.65-0.98) of peak tibial acceleration was found in the current study. Acceleration data were found to be heteroscedastic, the random error increased with increasing tibial acceleration. Therefore, a ratio was calculated for the MDD, which was 21 per cent between sessions. Barnes (2011) found similar results, regarding the ICC, also reporting a moderate to excellent between-session reliability (ICC = 0.87, 95% CI = 0.50-0.97). Considering an excellent agreement was found, the attachment of the accelerometer in the present study can be used with confidence in other studies outlined in this programme of research.

Compared to the between-days reliability, in the current programme of research, higher ICC values were found for the within-session measurements. Good to excellent within-session reliability (ICC = 0.92, 95% CI = 0.81-0.99) of peak tibial acceleration was found. The MDD comparing tibial acceleration within sessions was 16 per cent. This difference in between- and within-session reliability was expected based on previous research. While skin movement, the ability of the system to make an accurate measurement, and natural variation in running, will affect both between- and within-session variability, the application and reapplication of the accelerometer will only affect the between session variability (Ferber et al., 2002; McGinley et al., 2009; Weir, 2005). The difference found in within- and between-session reliability, emphasises the effect of application and reapplication of the sensor. It further emphasises the importance of using the MDD instead of the traditional p-value based analysis to define differences within participants, between sessions.

A significant difference was found in landing distance comparing the first and second session, with a higher landing distance in the second session. However, the difference was small (0.01 m) and could exist as a statistical type I error, due to performing fourteen comparisons. Hip flexion at initial contact (ICC = 0.80), knee flexion at initial contact (ICC = 0.54), peak hip adduction (ICC = 0.76) and peak ankle eversion (ICC = -0.03) had poor to good reliability, while all other kinematic parameters reported excellent reliability. Several factors have been associated with kinematic variability, including measurement error, skin marker movement and physiological variability during gait (Ferber et al., 2002). Further, marker re-application and placement on anatomical landmarks are associated with between-session reliability. The anatomical marker positions are used to define coordinate segment systems, with which joint angles are calculated. Small changes in marker placement can, therefore, cause cross-talk between planes of motion and cause a phase shift in kinematic data (Kadaba et al., 1989). To minimise a phase shift in kinematic data, an attempt should be made in minimising the systematic error of marker placement. This could be done by the same researcher applying all markers in a consistent way. The phase shift is predicted to have a more significant effect on peak joint angles, compared to joint excursion (Ferber et al., 2002). In the current research, all parameters which had a poor to good reliability, as opposed to excellent reliability, were parameters taken at initial contact as opposed to joint excursion values.

Hip adduction and ankle eversion are angles in the coronal plane, while the other angles were measured in the sagittal plane, and less reliable data is expected in the coronal plane as found by Ferber et al. (2002). However, comparing knee flexion at initial contact (sagittal plane) to peak hip adduction (coronal plane), knee flexion at initial contact reported a lower ICC value, while a larger ICC value would be expected based on the plane the angle is in. Comparing the measurement of peak hip adduction between sessions, a small difference between the two measurements (0.2 per cent) was found, while for knee flexion at initial contact a larger difference between measurements was found (5 per cent). Focussing on the 95% confidence intervals of the limits of agreement, peak hip adduction had a higher value compared to the knee flexion at initial contact. These data suggest there to be individual subject differences between measurements for peak hip adduction. However, these differences were equally and randomly distributed across participants, evidenced by finding a small relative difference between the measurements. Therefore caution should be taken when comparing individuals. Finally, the reliability of peak ankle eversion excursion was poor (ICC = -0.03) unlike previous research (Ferber et al., 2002; ICC = 0.63) which found moderate reliability. Peak ankle eversion outcomes should, therefore, be considered with care.

As expected, the variables which reported a lower variability (e.g. hip flexion at initial contact, ICC = 0.80; peak hip adduction, ICC = 0.76) were also the variables which displayed a higher minimal detectable difference (hip flexion at initial contact, MDD = 5.9°; peak hip adduction, MDD = 6.2°). Therefore, a larger change between days is required to be considered a real difference for these parameters. The dependent variables who found a large ICC, an excellent reliability (e.g. foot strike angle, ICC = 0.98; hip adduction excursion, ICC = 0.94), found smaller minimal detectable differences (foot strike angle, MDD =3.9°; hip adduction excursion, MDD = 1.3°), suggesting a smaller change between days was required to be considered a real difference. Though excellent reliability was not found between sessions for every dependent variable, this problem is likely to be resolved with the use of the MDD. Since the minimal detectable difference was calculated to determine the minimum amount of change which was sufficiently greater than the measurement error for the variables of interest and could be considered "real". To confirm this study's MDD values reflected a previous study's findings, they were compared to the data of Alenezi et al. (2016). Overall, smaller minimal detectable differences were found when comparing angles of the current research to the previous study by Alenezi et al. (2016). While Alenezi et al. (2016) found minimal detectable differences of 13.1° and 6.70° for peak hip flexion angle and peak ankle dorsiflexion angle respectively, in the current study values of 5.92° and 5.93° were found for hip flexion at initial contact and ankle dorsiflexion at initial contact. This difference could exist due to differences in the method between studies, including a different choice of variables. While Alenezi et al. (2016) reported peak values, the current study compared angles measured at initial contact. Therefore, the comparison to Alenezi et al.'s (2016) should be interpreted with care. However, the comparison lends a degree of face validity to the findings in this study. The comparison indicates that the current study is reliable in terms of its MDD results, consequently, the attachment of the accelerometer and markers in the present study can be used with confidence in other studies outlined in this programme of research.

4.5 Chapter summary

The current study aimed to establish the reliability of the acceleration, kinematic, and spatiotemporal data. This allows for the real effect of the feedback intervention (chapter 6) to be determined. Ten out of 14 dependent variables had excellent reliability. Excellent reliability was found for tibial acceleration data, consequently, the attachment of the accelerometer in the present study can be used with confidence in other studies outlined in this programme of research. The kinematic parameters that did not have excellent reliability were hip flexion at initial contact, knee flexion at initial contact, peak hip adduction and peak eversion excursion, so caution should be exercised when comparing these parameters between sessions. These parameters were mainly absolute values as opposed to angular excursion values and in the coronal plane rather than the sagittal plane. These parameters had higher minimal detectable differences, suggesting a larger difference is needed to exceed the minimal detectable difference and to be considered as real. So even though excellent reliability was not found between sessions for these dependent variables, this problem is likely to be resolved with the use of the MDD. The minimal detectable difference was calculated to determine the minimum amount of change, which was sufficiently greater than the measurement error or movement variability for the variables of interest and could be considered as "real". The minimum detectable difference will be used as such in the intervention chapter, chapter 6, to establish whether and observed change was a "real" change and not depending on measurement error or movement variability.

Chapter 5: Developing a biofeedback intervention for modifying tibial acceleration.

5.1 Introduction

Previous studies found beneficial effects of feedback in decreasing tibial acceleration within one session (Creaby & Franettovich Smith, 2016; Crowell et al., 2010; Wood & Kipp, 2014). In those studies, the focus was on whether participants were able to reduce tibial acceleration post-session, but not on the time participants took to modify tibial acceleration in response to feedback. The time participants take to modify tibial acceleration could provide improved insight into how long feedback should be given to participants, to allow them to respond accordingly. Four feasibility studies were performed aimed to inform the intervention study. The first feasibility study had two objectives. The first objective of this exploratory study was to identify the time participants took to modify tibial acceleration in response to multisensory feedback on tibial acceleration. The second objective was to investigate the short-term retention effect of feedback on tibial acceleration. The first feasibility study formed three other objectives based around treadmill speed, target value and task instruction. For each objective a separate study was performed, with different participants for each study. This chapter will discuss the results of these four feasibility studies and how the results were implicated in the intervention study in four different subsections: learning response to one feedback session, treadmill speed, intervention target development, and verbal instruction.

5.2 Learning response to one feedback session

5.2.1 Introduction

This section will describe the first feasibility study done in this programme of research. The objectives were to identify the time participants took to modify tibial acceleration in response to multisensory feedback on tibial acceleration and to investigate the short-term retention effect of feedback on tibial acceleration.

5.2.2 Methods

Participants

Following institutional ethical approval (Appendix J), six runners volunteered to participate in the study (4 female, 2 male; 28 ± 3.0 years; stature: 1.69 ± 0.10 m; body mass: 68 ± 9.3 kg). All participants ran at least once a week and were injury-free at the time of testing. Participants completed a pre-screening questionnaire (Appendix K) and provided written informed consent (Appendix L) before participating in the study.

System

Tibial acceleration was measured using a uniaxial accelerometer (PCB Piezotronics, Stevenage, UK, Model: 352C22). The feedback was created with a custom-written program in LabVIEW™ (National Instruments, Austin, TX, USA). Visual feedback consisted of the signal shown on a screen, together with the target line (Figure 3.4). If participants failed to reach the target, they heard a sound and felt a vibration applied on the wrist by a vibration motor (Precision Microdrives, London, UK, model: 307-103) scaled to the error, with a higher-pitched sound and more intense vibration with an increased value above the target. The fiftieth percentile of peak positive tibial acceleration from the baseline measurement was set as a feedback target (Clansey et al., 2014; Crowell et al., 2010).

Study design

An overview of the testing schedule can be seen in Table 5.1. In previous studies (Clansey et al., 2014; Creaby & Franettovich Smith, 2016; Gray et al., 2012) participants run at a fixed running speed, which was the same for each participant. However, to create a more representative design, as described by Brunswik (1956) and Araújo, Davids, and Passos (2007), in this study, participants were asked to run at their own preferred comfortable running speed. A more representative experimental design provides a better representation of the behavioural setting, which could lead to more beneficial and representative results (Araújo et al., 2007). Further, tibial acceleration is related to running speed (Brayne et al., 2015), so, therefore, a running speed, representative of their own running, was chosen. Participants' preferred running speed was determined on the first day and kept constant through all measurements. Determining their preferred running speed was based on the methods of Hamill, Derrick and Holt (1995). Participants ran on a treadmill while increasing and decreasing the speed themselves until a comfortable speed was found and the participant could successfully identify the same speed (less than 0.5 m/s difference) on three successive runs.

Table 5.1 Overview of testing. min = minutes

Day 1	**Day 2**	**Day 3**
Find preferred running speed	Warming up (6 min)	Warming up (6 min)
Warming up (6 min)	Retention test (10 min)	Retention test (10 min)
Baseline measurement (2 min)		
Feedback (10 min)		
Retention test (10 min)		
Interview		

After warming up, which was six-minutes to familiarise themselves with running on a treadmill (Lavcanska, Taylor, & Schache, 2005), and taking baseline measurements on the first day, the participants received the instruction to change peak tibial acceleration by landing softer. All participants received the following verbal instruction: "feedback is given on how hard you hit the ground". The first day finished with a ten-minute retention test. At the end of the first sessions, all participants were interviewed on their experience of running with feedback. The interview consisted of six open questions capturing participants' experience of the feedback system and trying to reach the feedback target (Appendix M).

In the second and third session, the participants performed a retention test after the warm-up. On the first day, participants were given a rest period between the baseline measurement and the measurement taken during the feedback condition. A further rest was given between the measurement taken during the feedback condition and the retention test. On the second and third day, the participants did the retention test directly after the warming up, without rest.

Outcome measures

The raw signal from the accelerometer was exported to Matlab and filtered with a 400th order Hamming band-pass filter with lower and upper cut-off frequencies of 8 and 60 Hz, respectively. After filtering, the mean was subtracted from the data to standardize the data and the peaks of the signal were determined. Finally, peaks which were three standard deviations above or below the mean were removed.

To identify the time it took participants to change tibial acceleration, a plateau representing stabilisation of the acceleration was defined (van Gelder et al., 2018a). First, the signal for each measurement taken during the feedback condition was smoothed by using a moving average filter with a window of 31 samples. Subsequently, the start of the plateau was indicated by the point at which acceleration fell within a threshold of ± 2 standard deviations of the mean tibial acceleration of the final 100 steps of the measurement. To detect the short-term learning effect of feedback for each participant, the mean peak tibial acceleration of the final 20 steps (Bates et al., 1992) of each measurement was calculated and compared to the baseline measurement for a participant.

Data analysis

Since participants were expected to respond differently to the feedback, a typical statistical analysis of group data might have masked individual changes. Therefore, a single-subject analysis was used to characterise the learning effects (Bates, 1996). The minimal detectable difference was used to characterize individual differences. When a difference between measurements was greater than the minimal detectable difference, the difference was interpreted as "real" (Atkinson and Nevill, 1998; Weir, 2005). Differences of 21 per cent and 16 per cent of mean peak tibial acceleration were considered as real within- and between-session differences, respectively (chapter 4).

The data from the interviews were recorded in note form by the researcher at the time of asking on a measurement log (Appendix M). Participants' responses were informally analysed to identify their experiences and the experience of the group as a whole. A more formal analysis, such as thematic analysis, was not undertaken as the data were not considered to be rich enough to support such an approach.

5.2.3 Results

Participants ran at a mean speed of 10.2 km/h with a range of: 8.6-12.3 km/h. The mean feedback target was set at 2.8 g with a range of: 1.8 - 3.6 g.

All participants had a decreased peak tibial acceleration, while comparing the first step of the measurement taken during the feedback condition to the mean of the baseline measurement (Figure 5.1). Two participants (participants 2 and 4) further decreased peak tibial acceleration to reach a plateau after 16 steps (10 seconds) and 91 steps (68 seconds). No plateau was found for participants 5 and 6, and for participants 1 and 3 peak tibial acceleration increased, plateauing after 2 steps (2 seconds) and 599 steps (465 seconds).

Participant 1 was the only participant who was unable to respond to the feedback with a decrease in tibial acceleration (Figure 5.2). Instead, no real difference was found between any of the measurements compared to the baseline measurements. Two participants (2 and 5) showed a real decrease in mean peak tibial acceleration for all measurements compared to baseline measurements.

Compared to the baseline measurement, participant 3 showed a real decrease in mean peak tibial acceleration for the retention measurement taken directly after the feedback and a real increase in mean peak tibial acceleration comparing the retention measurement taken after a day. Participant 4 showed a real reduction in mean peak tibial acceleration during the measurement taken during the feedback condition and during the retention test recorded after one day compared to the baseline measurement.

Participant 6 showed a real decrease in mean peak tibial acceleration comparing the feedback measurement to the baseline measurement.

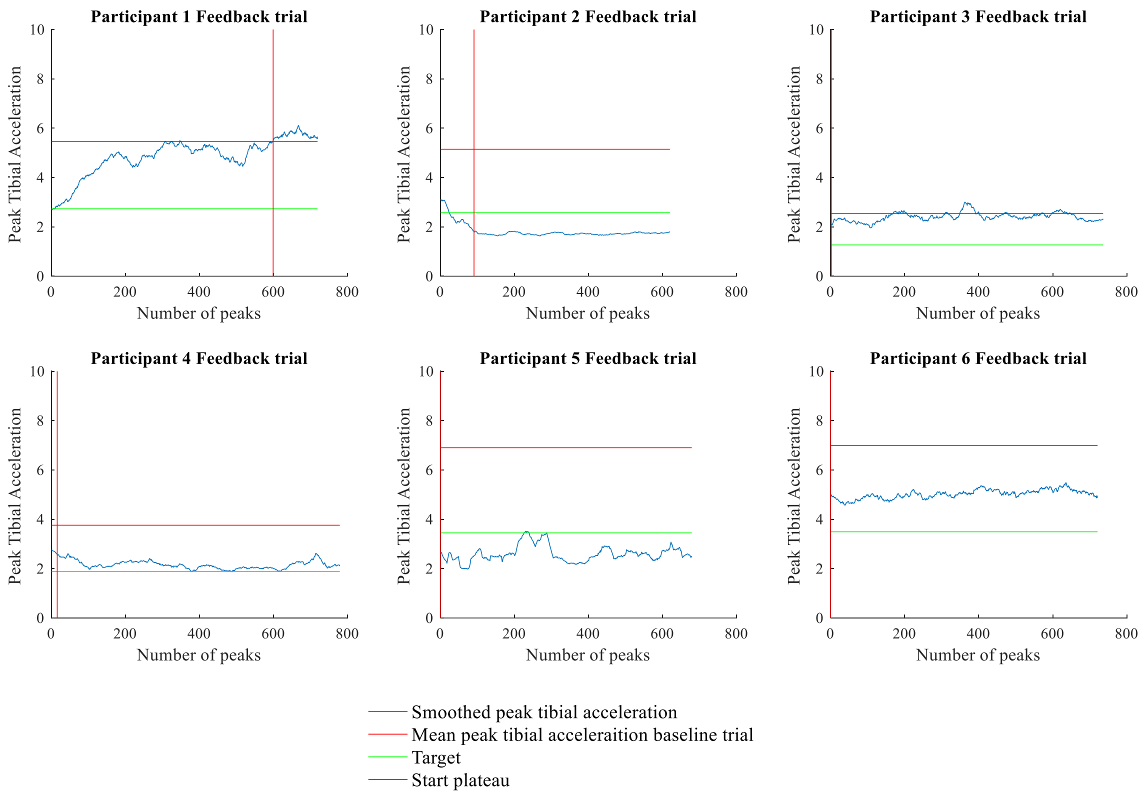

Figure 5.1 Moving average of peak tibial acceleration during the measurement taken during the feedback condition, separate subplots for every participant. The blue line (spiked line) shows the peak tibial acceleration, the red line (upper horizontal line) represents the mean peak tibial acceleration of the baseline measurement and the green line (lower horizontal line) represents the target that was set for that participant. The red vertical line represents the start of the plateau.

In the interviews, four participants (participant 1, 3, 4, and 6) declared they found it difficult to reach the target. Participant 1 felt disappointed at not being able to reach the target and participant 4 got frustrated and felt they were being punished, told off, the whole time for not being able to reach the target consistently. Participant 3 found it hard to run in a squatted position and participant 6 believed that even though the target was hard to reach, the feedback helped. All participants felt the preferred running speed was right for them.

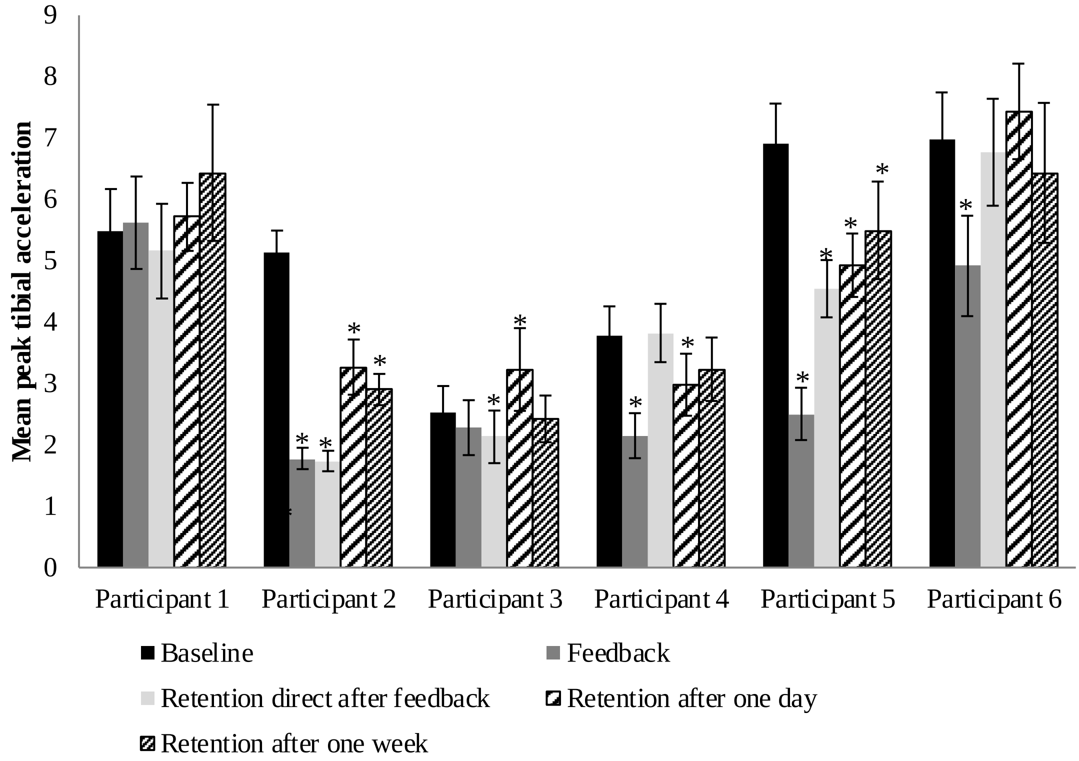

Figure 5.2 Mean peak tibial acceleration for the final 20 steps for each measurement of each participant. The error bars display one SD.* indicates a real difference for that measurement compared to the baseline measurement.

5.2.4 Discussion

The purpose of this feasibility study was to inform the design of the intervention study. The objectives included identifying the time participants took to modify tibial acceleration in response to multisensory feedback on tibial acceleration and investigating the short-term retention effect of feedback on tibial acceleration. All participants changed peak tibial acceleration within the first step of running during the time feedback was given. The further response to feedback was individual with four out of six participants showing a real decrease in mean peak tibial acceleration in the measurement taken during the feedback condition. Two participants maintained this real decrease in mean peak tibial acceleration after one week.

Unlike previous studies (Creaby & Franettovich Smith, 2016; Crowell et al., 2010; Wood & Kipp, 2014), in this study, there was a focus on the initial phase of changing a gait pattern. Results indicated that in this initial phase of changing a gait pattern all participants directly changed peak tibial acceleration within the first step of running in the measurement taken during the feedback condition. The instruction to change peak tibial acceleration by landing softer might, therefore, be enough to affect change and biofeedback might not be needed. Creaby and Franettovich Smith (2016) support this statement, finding no difference in the decrease between participants who received tibial acceleration feedback versus clinician-guided feedback. However, in the current research, two participants appeared to have found an extra benefit from the feedback by further reducing peak tibial acceleration over time and reaching a plateau within 1.5 minutes. Further research with a control group who only receive the instruction to reduce peak tibial acceleration or in which participants do not receive an instruction at all could give a better insight into the effect of biofeedback, which will be further explored in section 5.5.

One participant, participant 1, was unable to decrease mean peak tibial acceleration during the measurement taken during the feedback condition compared to the baseline measurement. Even though the participant did decrease tibial acceleration in the first few steps of the measurement taken during the feedback condition, the participant was not able to continue this decrease and even increased mean peak tibial acceleration compared to the baseline measurement. In the interview, the participant highlighted that they experienced a lack of motivation because of being unable to reach the target. Future research could focus on counteracting this effect by changing the target during the measurement taken during the feedback condition according to the performance of the participant, which will be further explored in section 5.4.

Participants were asked to run at a comfortable speed during this study to create a more representative design (Araújo et al., 2007; Brunswik, 1956). However, it was noticed that participants interpreted comfortable to be a speed far below their maximal capacity. To be able to create a representative design, participants should be running at representative speeds, which are likely to be higher than the speeds they ran during this study. It should further be noticed that peak tibial acceleration is related to running speed (Brayne et al., 2015), so the faster participants run, the more representative the peak tibial acceleration will be. Therefore, further research should take running speed into account, which will be further explored in section 5.3.

It was noticed that each participant responded differently to the feedback on peak tibial acceleration, but overall most participants responded positively to the feedback and were able to reduce tibial acceleration. It was noticeable that all participants directly decreased tibial acceleration within one step in the measurement taken during the feedback condition. Two participants decreased peak tibial acceleration further until a plateau was reached, suggesting that feedback could help some participants to reach a lower peak tibial acceleration. From this feasibility study, three different aspects were identified which needed further investigation: treadmill speed, a changing target, and verbal instruction. These aspects will further be discussed in the following sections.

5.3 Treadmill speed

5.3.1 Introduction

Participants in section 5.2 were asked to run at a self-selected comfortable speed. It was noticed that some of the participants interpreted this to mean to run far below their maximal capacity. To be able to create a representative design, participants should be running at representative speeds, which are more likely to be higher compared to the speeds participants ran at during the study in section 5.2. The aim of this study was to investigate the effect of treadmill speed on the ability of a participant to reduce peak tibial acceleration.

5.3.2 Methods

Participants

Participants in the current study included two runners who participated in the study of section 5.2 (participant 2 and 4, 2 female, 29.5 ± 4.9 years; stature: 1.65 ± 0.02 m; body mass: 60.6 ± 1.0 kg).

System, study design, outcome measures and data analysis

The same system was used as in section 5.2.2. Two participants were asked to come again after finishing the study in section 5.2. For this part of the study participants came one session and were asked to run at 90 per cent of the speed they ran at a five-kilometre time trial. In the session, participants had a warm-up (6 min), a baseline measurement (2 min), feedback (10 min) and a retention test (10 min). In the time feedback was given, participants received the same instructions as were given in the first session (section 5.2.2). The same outcome measurements and data analysis was used as in section 5.2.2. In addition, data were analysed for each participant separately on the two different sessions in which they received feedback. The sessions for each participant were compared to each other.

5.3.3 Results

In the first session, participant 1 ran at 8.6 km/h and in the second session at 9.6 km/h. Participant 2 ran at 9.8 km/h in the first session and in the second session at 11.8 km/h.

In the first session, participant 1 showed a real decrease in mean peak tibial acceleration from the baseline measurement to the measurement taken during the feedback condition and the retention test (Figure 5.3). In the second session, where the participant ran at a higher speed, this decrease was reduced. There was a real difference between the baseline measurement and the measurement taken during the feedback condition, but no real difference was found between the baseline measurement and the retention measurement. Further, in the first session, it took 91 steps before the participant reached a plateau, in the second session a plateau was reached after 146 steps, however, this plateau was at a higher tibial acceleration compared to the start of the measurement taken during the feedback condition (Figure 5.4).

In the first session, participant 2 showed a real decrease in mean peak tibial acceleration in the measurement taken during the feedback condition compared to the baseline measurement and no real difference between the retention measurement and the baseline measurement (Figure 5.3). In the second session, no real difference was found in mean peak tibial acceleration between the measurements. In the first session, it took 16 steps before the participant reached a plateau, in the second session no plateau was reached (Figure 5.4).

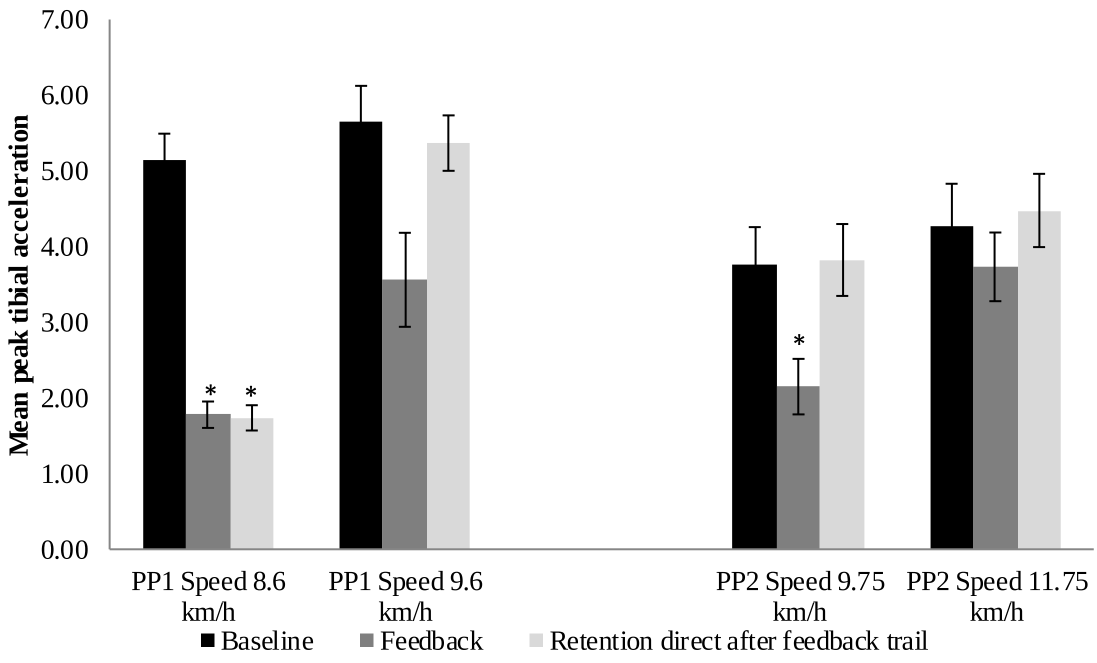

Figure 5.3 Mean peak tibial acceleration for the final 20 steps for each measurement of each participant. The error bars display one SD.* indicates a real difference for that measurement compared to the baseline measurement.

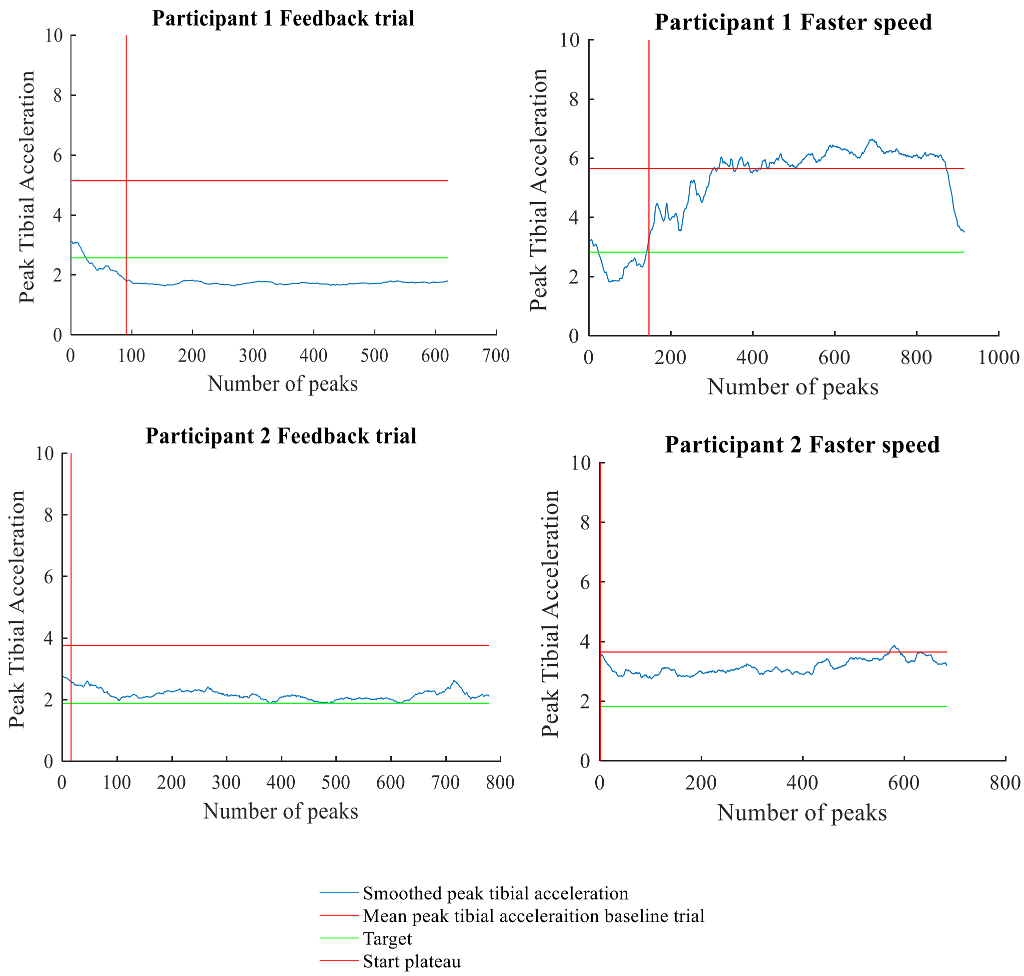

Figure 5.4 Moving average of peak tibial acceleration during the measurement taken during the feedback condition, separate subplots for every participant. The blue line (spiked line) shows the peak tibial acceleration, the red line (upper horizontal line) represents the mean peak tibial acceleration of the baseline measurement and the green line (lower horizontal line) represents the target that was set for that participant. The red vertical line represents the start of the plateau. The measurements with higher speeds can be found on the right side.

5.3.4 Discussion

The aim of this feasibility study was to investigate the response to biofeedback on tibial acceleration when participants were asked to run at higher speeds. Two participants participated in this study and both participants found a reduced decrease in mean peak tibial acceleration in the session they were asked to run at a higher speed. Further, both participants reached a plateau at a slower speed, at a higher speed both participants were no longer able to reach this plateau.

In this study, treadmill speed appeared to influence participant's response to feedback on tibial acceleration, with higher running speeds giving less decrease in tibial acceleration. At higher speeds, the variability in the different joint angles of runners decreases (Valizadeh et al., 2018) and, therefore, it is likely that fewer solutions can be found. Participant 1, for example, adopted a speed walking pattern, always had one foot on the ground, in the first session, but was not able to maintain this in the second session due to the higher speed.

It appeared that both participants were able to reduce tibial acceleration when they started running at a higher speed, but increased over time, which might be due to fatigue. Therefore, if participants run at higher speeds, more sessions might be needed, to establish a new running pattern, which is sustainable.

To create an intervention study which has a greater ecological validity the treadmill speed should be based on representative running speeds for participants. Considering different results were found on different speeds asking the participants to run at a comfortable speed might not be sufficient. Participants appeared to interpret this to mean to run far below their maximal capacity. Therefore, finding a running speed which is more representative of their normal running speed is crucial for the intervention study.

5.4 Intervention target development

5.4.1 Introduction

In the first feasibility study, section 5.2, participants were asked to reduce tibial acceleration. In the study in section 5.2, the same method as in the study by Crowell and Davis (2011) was used in which the target was set to 50 per cent of the baseline measurement. In the study performed in section 5.2, some of the participants admitted they got demotivated by not being able to reach the target. It was believed that a changing target could help participants to stay motivated to decrease tibial acceleration. The aim of this study was, therefore, to investigate the effect of a changing target on the ability of participants to reduce tibial acceleration.

5.4.2 Methods

Participants

Following institutional ethical approval, four runners were recruited for the study (2 female, 2 male; 32.3 ± 5.6 years; stature: 1.72 ± 0.14 m; body mass: 73.2 ± 19.8 kg), separate from previous sections. All participants ran at least once a week and were injury-free at the time of testing. Participants completed a pre-screening questionnaire and provided written informed consent before participating in the study.

System

The same system was used as in section 5.2.2, however, the target was set at the lowest 10 percentile of the baseline measurement (so participants were able to reach the target every tenth step) to start with and when participants were able to go below the target for 24 out of 30 steps, the target decreased by 10 per cent. However, if they were above the target for 24 out of 30 steps the target increased. The target would never go below 4 g or above the value the target started on.

Study design

An overview of the testing schedule can be seen in Table 5.2. Participants preferred running speed was determined based on the methods of Hamill, Derrick and Holt (1995), as in section 5.2.2. After warming up and taking baseline measurements on the first day, the participants received the instruction to change peak tibial acceleration by landing softer during two feedback conditions. In the first condition in which participants received feedback, participants ran with a changing target and in the second condition participants ran with a fixed target, which was based on the target the participant finished the first condition with. The first day finished with an eight-minute retention test and participants were interviewed on their experience of running with feedback. During all days participants completed a six-minute warm-up to familiarise themselves with running on a treadmill (Lavcanska et al., 2005). On the subsequent days, the participants performed a retention test after the warm-up. On the first day, participants were given a rest period between all measurements. On the subsequent days, participants ran for eight minutes without rest. The interview consisted of six open questions capturing participants' experience of the feedback system and trying to reach the feedback target.

Table 5.2 Overview of testing. min = minutes

Day 1	**Day 2**	**Day 3**
Find preferred running speed	Warming up (6 min)	Warming up (6 min)
Warming up (6 min)	Retention test (2 min)	Retention test (2 min)
Baseline (2 min)		
Changing feedback (8 min)		
Fixed feedback (8 min)		
Retention test (8 min)		
Interview		

Outcome measures and data analysis

The same outcome measures and data analysis were used as in section 5.2.2, only using Appendix N as opposed to Appendix M. Further, the results of finding a real difference for the current study were compared to the results found in section 5.2.3 to receive a better insight into the effect of a changing target on the decrease of mean peak tibial acceleration.

5.4.3 Results

Four participants completed all six measurements. Participants ran at a mean speed of 11.4 km/h with a range of: 10.0-12.4 km/h. The mean feedback target was set at 5.2 g with a range of: 4.7-6.0 g.

All participants changed peak tibial acceleration within the first step of running in the measurement taken during the changing feedback condition (Figure 5.5). Participants 1 and 3 decreased peak tibial acceleration in the measurement taken during the changing feedback measurement to reach a plateau after 255 (172 seconds) and 493 steps (334 seconds). Participant 1 slightly increased over time in the measurement taken during the fixed feedback condition to reach a plateau after 194 steps (128 seconds), participant 3 decreased in tibial acceleration over time in the measurement taken during the fixed feedback condition to reach a plateau after 112 steps (79 seconds) (Figure 5.6). Peak tibial acceleration slightly increased for participant 4 during the measurement taken during the changing feedback condition and a plateau was reached after 6 steps (4 seconds), no plateau was reached in the measurement taken during the measurement in which the feedback was fixed. Participant 2 remained constant in the measurement taken during the changing feedback condition but were able to reduce peak tibial acceleration to a new plateau after 232 steps (176) seconds in the measurement taken during the measurement in which the feedback target was fixed.

All participants demonstrated a real decrease in tibial acceleration in the measurement taken during the fixed feedback condition compared to the baseline measurement (Figure 5.7). Participant 1 showed a real decrease in tibial acceleration in all measurements compared to the baseline measurement. Other individual responses can be found in figure 5.7.

In the interviews, three of the participants (participant 1, 2, and 3) declared they found it easy to reach the target. Two of them found it difficult to run in the new pattern but were able to do it. The other participant found the feedback useful to be able to learn to run on the forefoot. Participant 4 became frustrated and felt like a failure and found the beeping (sound) annoying. All participants felt the preferred running speed was right for them.

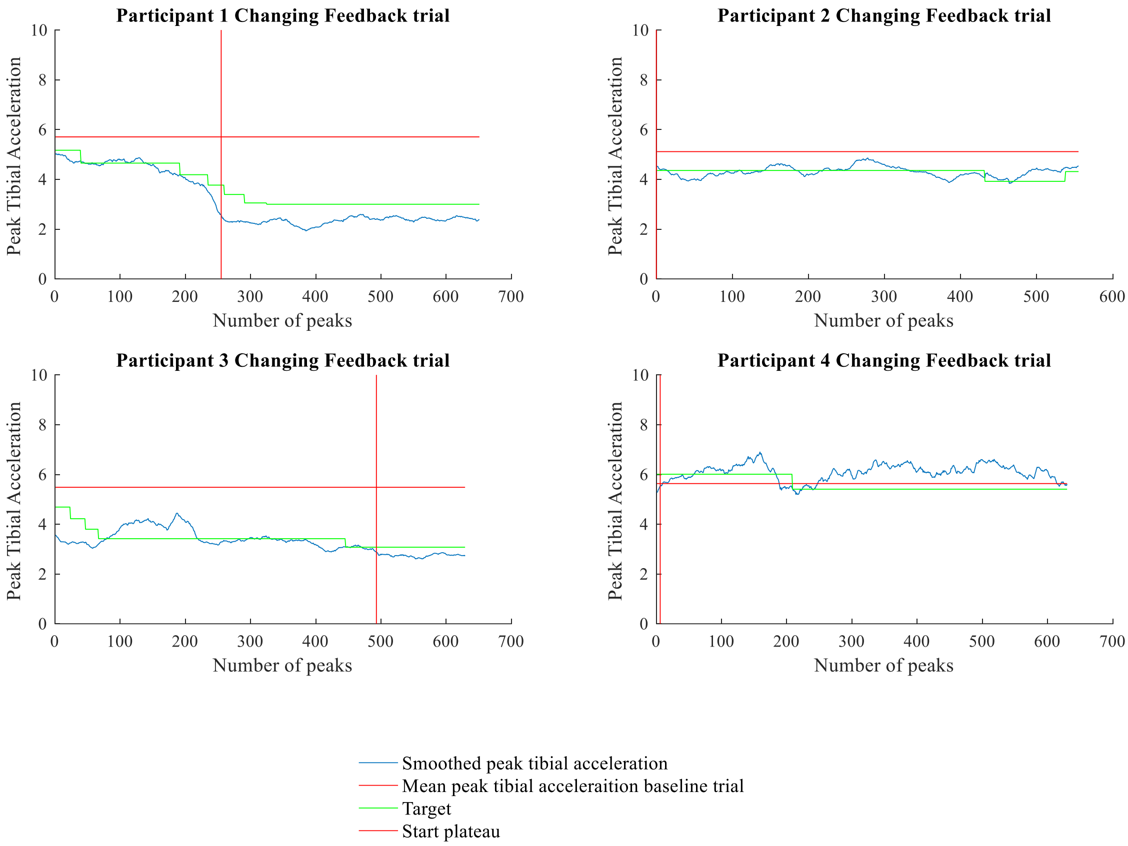

Figure 5.5 Moving average of peak tibial acceleration during the measurement taken during the changing feedback condition, separate subplots for every participant. The blue line (spiked line) shows the peak tibial acceleration, the red line (upper horizontal line) represents the mean peak tibial acceleration of the baseline measurement and the green line (lower horizontal line) represents the target that was set for that participant. The red vertical line represents the start of the plateau.

Comparing individual results between groups (current study vs. study of section 5.2.2), all participants in the changing feedback group (current section) were able to respond with a decrease in mean peak tibial acceleration comparing the measurement taken during the feedback condition to the baseline measurement, while only 4 out of 6 participants showed this decrease in the fixed feedback group (section 5.2.2).

5.4.4 Discussion

This study aimed to investigate the effect of a changing target on the ability of participants to reduce tibial acceleration. Comparing individual results, participants in the group who received a changing target (current section) were able to decrease tibial acceleration in one of the measurements taken during the feedback conditions, while two of the participants in the group with the fixed feedback (section 5.2.2) did not show this decrease. Further, the group who received a changing target (current section) did not report to be demotivated and the group who received a fixed target (section 5.2.2) did. The participants who were able to respond to the feedback, however, stayed motivated and a changing target might, therefore, be more beneficial for the participants.

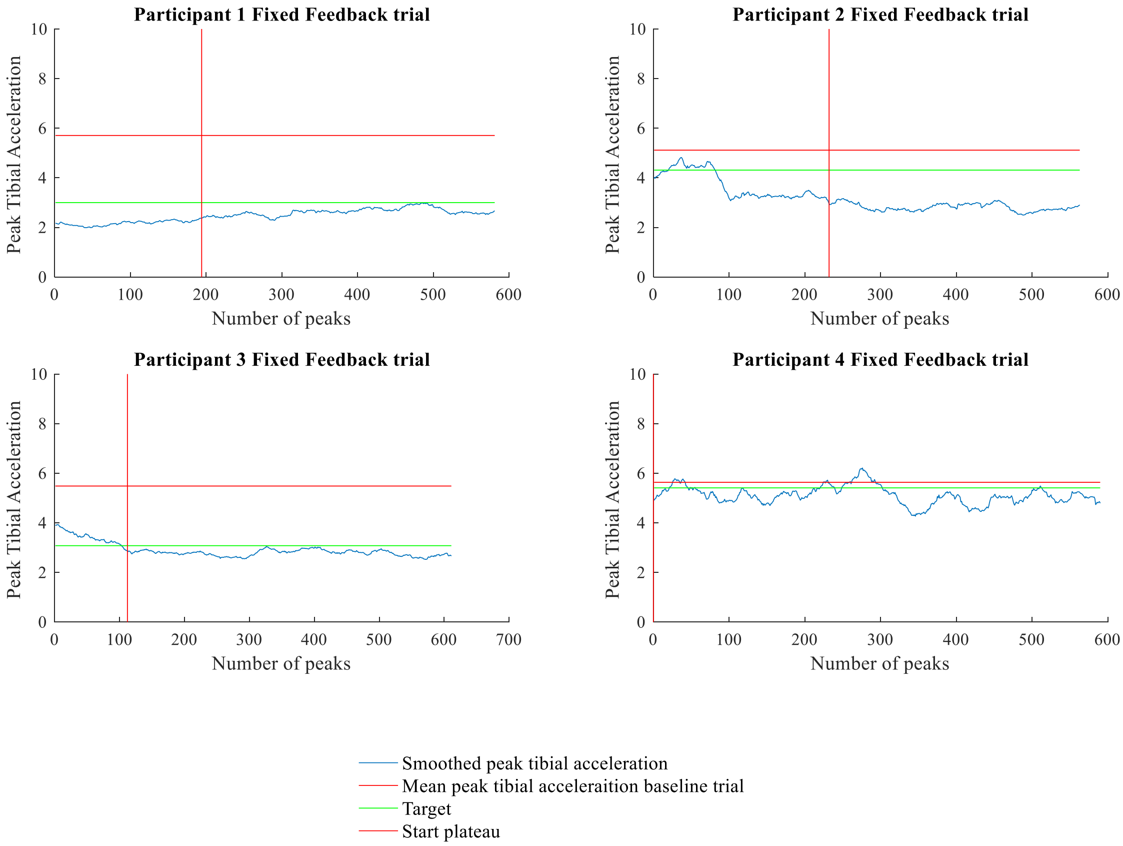

Figure 5.6 Moving average of peak tibial acceleration during the measurement taken during the fixed feedback condition, separate subplots for every participant. The blue line (spiked line) shows the peak tibial acceleration, the red line (upper horizontal line) represents the mean peak tibial acceleration of the baseline measurement and the green line (lower horizontal line) represents the target that was set for that participant. The red vertical line represents the start of the plateau.

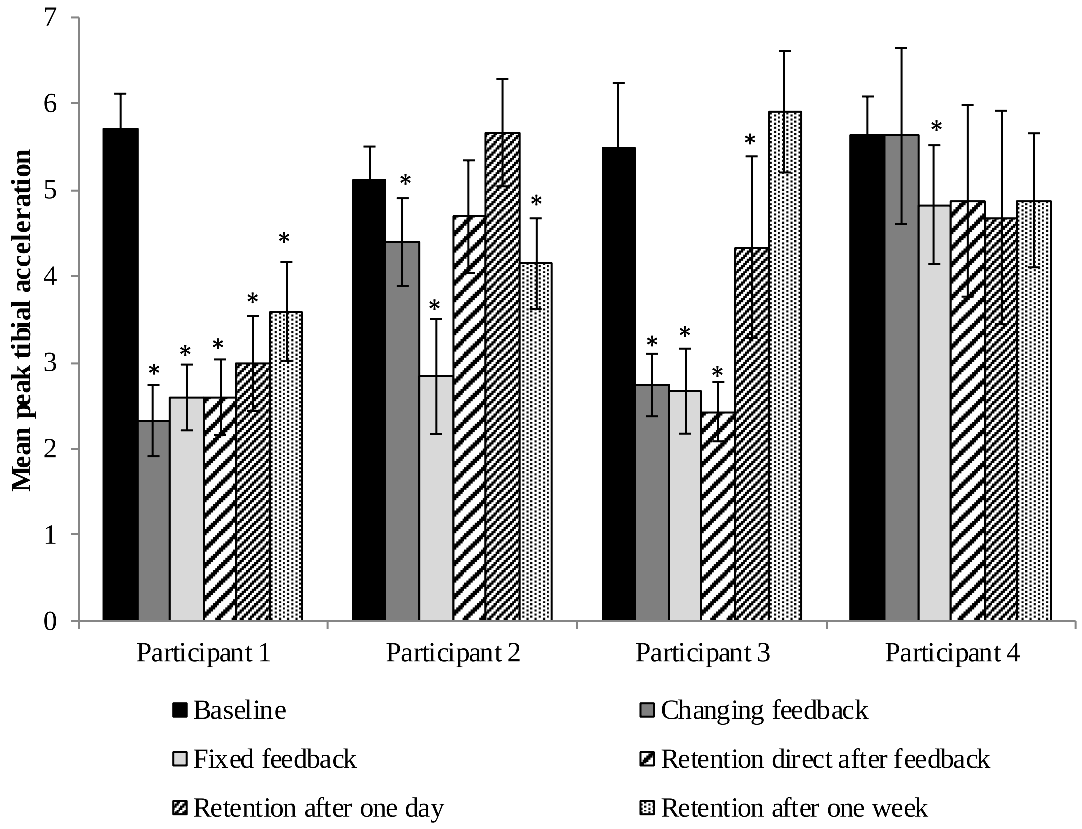

Figure 5.7 Mean peak tibial acceleration for the final 20 steps for each measurement of each participant. The error bars display one SD.* indicates a real difference for that measurement compared to the baseline measurement.

It was further noticed that participants were still able to change in the second feedback session, in which the target was fixed. It was, therefore, believed that in the intervention study the target should keep changing, in case participants went up again or reduce peak tibial acceleration even more.

5.5 Verbal instruction

5.5.1 Introduction

In the previous feasibility studies in this programme of research (Section 5.2, 5.3, and 5.4), participants reduced peak tibial acceleration during their first step in the measurements taken during the feedback conditions. Even though participants did not receive instruction on how to change their running pattern, the following instruction was given: "feedback is given on how hard you hit the ground", which could explain the change in the first step. With people changing peak tibial acceleration immediately, with the peak tibial acceleration of the first step in the feedback condition being lower than the mean of the baseline measurement, the question raised on what the effect of that instruction was. Therefore, the aim of this study was to investigate the effect of the instruction given to the participants on reducing peak tibial acceleration.

5.5.2 Methods

Participants

Following institutional ethical approval, four runners were recruited for the study (3 female, 1 male; 28.8 ± 4.5 years; stature: 1.66 ± 0.06 m; body mass: 62.5 ± 9.5 kg). All participants ran at least once a week and were injury-free at the time of testing. Participants completed a pre-screening questionnaire and provided written informed consent before participating in the study.

System, study design, outcome measures and data analysis

The same system and study design were used as in section 5.4.2, however, instead of three days, the participants come to the lab once (Table 5.3). The same outcome measures and data analysis were performed as in section 5.2.2, only using Appendix N as opposed to Appendix M. Further, the effects of the different forms of instruction (instruction on where feedback was given on, no instruction) on the results of both groups were compared. The results from participants from the study in section 5.4 were used for the group who received instruction and the participants of the current study were used for the group who did not receive instruction.

Table 5.3 Overview of testing. min = minutes

Day 1
Find preferred running speed
Warming up (6 min)
Baseline (2 min)
Changing feedback (8 min)
Fixed feedback (8 min)
Retention test (8 min)
Interview

5.5.3 Results

Four participants completed all four measurements. Participants ran at a mean speed of 11.2 km/h with a range of: 9.65-13.5 km/h. The mean feedback target was set at 7.3 g with a range of: 6.4-9.7 g.

All participants changed peak tibial acceleration within the first step of running in the changing feedback condition (Figure 5.8). Participant 4 further decreased peak tibial acceleration in the measurement taken during the changing feedback condition to reach a plateau after 51 steps (37 seconds). Participants 1 and 2 increased to reach a plateau after 56 (49 seconds) and 124 steps (87 seconds). Participant 2 reached a plateau in the measurement taken during the fixed feedback condition after 6 steps (3 seconds), however, an increase in tibial acceleration was found compared to the first steps (Figure 5.9).

All participants showed a real decrease in mean peak tibial acceleration in the measurements taken during the changing feedback condition (accept for participant 2, who showed no real difference), the fixed feedback condition, and the retention test compared to the baseline measurement (Figure 5.10).

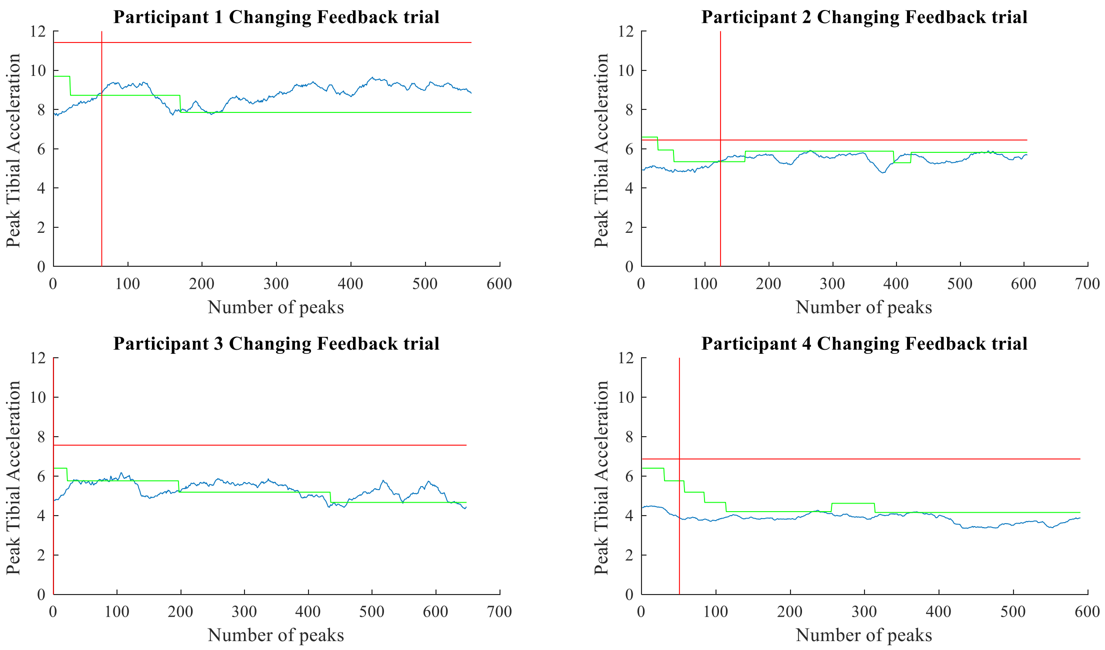

Figure 5.8 Moving average of peak tibial acceleration during the measurement taken during the fixed feedback condition, separate subplots for every participant. The blue line (spiked line) shows the peak tibial acceleration, the red line (upper horizontal line) represents the mean peak tibial acceleration of the baseline measurement and the green line (lower horizontal line) represents the target that was set for that participant. The red vertical line represents the start of the plateau.

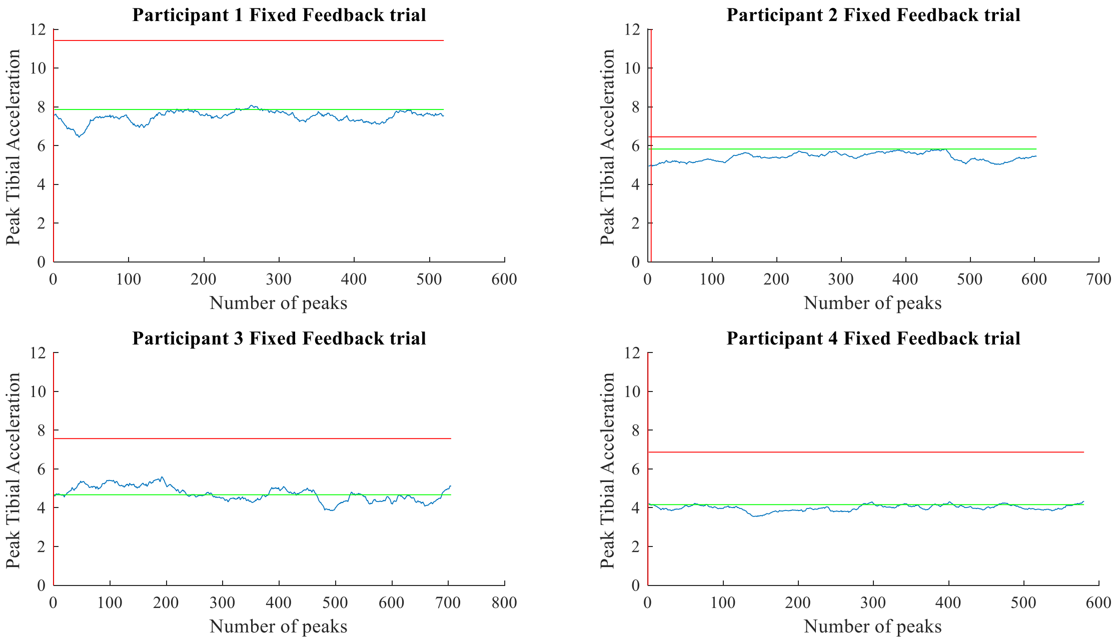

Figure 5.9 Moving average of peak tibial acceleration during the measurement taken during the fixed feedback condition, separate subplots for every participant. The blue line (spiked line) shows the peak tibial acceleration, the red line (upper horizontal line) represents the mean peak tibial acceleration of the baseline measurement and the green line (lower horizontal line) represents the target that was set for that participant. The red vertical line represents the start of the plateau.

From the interviews, it was concluded that all participants felt ok with reaching the target. Two of the participants found it slightly more difficult in the measurement taken during the changing feedback condition but were ok with the measurement taken during the fixed feedback condition. One participant thought the feedback was given on the centre of mass, one participant on step length, one on cadence, and the last one on how to land your foot. All participants felt the preferred running speed was right for them.

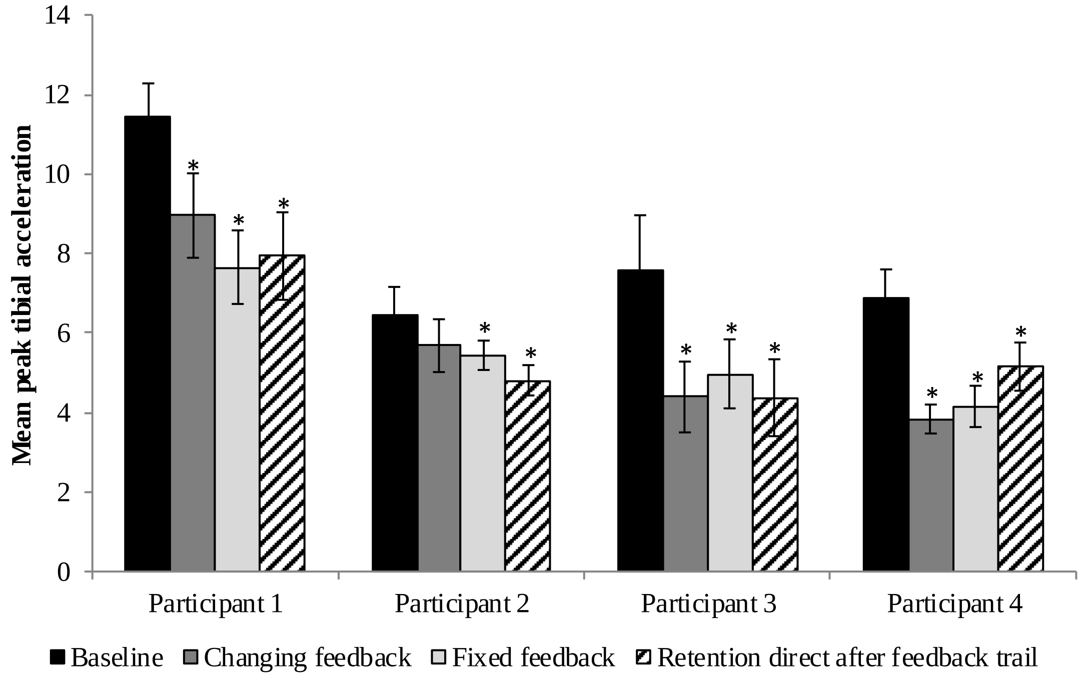

Figure 5.10 Mean peak tibial acceleration for the final 20 steps for each measurement of each participant. The error bars display one SD.* indicates a real difference for that measurement compared to the baseline measurement.

Comparing individual results of both groups (instruction, participants from study 5.4, vs. no-instruction, current study), all participants who did not receive instruction on where feedback was given on were able to respond with a decrease in mean peak tibial acceleration comparing the retention measurement to the baseline measurement. In contrast, in the group who received instruction of landing softer, only two participants found that result.

5.5.4 Discussion

The aim of this study was to investigate whether the verbal instruction that was given to the participants before the measurement taken during the feedback condition was of importance. In the previous studies of this programme of research (sections 5.2, 5.3, and 5.4), participants were told feedback was given on how hard they hit the ground and in this study, participants were not told where the feedback was given on. The results demonstrate that regardless of the instruction participants still change peak tibial acceleration within the first step. Further, all participants who did not know where feedback was given on showed a real decrease in mean peak tibial acceleration. Based on an ecological dynamics framework, in which to be able to find the optimal solution to a movement task, participants should be able to explore the different movement solutions (Newell, 1986), in the intervention study participants will not be told where feedback is given on, so they have the possibility to explore different solutions.

5.6 Chapter summery

In this chapter, four feasibility studies were performed. These feasibility studies had three objectives. The first objective was to identify the time participants took to modify tibial acceleration in response to multisensory feedback on tibial acceleration. The second objective was to investigate the short-term retention effect of feedback on tibial acceleration. The final objective was to inform the design of the intervention study.

Results indicated that in this initial phase of changing a gait pattern, all participants directly changed peak tibial acceleration within the first step of running in the measurement taken during the feedback condition. The further response to feedback was individual with twelve out of fourteen participants showing a real decrease in mean peak tibial acceleration in the feedback measurement compared to the baseline measurement. For nine of these participants a decrease in mean peak tibial acceleration was found comparing the measurement taken directly after the feedback trial to the baseline measurement. Four of the 10 measured participants maintained this real decrease in mean peak tibial acceleration after one week. This suggests that participants were able to respond to the biofeedback directly, but more sessions might be needed to find an effect for more participants after a week.

Based on the different feasibility studies the design for the intervention chapter was formed. To create an intervention study with a greater ecological validity the treadmill speed should be based on representative running speeds for participants, a changing feedback target should be used and no instruction on how participants should change their running pattern should be given.

Chapter 6: The effect of a six-session biofeedback intervention on tibial acceleration in runners

This chapter describes a six-session biofeedback intervention designed to reduce tibial acceleration in a group of recreational runners, it addresses objectives four and five of this programme of research. Objective four is to investigate the learning response to a biofeedback intervention aimed to reduce tibial shock in a group of runners, with a focus on fast and slow learning responses and task automatization. Objective five of this programme of research is to establish the kinematic strategies participants used in response to a biofeedback intervention aimed at reducing tibial acceleration.

6.1 Introduction

Tibial stress fractures are common overuse injuries among runners (section 2.5.5). Increased peak tibial acceleration is seen as a proxy measurement of tibial shock, which is associated with tibial stress fractures (section 2.5.5). Interventions focusing on decreasing tibial acceleration could, therefore, help to reduce the prevalence of tibial stress fractures and aid rehabilitation in runners. Previous studies have shown biofeedback to have a positive effect on reducing tibial acceleration, which was maintained at one-month follow-up (Clansey et al., 2014; Crowell & Davis, 2011, section 2.4.3) and one-year follow-up (Bowser et al., 2018). However, none of these studies focused on the time participants took to modify tibial acceleration in response to real-time feedback within the feedback session. It remains uncertain how many sessions are needed for a participant to respond. To gain a better insight into how long feedback should be given to participants, the time participants take to modify tibial acceleration is of interest.

Objective four of this programme of research was to investigate the learning response to a biofeedback intervention aimed to reduce tibial shock in a group of runners, with a focus on fast and slow learning responses and task automatization. Fast learning refers to the learning within a session and slow learning refers to the learning that occurs over several sessions, leading to progressive improvements and long-term retention of the task to be learned (Kami et al., 1995). Further, as described in section 2.3.4, Fitts and Posner (1967) suggested a three-stage model of motor learning, in which in the last phase the task is automatized and requires little or no cognitive demand. One way to measure cognitive loading is through the use of dual-tasks (Neumann, 1984; Richards, van der Esch, van den Noort, & Harlaar, 2018; Wickens, 1989, for more information see section 2.3.6). Previous research in biofeedback in gait (Richards et al., 2018) has used dual-tasks at the beginning and the end of a biofeedback intervention to investigate the additional cognitive demand when learning a new gait pattern. In the current study, a dual-task will be performed in every session to gain an insight into how automatization of the task occurs over the biofeedback sessions. In relation to objective 4, the aim of this chapter is to explore the learning response over the feedback intervention, with learning assessed through the application of a dual-task, and whether adaptations persisted up to a month following the intervention.

Objective five of this programme of research was to establish the kinematic strategies participants used in response to a biofeedback intervention aimed at reducing tibial acceleration. As described in section 2.4.4, previous research by Clansey et al. (2014) reported that a reduction in tibial acceleration was accompanied by group changes in foot strike angle, with participants moving from a rearfoot to midfoot strike pattern, a significant increase in ankle plantarflexion, and a significant decrease in heel velocity and initial contact. No significant changes were found in neither hip nor knee kinematics (Clansey et al., 2014). However, with a change in foot strike, from a rearfoot to midfoot strike pattern, an increase in knee flexion angle at initial contact would be expected (Almeida et al., 2015; Goss & Gross, 2012). As discussed in section 3.5, calculating group statistics could mask individual performance strategies due to aggregation and, therefore, falsely support the null-hypotheses (Bates, James and Dufek, 2004). It could be that no change in knee flexion at initial contact was found, because in the group both responders, as well as non-responders, could co-exist

(Crowell et al., 2010). Further, as well as a change in foot strike pattern as found by Clansey et al. (2014), other shock-attenuating mechanisms (as described in section 2.5.3) could be found between participants, which could affect the group results. Since this intervention aimed at reducing tibial shock, the variables associated with shock-attenuating mechanisms were included in the current study to be able to establish the kinematic strategies participants used. These variables included: foot strike angle, ankle dorsiflexion at initial contact, knee flexion at initial contact, knee flexion excursion, hip flexion at initial contact, hip adduction excursion, ankle eversion excursion, cadence, landing distance, and heel velocity at initial contact (section 2.5.3).

Changing a running pattern to reduce tibial acceleration might reduce the prevalence of tibial stress fractures, but could put more load on other structures. As described in section 2.5.2, rearfoot strikers might be more prone to knee injuries, while forefoot strikers might be prone to calf injuries (Daoud et al., 2012; Goss & Gross, 2012). Further, as described in section 2.5.6, excessive eversion might be related to exercise-related lower leg pain (Chuter & Janse de Jonge, 2012), and excessive peak hip adduction might be related greater compressive stresses on the patellofemoral joint (Noehren et al., 2012). However, the relationship between these parameters and injury should be interpreted with caution, since the cause of overuse injuries is likely to be multifactorial and diverse (Hreljac, 2004). Though there are other risk factors that are related to injuries, these were beyond the scope of the programme of research. The decision to focus on peak ankle eversion and peak hip adduction was made as these parameters are associated with over overuse injuries in running (Chuter & Janse de Jonge, 2012; Noehren et al., 2012). Therefore, excessive peak eversion and hip adduction were used as a marker for the potential development of injuries from changing gait patterns.

The aim of this chapter was to understand the learning response over the feedback intervention when assessing learning with a dual-task and establish how long the adaptations persist following the intervention. Further, this chapter aims to establish which different strategies participants used in response to a biofeedback intervention aimed at reducing tibial acceleration.

Based on previous research it is expected most participants will reduce mean peak tibial acceleration after a biofeedback intervention aimed at reducing tibial acceleration. It is hypothesised that in this study participants will find a fast learning response (Creaby & Franettovich Smith, 2016; Crowell et al., 2010; Wood & Kipp, 2014), as well as, a slow learning response (Bowser et al., 2018; Clansey et al., 2014; Crowell & Davis, 2011). Since participants were expected to find a slow learning response, it was, further, expected participants were able to automatize reduction of peak tibial acceleration. However, it remains uncertain how many sessions were needed to reduce tibial acceleration. Finally, participants were expected to find a change in foot contact pattern as an adaptation to the feedback intervention (Clansey et al., 2014). However, where Clansey et al. (2014) only found an increase in plantarflexion accompanied by the change in foot strike, an increase in knee flexion at initial contact was expected as well for individuals (Almeida et al., 2015; Goss & Gross, 2012). Other strategies might be used to reduce mean peak tibial acceleration (Almeida et al., 2015; Diss et al., 2018; Hreljac et al., 2000; Lieberman et al., 2015; Milner et al., 2007; Novacheck, 1998), but it was hypothesised that the main response to a biofeedback intervention was a change in foot contact pattern, accompanied by an increase in plantarflexion at initial contact (Clansey et al., 2014).

6.2 Methods

6.2.1 Participants

Based on an *a priori* statistical power calculation, a minimum of 12 participants were required for a repeated measures ANOVA with three measurement time points (baseline, retention test taken directly after intervention, and one-month follow-up), with a power of 0.80, an alpha level of 0.05 and effect size of 0.40 (Faul, Erdfelder, Buchner, & Lang, 2013). To account for the possibility of participants not completing the intervention, 14 participants initially were recruited, following institutional ethical approval (Appendix D). The inclusion criteria required participants to run at least once a week, to be injury-free during testing and to be at least 18 years old. Previous research has selected participants with high tibial acceleration (Clansey et al., 2014; Crowell & Davis, 2011), based on their increased risk of tibial stress injuries (Davis et al., 2004). A similar approach was taken in the present study. Participants had an initial screening to determine whether they had an increased tibial acceleration relative to a larger sample of runners. To be able to measure a high number of participants, a local parkrun was used as a fixed five-kilometre time trial to measure participants' tibial acceleration. parkrun is a weekly, free, five-kilometre timed event which takes place all over the world ("parkrun," 2019). A total of 132 runners were measured for the duration of the five-kilometre run. The top 30 per cent of participants with a mean peak tibial acceleration of at least 11 g were invited to take part in the intervention study (Appendix C). Fourteen participants of this top thirty per cent agreed to participate in the study. Previous studies (Bowser et al., 2018; Clansey et al., 2014; Crowell & Davis, 2011) only included participants with mean peak tibial acceleration values greater than 8 g or 9 g, based on laboratory measurements. Since mean peak tibial acceleration measured in the field is higher compared to mean peak tibial acceleration measured in the lab (Hollis, Koldenhoven, Resch, & Hertel, 2019; Ruder et al., 2019), recruiting participants using a cut-off of 9 g was not appropriate for the current study and the participants with the highest tibial acceleration were recruited.

Of the fourteen participants included in the study, 11 participants completed the intervention (2 female, 9 male; 43 ± 10 years; stature: 1.74 ± 0.07 m; body mass: 74 ± 11 kg). One participant dropped out and for two participants the system malfunctioned, resulting in an incomplete data set. Participants completed a pre-screening questionnaire (Appendix O) and provided written informed consent (Appendix P) before participating in the study.

6.2.2 Study design

Participants were required to attend the lab for six biofeedback sessions, and a one-month follow-up session (Table 6.1). The six feedback sessions took place over a 2 to 3.5 week time period, depending on the availability of the participants. In each session, participants started with a six-minute warm-up to familiarise themselves with running on a treadmill and to achieve a stable running pattern (Lavcanska, Taylor and Schache, 2005). The treadmill speed was set to 95 per cent of participants' five-kilometre time-trial (Appendix C), as described in section 4.2.2. The five-kilometre time-trial to define the speed was performed before the first session in the lab.

Table 6.1 Overview of the feedback intervention, where the first 6 sessions were within 3.5 weeks.

	Ses 1	Ses 2	Ses 3	Ses 4	Ses 5	Ses 6	One-month follow-up
Warming-up	6 min	6 min	6 min	6 min	6 min	6 min	6 min
Baseline	2 min	NA	NA	NA	NA	NA	NA
Feedback	15 min	16 min	17 min	18 min	19 min	20 min	NA
Retention	1 min	1 min	1 min	1 min	1 min	2 min	2 min
Stroop test	1 min	1 min	1 min	1 min	1 min	1 min	1 min

Ses = session, min = minutes, NA = not applicable

In the first session, two-minute baseline measurements of tibial acceleration, kinematic and spatiotemporal parameters were taken directly after the warm-up. After the baseline measurement, participants received feedback on tibial acceleration, with the length of the trial ranging from 15 to 20 minutes, increasing in time over the six sessions. The feedback time was faded out over the sessions (Figure 6.1), such that participants did not become dependent on the feedback, facilitating improved learning (Winstein, 1991). The participants were instructed on how the feedback system worked, but were not given any instruction on which parameter feedback was given on or how to change their gait pattern. Based on a feasibility study (section 5.5), the verbal instruction that was given ("feedback is given on how hard you hit the ground" versus "try to reduce the target") did not seem to be of importance, but by not being given a solution, participants could explore the possible shock-absorbing mechanisms available to them.

After each feedback trial, the participants' learning effect was measured with a retention test and a dual-task test (Neumann, 1984; Richards et al., 2018; Wickens, 1989). A Stroop test was chosen as a dual-task, as it presents a cognitive demand to the participant in addition to the task of reducing tibial acceleration. During the Stroop test (1 minute), words (names of colours) were displayed on the screen in front of the participant at two-second intervals, in a different colour to that described by the word. Participants were asked to say the colour of the word instead of the printed name of the word (Stroop, 1935).

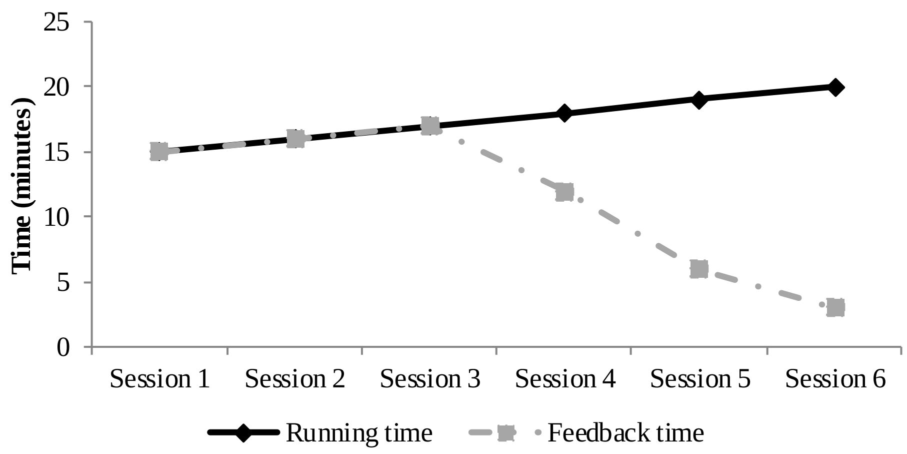

Figure 6.1 Schedule of running time and feedback time of the 6 feedback sessions. The feedback was gradually removed after the third session.

Finally, a seventh session, at least a month after the intervention, at longest two and a half months after the intervention, was performed to measure any long-term learning effect. In this seventh session, participants performed a warm-up of six minutes, a retention test of two minutes, and a dual-task test (Stroop test). Tibial acceleration, kinematic and spatiotemporal data were collected during the first, sixth and seventh session. During the other sessions (session 2-5) only tibial acceleration was measured.

After every session, the participants were asked the following open questions to identify their experiences: "How do you feel, any pain or soreness?", "Was it easy to reach the target? If not, how did that make you feel?", "What do you think you needed to do to reach the target?" and "Do you have any other comments?". The answers to the questions were recorded in note form by the researcher at the time of testing, on a measurement log. Participants' responses were informally analysed to identify their experiences and the experience of the group as a whole. A more formal approach, such as thematic analysis, was not undertaken as the data were not considered to be rich enough to support such an approach.

6.2.3 Systems

Tibial acceleration was measured using a uniaxial accelerometer (PCB Piezotronics, Stevenage, UK, Model: 352C22), with its sensitive axis visually aligned with the long axis of the right tibia. The accelerometer was mounted on a small piece of thermoplastic (total mass: 1.65 g), which was attached with double-sided tape to the wireless accelerometer manufactured by RunScribe (Figure 3.1). Both sensors together were then attached to the anteromedial aspect of the right tibia, five centimetres above the medial malleolus and wrapped in cohesive bandage, as described by Barnes, Wheat and Milner (2011). The accelerometer was connected via a cable to a PCB signal conditioner (PCB Piezotronics, Stevenage, UK, model: 480E09; gain = 10) and sampled at 1000 Hz.

The feedback system was created in a custom-written LabVIEW™ program (National Instruments, Austin, TX, USA). More information on the feedback system can be found in section 3.4. Visual, auditory, and sensory feedback was given on peak tibial acceleration. Visual feedback consisted of the signal shown on a screen, together with the target line. Based on the feasibility study described in section 5.4, the initial target was set at the tenth percentile of the peak tibial acceleration recorded during the baseline measurement and changed according to the performance of the participant. Participants received vibrotactile (on the wrist - Precision Microdrives, London, UK, model: 307-103) and auditory feedback when the measured tibial acceleration was greater than the target acceleration. The intensity of the vibration and pitch of the sound was scaled to the magnitude of the difference between the measured tibial acceleration and the target acceleration.

6.2.4 Data processing

The raw signal from the accelerometer was exported to Matlab (Mathworks, R2016a) and filtered with a 400th order, finite impulse response, Hamming, band-pass filter with lower and upper cut-off frequencies of 8 and 60 Hz, respectively (section 3.2.2). After filtering, the mean of the signal was subtracted from the data to standardize the data and the peaks of the signal were determined (for more information see section 3.2.3).

Kinematic and spatiotemporal data were collected during the first, sixth and seventh session, using a 14-camera optoelectronic motion capture system sampling at either 240 Hz or 250 Hz (section 3.3.1). A marker set was chosen in accordance with Cappozzo et al. (1995, 1997), for more information see section 3.3.2. After participant preparation, a static trial was recorded in which participants were asked to stand in the anatomical position, after which the calibration markers were removed (medial and lateral femoral condyles, medial and lateral malleoli). Next, a trial to calculate the functional hip joint centre was recorded (Begon et al., 2007), followed by the running trials. The data recorded from the motion capture system were first processed in Cortex software (version 5.3, Motion Analysis Corporation, Santa Rosa, CA, USA) by filling the gaps in the data. The exported data were then filtered in Visual 3D software (C-Motion Inc., Germantown, USA) with a low-pass, fourth order, zero-phase-shift, Butterworth filter with a cut-off frequency of 14 Hz or 18 Hz, based on whether the data was used to calculate acceleration or position, respectively (see section 3.3.4). The filtered signal was used to calculate hip, knee and ankle joint coordinate system angles (Grood & Suntay, 1983) as was described in section 3.3.2. Joint angles and filtered marker data were exported from Visual 3D (C-Motion Inc., Germantown, USA) and parameters of interest were calculated using Matlab (Mathworks, R2016a). More information on the system and details of the joint angles and initial foot contact calculations can be found in section 3.3.

6.2.5 Outcome measures

The mean of the final 20 steps of each measurement was used to calculate dependent variables (Bates et al., 1992). The dependent variables were related to different shock attenuating variables or risk factors for injuries as described in section 2.5. The parameters of interest were calculated as described in section 4.2.3 and included: mean peak tibial acceleration, foot strike angle, ankle dorsiflexion at initial contact, knee flexion at initial contact, knee flexion excursion, hip flexion at initial contact, hip adduction excursion, ankle eversion excursion, landing distance, cadence, heel velocity at initial contact, peak hip adduction, and peak ankle eversion.

6.2.6 Data analysis

In the current programme of research, there was an interest in individual-, over group-results, to be able to distinguish between responders and non-responders. However, to be able to compare the current results to previous research, group results were calculated as well on outcome measures. Further, the group analysis was performed to be able to get further insight into how single-subject analysis related to group analysis.

Fast learning response to the biofeedback intervention

For each participant, fast learning was defined as a difference between the baseline measurement and the measurement taken during the retention test within a session. For the group, a paired-samples *t*-test was performed comparing the baseline measurement to the retention measurement taken in the first session to define a significant fast learning response for the group. The level of significance was set at 0.05. A single-subject analysis was then used to characterise individual learning effects (Bates, 1996). As described in section 3.5 and chapter 4, the minimal detectable difference was used to characterize individual differences. When a difference was greater than the minimal detectable difference, the difference was interpreted as "real" (Atkinson & Nevill, 1998; Weir, 2005). The minimal detectable difference for mean peak tibial acceleration, comparing values within a session is 16% (Table 4.1).

Slow learning response to the biofeedback intervention

Slow learning and the effectiveness of the intervention was defined as a real difference between the measurement taken during the one-month retention test and the baseline measurement. Further, to assess the effectiveness of the intervention in reducing participants' tibial acceleration directly after the intervention and after a month, the baseline mean peak tibial acceleration (session 1) was compared to the retention test measured directly after the final feedback session (session 6) and the mean peak tibial acceleration measured after a month (session 7).

To compare the measures between sessions, a group analysis was performed along with a single-subject analysis. Firstly, a repeated measures analysis of variance (ANOVA) was performed to compare the different measurements for the group analysis. The assumption of sphericity was checked according to Girden (1992). If the assumption was violated and the Greenhouse-Geisser epsilon was ≥ 0.75, the Huynh-Feldt correction was used, if the assumption was violated and the Greenhouse-Geisser epsilon was < 0.75 the Greenhouse-Geisser correction was used. Paired *t*-tests were used as a post hoc test to identify where the specific differences occurred between the measurements, with the main interest being in the difference between the baseline measurement and the measurement taken after one month. The level of significance for all statistical calculations was set at 0.05. The calculations were made using SPSS, version 24 (SPSS; Inc, Chicago, IL). Effect sizes were calculated with the use of Hedges' g. Hedges' g above 0.2, 0.5 and 0.8 were considered to represent small, medium, and large differences, respectively.

A single-subject analysis was then used to characterise individual learning effects (Bates, 1996). As described in section 3.5 and chapter 4, the minimal detectable difference was used to characterize individual differences. When a difference was greater than the minimal detectable difference, the difference was interpreted as "real" (Atkinson & Nevill, 1998; Weir, 2005). The minimal detectable difference for mean peak tibial acceleration, comparing values between sessions is 21% (Table 4.1).

Finally, to identify participants with a larger response to the feedback intervention the effect size was calculated for each participant. The effect size was calculated with the use of Cohen's d comparing the last 20 steps of mean peak tibial acceleration of the measurement taken after a month to the baseline measurement.

Automatization of reducing mean peak tibial acceleration

Whether a participant automatized the reduction in mean peak tibial acceleration was checked with the use of dual-tasks. Within each session, the following measurements were compared: baseline, retention after feedback, and dual-task (Stroop test), using the minimal detectable difference. If participants displayed an increased mean peak tibial acceleration during the measurement, in which they also performed a Stroop test compared to the measurement, taken during the retention test, it was expected that the participants had not reached the third stage of learning and cognitive resources were needed to perform the task of reducing tibial acceleration. Alternatively, if a participant did not show an increase in mean peak tibial acceleration during the Stroop condition, it was expected to be automatized (Neumann, 1984; Richards et al., 2018; Wickens, 1989). The mean of the sessions in which the participants automatized reducing tibial acceleration was calculated to define a group result.

Kinematic and spatiotemporal response to the biofeedback intervention

To establish the different running strategies participants used, there was a comparison of parameters of interest at the measurements: at baseline, at the retention test taken directly after the feedback intervention, and at the retention test taken after a month. Firstly, a repeated measures ANOVA was performed to compare the different measurements for the group analysis as described in the section "Slow learning response to the biofeedback intervention".

A single-subject analysis was used to characterise individual changes (Bates, 1996). For the single-subject analysis, similar methods were used as described in the section on "Slow learning response to the biofeedback intervention ". Participants with similar movement characteristics were placed in groups. For these groups, separate repeated measures ANOVAs were performed to identify similarities between participants (Bates et al., 2004). In case of the occurrence of small groups, the effect size was calculated instead of the significance for the parameters, to check whether the differences between sessions (that are common to all participants in the group) were of meaningful magnitude.

6.3 Results

6.3.1 Fast learning response to a biofeedback intervention

For the group, mean peak tibial acceleration measured during the retention test, taken during the first session, was significantly lower compared to the baseline measurement (baseline = 7.84 g, retention = 6.26 g, $t(10) = 3.22$, $p = 0.009$). These group results suggest that the group found a fast learning response. Focussing on individual responses, eight (participant 1, 2, 3, 5, 6, 7, 8 and 10) out of eleven participants showed a real decrease in mean peak tibial acceleration in the first session, comparing the retention measurement to the baseline measurement (Table 6.2, Appendix Q).

6.3.2 Slow learning response to a biofeedback intervention

A significant effect ($F(2,20) = 4.07$, $p = 0.03$) of the intervention was found on mean peak tibial acceleration (Figure 6.2). The baseline of session one was significantly higher from the other two measurement points (retention directly after the intervention:

p = 0.046; one-month retention: p=0.042). These results suggest a slow learning response for the group was present. A large effect size (g = 0.94) was found when comparing the baseline measurement to the retention measurement taken after a month, and a medium effect size (g = 0.72) was found comparing the measurement taken directly after the intervention to the baseline measurement. The group mean peak tibial acceleration at baseline was 7.84 g ± 1.94 g. The group mean peak tibial acceleration at the one-month follow-up was 5.79 g ± 2.25 g.

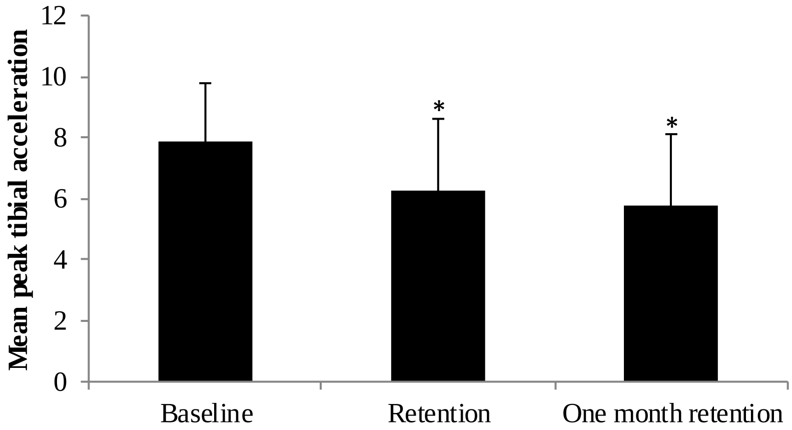

Figure 6.2. Mean for all participants of the mean peak tibial acceleration for the different measurements displayed with one standard deviation. * defines a significant difference compared to baseline.

Nine participants had a decreased tibial acceleration after a month compared to the baseline measurement, suggesting a slow learning response (Table 6.2). Mean peak tibial acceleration was lower in both retention trials compared to the baseline trial, for six participants (participants 1, 2, 3, 8, 10, and 11, Figure 6.3). Mean peak tibial acceleration was lower in one of the retention measurements compared to the baseline measurement, for four participants (Participant 5, 6, 7, and 9). Of the two non-responders, one participant (participant 6) found a reduction directly after the intervention, but did not maintain this reduction after a month. The other non-responder found an increase in mean peak tibial acceleration in both retention measurements compared to the baseline measurement (participant 4).

A large effect size was found for participants 2 (Cohen's D = 11.8), 5 (Cohen's D = 5.0), 7 (Cohen's D = 2.9), and 11 (Cohen's D = 5.1) when comparing peak tibial acceleration from the baseline measurement to the one-month retention measurement. A larger effect size indicates a participant was a good responder to the intervention.

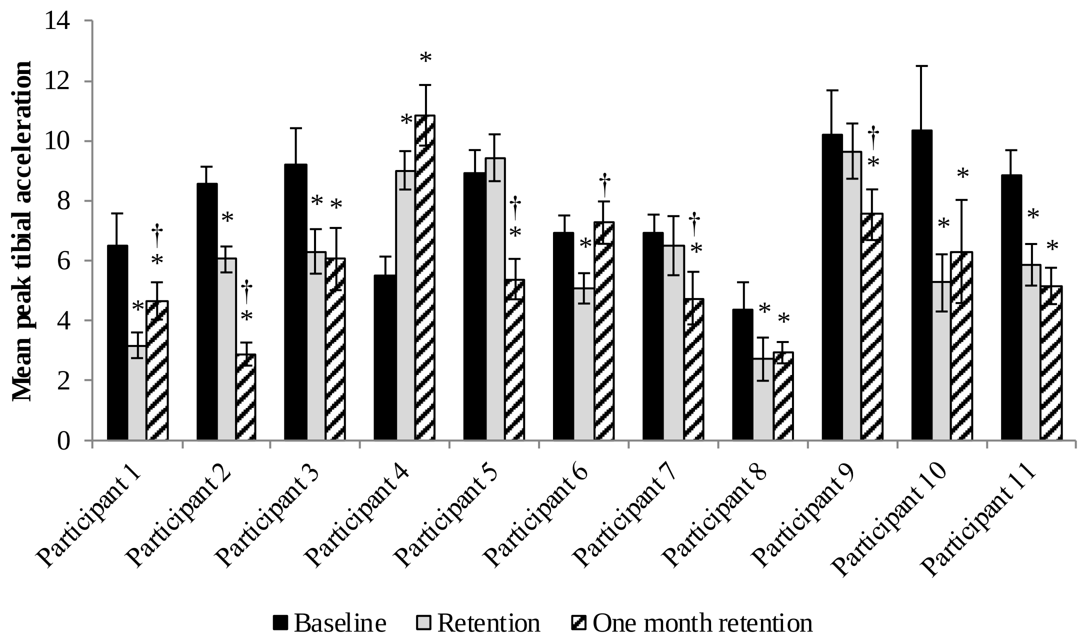

Figure 6.3. Mean peak tibial acceleration for the participants for the different measurements displayed with one standard deviation. * = real difference between retention measurement and baseline measurement, † = real difference between retention measurement taken directly after the measurement and retention taken after a month.

6.3.3 Automatization of reducing tibial acceleration

The Stroop test results (Appendix Q) suggest that nine of the eleven participants (participants 1, 3, 5, 6, 7, 8, 9, 10, 11) automatized the task between the first and fifth session (Table 6.2). Most of these participants (participants 1, 3, 5, 6, 7, 8, and 10) decreased in mean peak tibial acceleration comparing later sessions to the session in which the participant automatized tibial acceleration (Table 6.2). Participant 1 will now be used as an example of participants' pathway to automatization of the task (reducing tibial acceleration) through the intervention. Participant 1's mean peak tibial acceleration was higher in the measurements taken during the Stroop test compared to the measurements taken in the retention tests for the first three sessions (Figure 6.4), suggesting the task (reducing tibial acceleration) was not automatized. In session 4, participant 1 showed no increase in mean peak tibial acceleration when comparing the measurement taken during the Stroop test to the retention measurement (Figure 6.4). This indicates that by their fourth session the task, reducing tibial acceleration, was automatized by participant 1. This was confirmed by a real decrease in mean peak tibial acceleration of the baseline measurement of the fifth session, compared to the baseline measurement of the first session (Figure 6.4). In the fifth session, participant 1 showed a further decrease in mean peak tibial acceleration, comparing the retention measurement to the baseline measurement (Figure 6.4), suggesting that participant 1 was still exploring different solutions. In-depth results of the other participants who found an automatization of the task can be found in Appendix Q. By comparison, participant 2 did not automatize reducing tibial acceleration within the first six sessions, but did find a reduction in mean peak tibial acceleration, comparing the seventh session to the sixth session, and participant 4 was unable to reduce tibial acceleration (Appendix Q). For the group, the reduction of mean peak tibial acceleration was automatized after 3 sessions.

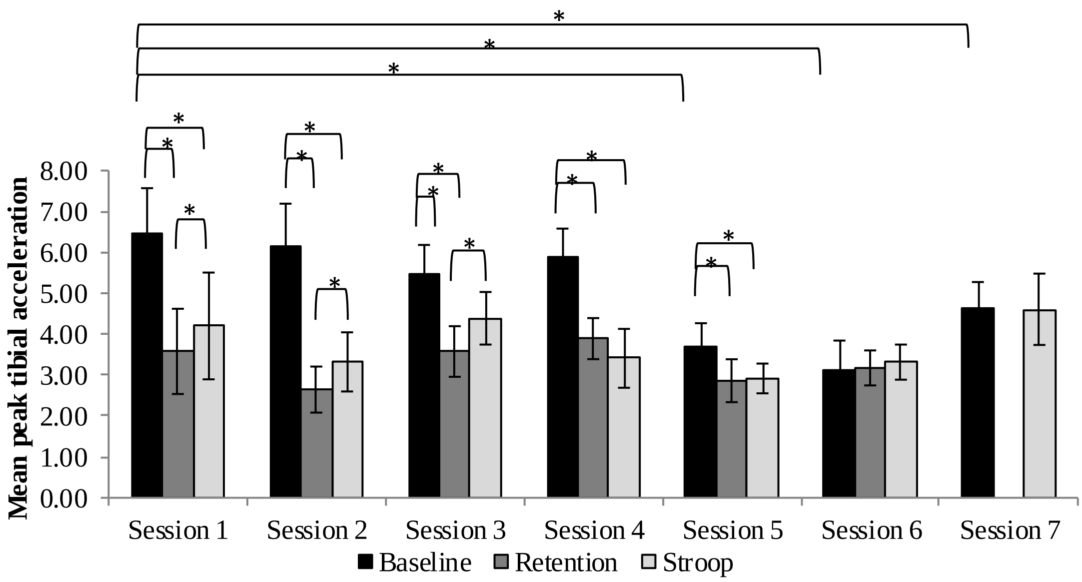

Figure 6.4 Mean peak tibial acceleration for each measurement for each session for participant 1. * = real difference between measurements. Compared measurements within a session and baseline measurements of each session to the first session.

Table 6.2 Learning response to a six-session biofeedback intervention. Learning split up in fast learning, slow learning, and in which sessions the task got automatized. The final column gives insight on whether a reduction in mean peak tibial acceleration was found comparing the retention measurements to baseline measurements of the sessions after the task was automatized.

PP	Fast learning	Slow learning	Automatization session	Decrease after automatization
1	yes	yes	4	yes
2	yes	yes	7	n.a.
3	yes	yes	2	yes
4	no	no	no	n.a.
5	yes	yes	3	yes
6	yes	no	3	yes
7	yes	yes	1	yes
8	yes	yes	1	yes
9	no	yes	3	no
10	yes	yes	1	yes
11	no	yes	5	no

PP = participant number

6.3.4 Kinematic and spatiotemporal response to the intervention

No significant group effect was found for the intervention in any of the kinematic or spatiotemporal variables (Table 6.3). However, a large effect size (g = 0.89) was found for the decrease in heel velocity at initial contact when comparing the retention measurement taken directly after the intervention to the baseline measurement. A moderate effect size (g = 0.52) was found for the increase in ankle plantarflexion at initial contact when comparing the retention measurement taken after a month to the baseline measurement. Finally, moderate effect sizes (g = 0.65 and g = 0.58) were found for the increase in peak ankle eversion during stance, between both retention measurements and baseline. Further, large standard deviations were found for most variables reflecting the inter-individual differences.

Several adaptions were seen across participants (Table 6.4). Three participants (participant 2, 5, and 7) changed from a rear/midfoot contact to a midfoot/forefoot contact, when comparing the retention measurement taken after a month to the baseline measurement (Appendix Q). The other participants found different shock-absorbing mechanisms comparing the one-month retention measurement to the baseline measurement, including increased knee flexion excursion (participants 1, 3, and 9), increase in knee flexion at initial contact (participants 8 and 11), hip adduction excursion (participant 10), and/or ankle eversion excursion (participant 1, 8, 9, and 10). Different strategies were found for individuals between both retention measurements (Table 6.4, Appendix Q). For example, comparing the retention measurement taken directly after the feedback intervention to the baseline measurement, participant 3 showed a real increase in ankle eversion excursion while comparing the measurement taken after a month to baseline measurement the participant showed a real increase in knee flexion excursion. Tibial acceleration was lower in both retention measurements compared to the baseline measurement.

Table 6.3 Kinematic and spatiotemporal results for all participants.

Variable	Baseline	Reten direct	Reten month	ANOVA		Hedges' g	
	Mean (SD)	Mean (SD)	Mean (SD)	F	p	1- 6	1- 7
Peak tibial accel (g)	7.8 (1.9)	6.3 (2.3) *	5.79 (2.3) *	4.07	**0.03**	0.70	0.94
Foot strike angle (°)	14.7 (8.7)	16.6 (9.2)	13.2 (11.9)	1.10	0.35	0.18	0.10
Ankl dorsiflexion IC (°)	2.4 (4.4)	1.2 (4.7)	-0.6 (6.1)	1.53	0.24	0.21	0.52
Knee flexion IC (°)	17.5 (5.6)	16.3 (7.0)	18.9 (5.6)	1.07	0.36	0.14	0.22
Knee flexion excurs (°)	25.2 (4.8)	25.3 (5.9)	23.6 (5.8)	0.88	0.43	-0.03	0.26
Hip flexion IC (°)	40.3 (6.3)	38.5 (5.4)	39.2 (4.6)	0.80	0.46	0.27	0.17
Hip adduction excurs (°)	5.8 (3.5)	7.0 (3.7)	5.9 (3.8)	1.36	0.28	0.28	-0.02
Ankl eversion excurs (°)	10.1 (3.3)	115 (5.2)	12.4 (7.6)	1.22	0.41	0.28	0.36
Landing distance (m)	0.25 (0.06)	0.27 (0.05)	0.25 (0.06)	2.16	0.17	0.26	0.05
Cadence (steps/s)	1.42 (0.06)	1.45 (0.07)	1.45 (0.10)	1.83	0.20	0.45	0.39
Heel velocity IC (m/s)	0.37 (0.11)	0.27 (0.10)	0.30 (0.19)	4.19	0.06	0.89	0.38
Peak hip adduction (°)	19.7 (6.8)	19.5 (5.2)	19.2 (4.0)	0.03	0.97	-0.02	0.04
Peak ankle eversion (°)	5.5 (2.9)	8.8 (6.2)	8.4 (5.9)	0.14	0.18	0.65	0.58

Reten direct = retention measurement taken directly after the feedback intervention, Reten month = retention measurement taken after a month, SD = standard deviation, F = F-value, p = p-value, 1-6 = comparison baseline to retention measurement taken directly after the feedback intervention, 1-7 = comparison baseline to retention measurement taken after a month, accel = acceleration, ankl=ankle, IC = initial contact, excurs=excursion, * = significant different to baseline, $p<0.05$, **Bold** = significant, $p<0.05$

Only one subgroup of three participants with notably similar adaptations to each other could be identified (Table 6.5). Since this subgroup contained three participants, effect sizes were calculated instead of a repeated measures ANOVA. The three participants showed large effect sizes when comparing the retention measurement taken, after a month, to the baseline measurement for the decreases in foot strike angle (g = 1.28, more towards forefoot contact), landing distance (g = 1.50), and knee flexion excursion (g = 2.62), and increases in plantarflexion at initial contact (g = 1.88), knee flexion at initial contact (g = 1.44), hip adduction excursion (g = 1.59), and peak hip adduction (g = 1.34). Two participants were unable to find a decrease in mean peak tibial acceleration after a month, and of the other six participants, each participant found a different adaptation to decrease mean peak tibial acceleration, which made it impossible to place them into subgroups.

Table 6.4 Adaptations to a six-session biofeedback intervention. In the table, shock-absorbing mechanisms are shown participants found using comparing the session (direct after the intervention or a month after the intervention) to the baseline measurement. If no decrease in mean peak tibial acceleration was found the differences between the two sessions were not reported (n.a.).

PP	Direct after intervention	A month after intervention
1	ankle plantarflexion↑ cadence↑ heel velocity↓	ankle plantarflexion↑ knee flexion excursion↑ ankle eversion excursion↑
2	knee flexion excursion↑ heel velocity↓	foot strike angle↓ knee flexion↑ landing distance↓ heel velocity↓
3	ankle eversion excursion↑ heel velocity↓	knee flexion excursion↑ heel velocity↓
4	n.a.	n.a.
5	n.a.	foot strike angle↓ knee flexion↑ hip adduction excursion ↑landing distance↓
6	knee flexion↑ hip adduction excursion↑ cadence↑ heel velocity↓	n.a.
7	n.a.	foot strike angle↓ plantarflexion↑ knee flexion↑ hip adduction excursion ↑landing distance↓
8	cadence↑ heel velocity↓	knee flexion↑ ankle eversion excursion↑ cadence↑ heel velocity↓
9	n.a.	knee flexion excursion↑ ankle eversion excursion↑ cadence↑ heel velocity↓
10	hip adduction excursion↑ ankle eversion excursion↑ cadence↑ heel velocity↓	hip adduction excursion↑ankle eversion excursion↑ cadence↑ heel velocity↓
11	heel velocity↓	heel velocity↓ cadence↑ knee flexion↑

↑ = real increase between the session and the baseline measurement, ↓ = real decrease between the session and the baseline measurement

Table 6.5 Kinematic and spatiotemporal results for the group who changed their foot contact pattern (participant 2, 5, and 7).

Variable	Baseline Mean (SD)	Reten direct Mean (SD)	Reten month Mean (SD)	Hedges' g 1-6	Hedges' g 1-7
Peak tibial acceleration (g)	8.2 (1.1)	7.3 (1.8)	4.5 (1.4)	0.51	2.91
Foot strike angle (°)	14.3 (7.6)	14.7 (2.2)	3.3 (9.1)	0.04	1.28
Ankle dorsiflexion IC (°)	2.1 (4.5)	-1.1 (1.9)	-6.1 (4.1)	0.90	1.88
Knee flexion IC (°)	16.9 (5.9)	14.2 (13.2)	24.6 (4.4)	0.22	1.44
Knee flexion excursion (°)	23.3 (3.8)	22.7 (9.3)	16.1 (0.6)	0.04	2.62
Hip flexion IC (°)	37.9 (8.1)	37.6 (8)	40.1 (9.1)	-0.01	0.22
Hip adduction excursion (°)	3.6 (1.2)	6.1 (2.0)	6.0 (1.7)	1.45	1.59
Ankle eversion excursion (°)	10.8 (1.6)	7.3 (4.9)	8.0 (5.3)	0.93	0.68
Landing distance (m)	0.25 (0.05)	0.25 (0.07)	0.18 (0.04)	-0.01	1.50
Cadence (steps/s)	1.46 (0.05)	1.43 (0.02)	1.43 (0.03)	0.65	0.50
Heel velocity IC (m/s)	0.30 (0.14)	0.22 (0.13)	0.35 (0.21)	0.58	0.25
Peak hip adduction (°)	16.4 (4.9)	18.3 (3.9)	21.6 (2.1)	0.38	1.34
Peak ankle eversion (°)	2.9 (2.1)	8.8 (7.3)	4.4 (6.4)	1.07	0.30

Reten direct = retention measurement taken direcly after the feedback intervention, Reten moth = retention measurement taken after a month, SD = standard deviation, 1-6 = comparison baseline to retention measurement taken directly after the feedback intervention, 1-7 = comparison baseline to retention measurement taken after a month, IC = initial contact

One of the non-responders (participant 4) showed an increase in cadence and plantarflexion, comparing the measurement taken during the retention test after a month to the baseline measurement. This in combination with a change in foot strike angle might decrease tibial acceleration, however, no real difference in foot strike angle was found (Table 6.6). This suggests that whether a change in parameters is beneficial could depend on the combination of parameters and is not depending on individual parameters. Similar results were found for the other non-responder, participant 6. When comparing the baseline measurement to the retention measurement of participant 6 taken directly after the feedback intervention, in which a decrease in mean peak tibial acceleration was shown, a real increase in flexion in the knee at initial contact, hip adduction excursion, and cadence, and a real decrease in heel velocity at initial contact were found (Table 6.6). For participant 6, the increases in knee flexion at initial contact and hip adduction excursion were no longer present comparing the one-month follow-up retention measurement to the baseline measurement (Table 6.6). For participants who did find a reduction in mean peak tibial acceleration after a month, but not directly after the intervention, similar findings were found. Comparing both retention measurements to the baseline measurement, participant 5 found a real change in their foot strike pattern, changing from contact more towards the heel to contact more towards the front of the foot (Table 6.6). This was accompanied by a real increase in knee flexion at initial contact, and hip adduction excursion, and a real decrease in landing distance and knee flexion excursion (Table 6.6). For participant 5, when comparing the retention measurement taken after a month to the baseline measurement a real increase in plantarflexion at initial contact was found, this was not found when comparing the retention measurement taken directly after the feedback intervention to the baseline measurement (Table 6.6). Similar findings were found for participant 7 and 9 (Table 6.6). These results suggest a combination of the right parameters is important, and a change in one parameter alone might not be sufficient.

Table 6.6 Adaptations to a six-session biofeedback intervention of the non-responders (either direct after the intervention or after a month). In the table, all real differences are shown comparing the session (direct after the intervention or a month after the intervention) to the baseline measurement.

PP	Direct after intervention	A month after intervention
4	Peak tibial acceleration↑ hip adduction excursion↑ cadence↑ heel velocity↓	Peak tibial acceleration↑ ankle dorsiflexion↓ hip adduction excursion↑ cadence↑ heel velocity↓
5	foot strike angle↓ knee flexion↑ knee flexion excursion↓ hip adduction excursion↑ ankle eversion excursion↓ landing distance↓ heel velocity↓	Peak tibial acceleration↓ foot strike angle↓ ankle dorsiflexion↓ knee flexion↑ knee flexion excursion↓ hip adduction excursion↑ ankle eversion excursion↓ landing distance↓
7	ankle dorsiflexion↓ hip adduction excursion↑ cadence↓	Peak tibial acceleration↓ foot strike angle↓ ankle dorsiflexion↓ knee flexion↑ knee flexion excursion↓ hip adduction excursion↑ landing distance↓ cadence↓ heel velocity↑
6	Peak tibial acceleration↓ ankle dorsiflexion↓ knee flexion↑ hip adduction excursion↑ landing distance↑ cadence↑ heel velocity↓	Ankle dorsiflexion↓ knee flexion excursion↓ hip adduction excursion↓ landing distance↑ cadence↑ heel velocity↓
9	foot strike angle↑ knee flexion↓ knee flexion excursion↑ ankle eversion excursion↑ landing distance↑	Peak tibial acceleration↓ foot strike angle↑ knee flexion↓ knee flexion excursion↑ hip adduction excursion↓ ankle eversion excursion↑ landing distance↑ cadence↑ heel velocity↓

↑ = real increase between the sessions and the baseline measurement, ↓ = real decrease between the session and the baseline measurement

Concerning parameters related to injuries, participants 1 and 4 increased in peak hip adduction during the stance phase and participant 4 and 11 increased in peak ankle eversion during the stance phase, when comparing the retention measurement taken after a month to the baseline measurements. On the contrary, participants 3, 9, and 11 decreased in peak hip adduction.

6.4 Discussion

This study aimed to give a better insight into the time participants took to modify tibial acceleration by evaluating the motor learning process of a six-session feedback intervention, focused on reducing tibial acceleration. A distinction was made in modifying tibial acceleration within a session, considered the fast learning response, and the response over several sessions, considered the slow learning response (Kami et al., 1995). Further, at the end of each session participants performed a dual-task (Stroop test and running) to assess the automatization of the task of reducing tibial acceleration (Neumann, 1984; Richards et al., 2018; Wickens, 1989). Additionally, this chapter aimed to establish the difference in strategies participants used to change their gait patterns and relate this to their ability to change tibial acceleration. The discussion will focus on the fast learning response to the biofeedback intervention, the slow learning response to the biofeedback intervention, automatization of reducing tibial acceleration, difference in strategies participants used to change their gait patterns, the effect of the intervention on injury risk, how the results fit within motor learning theories, and the limitations of the current study.

6.4.1 Fast learning response to a biofeedback intervention

A significant decrease in mean peak tibial acceleration was found comparing the retention test taken in the first session to the baseline measurement, suggesting a fast learning response for the group (Kami et al., 1995). Eight of the eleven participants were able to modify their gait pattern within the first session, suggesting most participants were indeed able to respond to the feedback within one session. A reduction of 20 per cent in mean peak tibial acceleration within one session was in line with previous research (Creaby & Franettovich Smith, 2016; Crowell et al., 2010; Wood & Kipp, 2014), which found reductions in mean peak tibial acceleration varying between 8 and 30 per cent. These results indicate a beneficial effect of one biofeedback session can be found directly after a single session.

6.4.2 Slow learning response to a biofeedback intervention

For the group, a significant decrease in mean peak tibial acceleration was found directly and one month after the intervention had finished compared to the baseline measurement of the first session. Seven participants showed a real decrease in mean peak tibial acceleration when comparing the retention measurement, taken directly after the intervention, to the baseline measurement. Nine participants were able to respond to the feedback intervention with a reduction in mean peak tibial acceleration after a month, suggesting a slow learning response (Kami et al., 1995). One other participant was unable to respond to the feedback at all and showed an increase in mean peak tibial acceleration in all sessions compared to the baseline measurement. The final participant was unable to respond to the feedback intervention with a decrease in mean peak tibial acceleration after a month, but they appeared to be dependent on the feedback and did find reductions in mean peak tibial acceleration within sessions. The results of this final participant suggest that even though the feedback was faded to facilitate improved learning to not become dependent on the feedback (Winstein, 1991), the participant became depended on the feedback. It could be that the current feedback schedule was insufficient for this participant and future research should focus on how this feedback schedule could be individualised. However, for nine out of the eleven participants, the current feedback schedule was sufficient and they were able to reduce mean peak tibial acceleration. This finding demonstrates gait retraining is effective at reducing mean peak tibial acceleration and supports the work of Bowser et al. (2018), Clansey et al. (2014) and Crowell and Davis (2011).

In the current study, a decrease of 26 per cent in mean peak tibial acceleration was reported between the baseline measurements and the one-month follow-up. Crowell and Davis (2011) and Bowser et al. (2018) reported larger decreases of 44 and 41 per cent, respectively. Four reasons are proposed to account for this difference in percentage, which includes the number of session participants received, a difference in treadmill speed, a difference in baseline value of mean peak tibial acceleration, and the allowance of running between sessions. In the current study, participants received five or six feedback sessions compared to the eight feedback sessions of Crowell and Davis (2011) and Bowser et al. (2018). It has been suggested there are beneficial outcomes related to an increased duration of feedback interventions (Adamovich et al., 2009; Agresta & Brown, 2015). The current study showed that on average participants needed three sessions to automatize a reduction in tibial acceleration, however, participants were able to reduce tibial acceleration further after the session in which they automatized reducing tibial acceleration, suggesting more sessions might be beneficial.

In the current study, participants ran at 95 per cent of their five-kilometre time trial speed. By comparison, Crowell and Davis (2011) and Bowser et al. (2018) asked participants to run at a self-selected speed. As discussed in section 5.3, running at a self-selected speed made participants run at lower running speeds. At slower speeds, the intra-participant variability of joint angles increases (Valizadeh, Khaleghi, & Abbasi, 2018) and, therefore, it is likely that more solutions could be found to reduce tibial acceleration. However, though more solutions could be found at lower running speeds, the approach by Crowell and Davis (2011) and Bowser et al. (2018) is not representative of real-world running patterns, and, therefore, participants might struggle to retain the change they found during higher running speeds. A more representative experimental design provides a better representation of the behavioural setting, which could lead to more beneficial and representative results (Araújo et al., 2007). A strength of the current programme of research is having participants running at speeds based on individual running performances and, therefore, creating a more representative design, even though a smaller decrease in tibial acceleration was reported.

Further, the baseline measurement of mean peak tibial acceleration differed in the studies. In the current study, participants had a baseline measurement of 7.84 g, while in the studies of Crowell and Davis (2011) and Bowser et al. (2018) participants had baseline values of mean peak tibial acceleration of 8.1 g and 10.57 g, respectively. In the current study, efforts were made to select participants with high tibial acceleration. The participants had a mean peak tibial acceleration of at least 11 g when measured in the field (Appendix C). However, the mean peak tibial accelerations in the laboratory during the first baseline measurement of the first session ranged from 4.3 g to 10.3 g for the eleven participants. This discrepancy could be due to measurements in the laboratory not being representative of measurements taken in the field. Further, the treadmill used had a built-in cushioning effect while the run in the field was done on tarmac, potentially increasing participants' tibial acceleration (Sheerin et al., 2019). Finally, the use of different sensors could have affected the results. As described in section 3.2.4 a systematic error of 0.86 g was found between the two sensors (Runscribe and gold standard), with the wireless sensors used in the field reporting an increased tibial acceleration compared to the gold standard sensor, which was used in the lab. The lower baseline value of tibial acceleration in the current study, compared to previous studies could have affected the results. By having lower baseline values of mean peak tibial acceleration in the current study, there might have been a reduced capacity for change and a flooring effect could have occurred. However, by selecting participants based on field-based measurements is was aimed to improve the representative design (Araújo et al., 2007), which is a strength of the study.

Finally, in the current research, participants were allowed to run in between the training sessions. This, in the absence of feedback in the field, may have potentially reinforced their older, habitual pattern. Participants in the studies of Crowell and Davis (2011) and Bowser et al. (2018) were not allowed to run between sessions until they completed their retraining. Despite these differences between the studies, both studies found meaningful differences comparing the one-month retention measurement to the baseline measurement, suggesting multisensory feedback to be found meaningful in reducing the injury risk factor.

6.4.3 Automatization of reducing tibial acceleration

Based on the Stroop test results (Neumann, 1984; Richards et al., 2018; Wickens, 1989), three of the nine participants who found a slow learning response automatized the task within the first session, other participants took two to five sessions and one participant automatized the task after the intervention (between the sixth and the seventh session). As a group, the participants needed an average of three sessions to automatize reductions in tibial acceleration. The results based on the Stroop test measurements suggest that the participants reached the third stage of the three-stage model of motor learning (Fitts & Posner, 1967), in which the task is automatized and requires little or no cognitive demand. The current research with multisensory feedback allowed runners to automatize the task of reducing tibial acceleration whilst running at a relatively challenging pace.

6.4.4 Difference in running strategies participants used in response to a biofeedback intervention

For the group, no significant effect of the intervention was found on any of the kinematic or spatiotemporal variables, which were associated with shock attenuating mechanisms. On the contrary, Clansey et al. (2014) reported a significant increase in ankle plantarflexion at initial contact, a significant change in foot strike pattern from a rearfoot to midfoot strike pattern, and a significant decrease in heel vertical velocity at initial contact for an experimental group as a response to a biofeedback intervention aimed at reducing peak tibial acceleration. Even though no significant differences were found in the current study for the group, a large effect size was found for the decrease in heel velocity at initial contact (Clansey et al. (2014): pre = 0.36 ± 0.27 m/s, post = 0.19 ± 0.14 m/s; current study: pre = 0.37 ± 0.11 m/s, post = 0.27 ± 0.10 m/s) and a moderate effect size was found for the increase in ankle plantarflexion (Clansey et al. (2014): pre = 3.7 ± 5.6°, post = - 3.7 ± 9.8°; current study: pre = 2.4 ± 4.4°, post = -0.6 ± 6.1°), which is in line with the results of Clansey et al. (2014). However, in the current study, a negligible effect was found for foot strike angle (Clansey et al. (2014): pre = 12.78 ± 9.00°, post = 7.16 ± 11.6°; current study: pre = 14.7 ± 8.7°, post = 13.2 ± 11.9°). In the current research, 11 participants completed the study but for adequate power, a minimum of 12 participants was needed, it is therefore possible that the current study was underpowered and therefore no significant results were found.

Focussing on individual responses, three out of the eleven participants changed their foot contact pattern. This was accompanied by decreases in landing distance and knee flexion excursion and increases in plantarflexion at initial contact, knee flexion at initial contact, and hip adduction excursion (Figure 6.5). This confirms the hypothesis that participants would find an increase in knee flexion at initial contact accompanied by a change in foot strike pattern. This further implies that the group results found by Clansey et al. (2014) masked individual results. Clansey et al. (2014) might falsely supported the null-hypotheses of no difference in knee flexion at initial contact due to aggregation masking individual performance strategies across a group of subjects (Bates et al., 2004). In the current study, it was found that three participants changed their foot contact pattern to reduce tibial acceleration, however, other participants found an increase in knee flexion excursion accompanied by a decrease in knee flexion at initial contact. These strategies cancel each other out, statistically, when an average is calculated for a group. The results of this study showed the importance of a single-subject analysis in this area of research by finding different individual gait strategies to reduce tibial acceleration, but not finding a change in kinematic and spatiotemporal parameters as an effect of the intervention for the group.

In this study, as well as a change in foot contact pattern, different shock-absorbing mechanisms were found for reducing tibial acceleration, including increased knee flexion excursion (Milner et al., 2007), increased knee flexion at initial contact (Almeida et al., 2015; Goss & Gross, 2012), hip adduction excursion (Novacheck, 1998), ankle eversion excursion (Almeida et al., 2015; Hreljac et al., 2000), a decrease in heel velocity at initial contact (Gerritsen et al., 1995) or a combination of these parameters. These shock-attenuating mechanisms are based on either prolonging the period of time required to change a runners' downward velocity to zero or by reducing the amount of change in velocity (Goss & Gross, 2012). Prolonging the time required to change a runners' downward velocity could be achieved by increasing the range of motion or joint angle eversion (Bishop et al., 2006). Reducing the amount of change in velocity could be accomplished by reducing the vertical height from which the body's centre of mass falls (Heiderscheit et al., 2011). This will lead to a more gliding style as opposed to bouncing up and down. This could be achieved by a reduction in the range of motion or joint angle eversion, but an increase in joint angle at initial contact. None of these shock-attenuating mechanisms were found for the group.

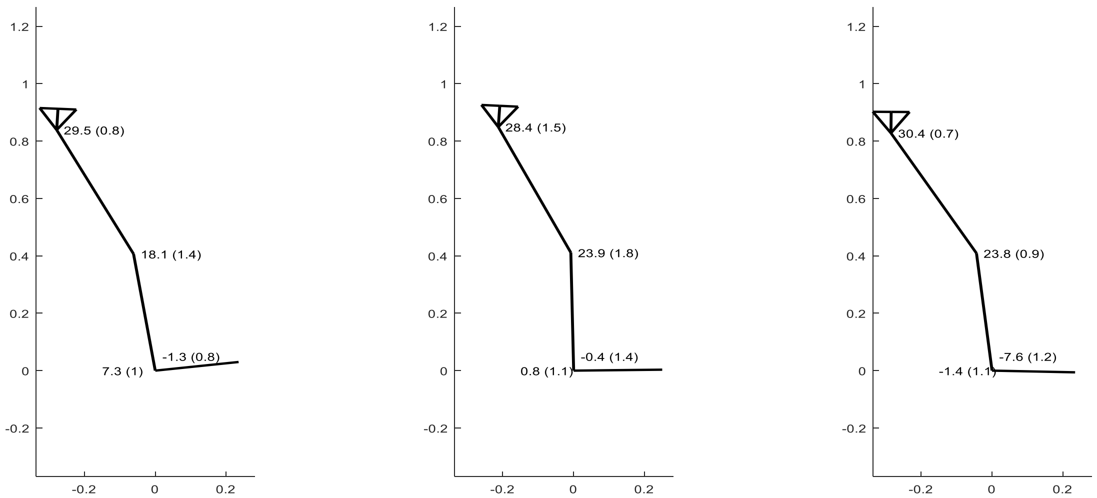

Figure 6.5 Stick figures displaying the foot contact, ankle, knee and hip angle, for participant 5. From left to right: baseline measurement, retention test direct after the feedback intervention, and retention test after a month.

Three of the larger responders (baseline measurement - one-month follow-up, Cohen's D = 2.9-11.8), changed their foot contact pattern from a rear/midfoot contact to a midfoot/forefoot contact (Appendix Q). To reduce tibial acceleration participants seemed to be more reliant on changing their foot contact pattern. However, one other participant (participant 11), with a larger response to the biofeedback intervention (baseline measurement - one-month follow-up, Cohen's D = 5.1), increased their knee flexion at initial contact without changing their foot strike pattern (Appendix Q). This suggests there are multiple beneficial individual solutions to decrease tibial acceleration in running. Two non-responders (participant 4 and 6) were found in the current programme of research. One participant was unable to respond and the other participant appeared to become dependent on the feedback provided (Appendix Q). From the kinematic and spatiotemporal results of these two participants (Appendix Q), it was suggested that whether a change in parameters is beneficial could depend on the combination of parameters and is not depending on individual parameters.

To make a better-informed decision on how a change in gait patterns relates to the ability of participants to change tibial acceleration, larger subgroups are needed. In the current study, only one subgroup could be formed of three participants who changed their foot contact pattern. No further subgroups could be identified due to participants having individually differing solutions to reduce their tibial acceleration. However, based on the current study, participants who seemed to be more reliant on changing their foot contact pattern reported a larger decrease in mean peak tibial acceleration.

6.4.5 The effect of a biofeedback intervention on injury risk

In the current study, real increases, as well as real decreases, were seen for individuals, for peak hip adduction, and real increases for peak ankle eversion comparing the retention measurements to the baseline measurement. These real differences suggest that these risk factors for injuries were modified. Increased peak rearfoot eversion has been related to increased risk of tibial stress fractures in runners (Pohl et al., 2008) and exercise-related lower leg pain (Chuter & Janse de Jonge, 2012). Excessive hip adduction may result in greater compressive stresses on the patellofemoral joint and can contribute to greater stress onto the tibia (Noehren et al., 2012). These results suggest that a change in gait pattern associated with a decrease in mean peak tibial acceleration could affect other parameters that are related to injury risk. However, after a two-week biofeedback intervention, Chan et al. (2018) found the occurrence of injuries to be 62 per cent lower during a 12-month follow-up period in the experimental group compared to a control group. This suggests a two-week biofeedback intervention does reduce injury prevalence. In the study by Chan et al. (2018), the experimental group received feedback on vertical impact peak and were asked to run softer. The control group did not receive any feedback, but were asked to run on a treadmill. A significant decrease was found in the vertical loading rates in the experimental group, whereas the control group found similar or a slight increase in the vertical loading rates. As well as finding fewer injuries in the experimental group after a year, it was noticed that participants in the feedback group incurred relative more Achilles tendinitis and calf strain injuries compared to the control group, which did not report such injuries. The most common injuries in the control group were plantar fasciitis and patellofemoral pain. In the current study, similar effects of the intervention on injury prevalence might be expected to those of Chan et al. (2018), based on both studies trying to let participants run softer. However, in the current programme of research feedback was given on tibial acceleration and in the study by Chan et al. (2018) feedback was given on vertical impact peak, which are not necessarily related (Matijevich et al., 2019). Future research should, therefore, investigate the occurrence of injuries after a feedback intervention based on reducing tibial acceleration.

6.4.6 Motor learning theories

The current programme of research was set in a representational motor learning framework. The two main streams in motor learning are representational theories and anti-representational theories. Representational theories, including Adams' closed-loop model (Adams, 1971) and Schmidt's schema theory (Schmidt, 1975), aim to explain perception and action by internal psychological processes and postulate mental representations (programs or schemes) connecting person and the environment. Anti-representational approaches, including the ecological dynamics approach (Araújo et al., 2007), the dynamical systems approach (Kelso, 2012) and the constraint led approach (Newell, 1985, 1986), eliminate these mental representations and focus on understanding the interaction the person has with the environment. Even though the current programme of research was set in a representational learning framework, the results might fit better within an anti-representational learning framework.

In the current study, most participants who found an automatized learning response, based on the Stroop test results, further explored the task in the subsequent sessions. Participants found further reductions in mean peak tibial acceleration in sessions after the reduction of mean peak tibial acceleration was automatized. Finding further reductions suggest that the task was not automatized and that not one, but several solutions could exist to reduce tibial acceleration. While the use of a dual-task fits within the representational learning theories, suggesting there is one motor programme for the task (Schmidt, 1975), the results of the current programme of research suggest that several solutions could exist. This theory was supported by participants finding different running patterns comparing the retention measurement taken directly after the intervention to the one-month follow-up measurement, while finding no difference in mean peak tibial acceleration. It appears that participants learned the concept of reducing tibial acceleration and were able to sense the magnitude of tibial acceleration, but did not find one specific solution.

Based on an anti-representational approach, it could be expected participants would display different independent neuromusculoskeletal solutions/strategies to perform the same task (Bates, 1996). Through an ecological dynamics perspective, learning emerges through a participant's interaction with constraints (Figure 6.6). These constraints include task, organism and environmental (Newell, 1986). The differences in strategies between participants are caused by these constraints. A strategy is defined as a unique neuromusculoskeletal solution for the performance of a motor task. The experience and perception of a participant will influence their strategy selection (Bates, 1996). It is, therefore, not only possible for responders to find different unique solutions, but it could also explain the results of having non-responders. It could be that it was impossible for non-responders to reduce their tibial acceleration given the organismic and task constraints (i.e. their anatomical constraints and fast running).

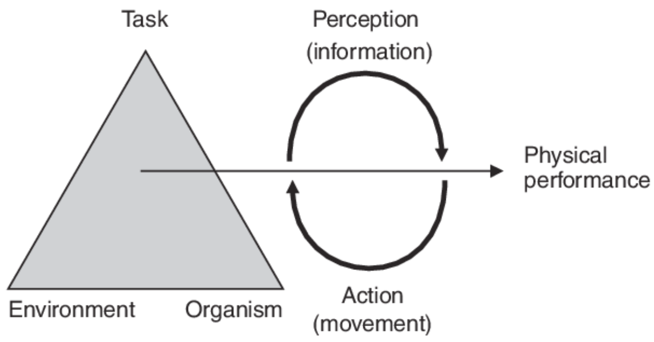

Figure 6.6 Newell's model of interacting constraints, learning emerges through a participant's interaction with constraints. Reprinted from Davids, Glazier, Araújo, & Bartlett (2003).

A study done over a similar period as the current study found a comparable result to the present study, finding participants were able to further reduce mean peak tibial acceleration after the task was automatized (Cheung et al., 2018). Cheung et al. (2018) aimed to evaluate the performance of landing kinetics control after a gait retraining in a distracted condition. Sixteen participants received a two-week biofeedback intervention. Visual feedback was given on peak positive acceleration. Peak positive acceleration was measured at the heel. The target was set at 80 per cent of the baseline measurement. During the pre- and post- (within one week of the intervention) intervention assessment, participants received the instruction to run softer during distracted running. The distraction included a cognitive and verbal counting task. Two measurements were taken during the assessment, one included visual feedback, and the other did not. Feedback was given by either a green light signal if the participant was under the target or a red light signal if the participant exceeded the target. Training consisted of eight sessions of biofeedback, in which the running time increased from 15 minutes to 30 minutes and the feedback was faded. Participants were able to reduce peak positive acceleration after the feedback intervention when being distracted by a dual-task. Cheung et al. (2018) further reported that when participants received feedback after the intervention, they were able to reduce peak positive acceleration even more compared to the measurement, in which they did not receive the feedback. This suggests participants did not automatize reducing peak positive acceleration, since they were able to further decrease peak positive acceleration when feedback was given (Cheung et al., 2018). A task such as gait does require a certain level of attention capacity and can be affected by a concurrent cognitively demanding task (Lindenberger, Marsiske, & Baltes, 2000). Therefore, by giving participants additional feedback, after they automatized the reduction of tibial acceleration, participants would prioritise their focus of attention to the running pattern, instead of the additional task, as was found in the study done by Cheung et al. (2018). In the current programme of research, no measurements were done in which participants received both biofeedback and a dual-task. However, it was found that in sessions after participants automatized reducing tibial acceleration, based on the dual-task results, participants were able to reduce tibial acceleration further. The results of both the study performed by Cheung et al. (2018) and the current study suggest that there is not one motor programme for the task (Schmidt, 1975), but several solutions could exist based on task, organism, and environmental constraints (Newell, 1986).

6.4.7 Limitations

There were various limitations which could have influenced the results of this study. Limitations included the lack of a control group, which would have allowed for a comparison to a control group and may have allowed for a greater understanding of the effect of the intervention. The lack of a control group makes it particularly difficult to assess how fatigue affected participants' running patterns. In the intervention study, it was noticed that some participants increased in mean peak tibial acceleration over a session. For example, participant 11 found a real increase in mean peak tibial acceleration comparing the retention test and the Stroop test to the baseline measurement of sessions 5 and 6 (Figure 6.7). The increase in tibial acceleration over the sessions might have been an effect of fatigue (Clansey et al., 2012; Derrick et al., 2002; Sheerin et al., 2019). Further, participant 5 and 7 reported they did a race before the sixth biofeedback session. Participant 5 found a decrease in mean peak tibial acceleration comparing the baseline measurement of all sessions to the baseline measurement of the first session, except for the sixth session (Appendix Q). Participant 7 found an increase in mean peak tibial acceleration comparing the retention measurement to the baseline measurement in session 6, but did not find this increase for any of the other sessions (Appendix Q). These results might have been affected by participants being fatigued after doing a race or by becoming fatigued within a session, due to the increase of running time.

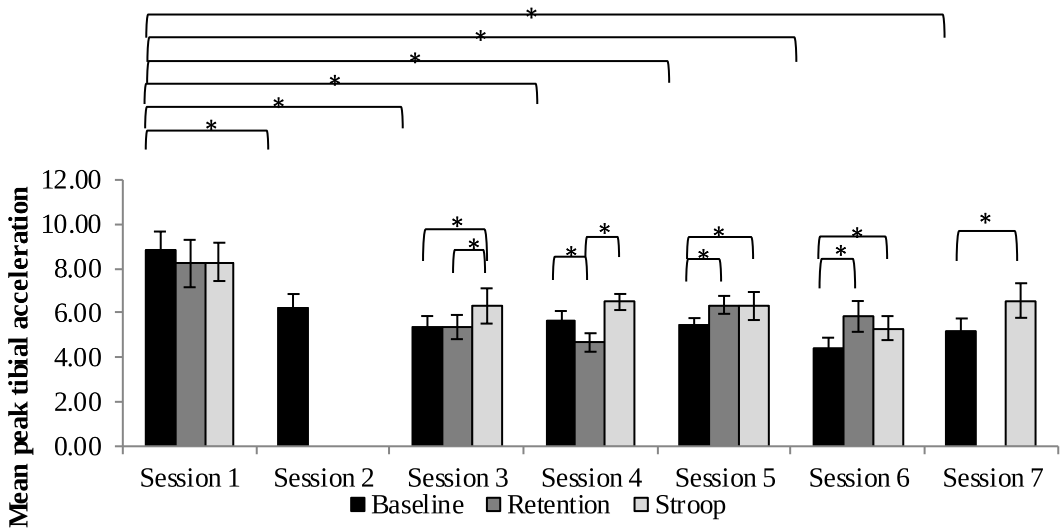

Figure 6.7 Mean peak tibial acceleration for each measurement for each session. * = real difference between measurements. Compared measurements within a session and baseline measurements of each session to the first session

Previous research of Clansey et al. (2014) found no effect of six sessions of running on a treadmill in a control group on kinematic and spatiotemporal parameters. Therefore, in the current study, no effect of six sessions of running in a control group on kinematic and spatiotemporal parameters would be expected for the one-month follow-up measurement. However, in the study by Clansey et al. (2014) the retention test was taken 1-2 days after the final measurement, while in the current study the retention measurement was taken directly after the final feedback measurement. The measurements taken during the sixth session as retention measurements in the current study should, therefore, be interpreted with care. The use of a control group would have allowed for a better understanding of the effect of fatigue. Due to a lack of time and resources, it was infeasible to include a control group in the current study. When possible, future research should include a control group. The current study did, however, define a minimal detectable difference to define when a difference in mean peak tibial acceleration could be considered "real".

The current study was laboratory-based and both the training and the measurements were conducted on a treadmill. However, biomechanics on a treadmill are comparable but not equivalent to running overground (Riley et al., 2008). Therefore, it remains uncertain how the results of the current study translate to running in the field. In the current research, it was aimed to measure tibial acceleration in the field. Before the first biofeedback session and after the one-month follow-up, participants completed a five-kilometre time-trial. However, due to clipping of the acceleration data measured in these time-trials (see section 3.2.3), the measurements were inaccurate, and these data were not presented. Future research should take into account that measurements in the field might not be comparable to measurements in the laboratory and should use accurate accelerometers.

6.5 Chapter summary

In this chapter, the learning response and the one-month follow-up effect to a feedback intervention were explored. In addition, this chapter aimed to establish the difference in strategies participants used to change their gait patterns in response to a biofeedback intervention aimed at reducing tibial acceleration. For the group, a significant decrease of 26 per cent in mean peak tibial acceleration was found a month after the intervention was finished compared to the baseline measurement. Nine out of the eleven participants showed a real decrease of tibial acceleration one month after the intervention compared to the baseline measurement. Most participants were able to respond to the feedback intervention with a reduction in mean peak tibial acceleration within one session, for three of these participants one session was enough to automatize the task, one participant automatized the task after the intervention (between the sixth and the seventh session) and other participants needed two to five sessions to automatize reducing tibial acceleration.

Participants used several strategies to reduce their peak tibial acceleration. These strategies included changing the foot-contact pattern, increasing knee flexion excursion, knee flexion at initial contact, hip adduction excursion, ankle eversion excursion or a combination of these parameters. These individual strategies were masked in the group results. The two non-responders were either still dependent on the feedback or were unable to find the right combination of parameters to reduce tibial acceleration. Three of the larger responders were participants who changed their foot contact pattern from a rear/midfoot contact to a midfoot/forefoot contact. It was found that changing a gait pattern to modify one risk factor (tibial acceleration) may impact other risk factors for other running injuries, positively or negatively. Finally, it appears that participants were able to reduce tibial acceleration after they automatized a reduction in tibial acceleration. Based on the results it appears that there was not one motor programme for the task, but several solutions could exist, between and within participants. It appears that participants learned the concept of reducing tibial acceleration and were able to sense the magnitude of tibial acceleration, but did not find one specific solution.

Chapter 7: Overall discussion

7.1 Introduction

In this final chapter, the results of this programme of research will be discussed. First, an overview of the findings will be given, by summarizing the findings for each objective. This will be followed by the limitations of the findings, implications, and future directions. Finally, a conclusion is presented.

7.2 Summary of findings

The aim of this programme of research was to investigate the individual responses of participants to a biofeedback intervention to reduce tibial acceleration. To address this aim, five different objectives were formed. In this section, a summary of the findings for each objective is given.

Objective 1: Provide a critical review of the literature in the area of biofeedback and gait retraining to establish current knowledge and identify areas that require further research.

First, a broader view of the field was given, since it was believed other research on biofeedback and gait could inform the current study. Several gait limitations and treatment options were discussed. Biofeedback is one of the less invasive treatment options and has been beneficial in different participant groups, including runners. A mapping review was performed to identify gaps in the literature and inform more specific future reviews and/or primary research studies. It was concluded that there is a growing body of research on the use of biofeedback in gait retraining, but more high quality, well-designed studies were needed. These studies should explore the fading of feedback, an appropriate number of sessions, as well as assessing long-term benefits of any intervention. It further gave an insight into which feedback parameters, modes of feedback and outcome parameters have been used in previous literature. These outcomes informed the current programme of research. The literature review informed the importance of giving feedback on knowledge of results opposed to knowledge of performance and the parameter of interest as opposed to an intermediate parameter. It further informed the current programme of research by suggesting multisensory feedback over single modes of feedback, since it gave significantly better results over single modes of feedback.

A further focus was on the use of biofeedback in reducing tibial acceleration. Increased peak tibial acceleration has been related to tibial stress fractures and, therefore, reducing tibial acceleration could help to prevent the injury. Several studies have found beneficial effects of feedback on tibial acceleration, but none of these studies focused on the time participants took to modify tibial acceleration in response to real-time feedback within the feedback intervention. The current research, therefore, aimed to define the number of sessions that was needed to automatize reducing tibial acceleration.

One previous study focused on the strategy participants used to reduce tibial acceleration with feedback and found that runners went from a forefoot contact to a midfoot contact, accompanied by a more plantarflexed ankle angle, but no differences were found in the knee or hip joint. Based on a change in strike pattern, from a rearfoot strike towards a forefoot strike an increase in knee flexion at initial contact was expected. However, with a different study finding responders as well as non-responders to the biofeedback on peak tibial acceleration, it might be that the group results were affected by the non-responders and an individual analysis of the data was suggested. As well as an increase in plantarflexion and knee flexion at initial contact, changing from a rearfoot strike to a forefoot has been associated with decreased vertical loading rates, greater angular work at the ankle and decreased angular work at the knee. These changes in angular work from the knee to the ankle might suggest more injuries around the ankle and less around the knee could be expected. Therefore, the kinematics were discussed in relation to overuse injuries. The cause of overuse injuries is likely to be multifactorial and diverse. Excessive eversion or mistiming of the eversion, excessive peak hip adduction, and hip internal rotation might be related to different overuse injuries. Finally, other shock-attenuating mechanisms were described, including an increase in knee excursion, ankle eversion excursion, or hip adduction excursion and a decreased landing distance.

Objective 2: Consider different methodological approaches in measuring tibial acceleration and gait patterns and develop a feedback system for laboratory-based use in real-time.

Tibial acceleration was used as a proxy-measurement of tibial shock. Tibial acceleration was measured by two different sensors, the PCB Piezotronics (gold standard) and the Runscribe (wireless sensor). Both sensors were placed on the anteromedial aspect of the right tibia, five centimetres above the medial malleolus and wrapped in cohesive bandage to maximise the coupling between the sensor and the bone and to minimise soft tissue movement. A motion capture system was used to measure gait patterns. Joint coordinate systems were defined and a separate trial was reported each session to define the hip joint centre. A multisensory feedback system was developed for participants to reduce tibial acceleration. The development of this feedback system and the intervention study was based on several exploratory studies. During these exploratory studies, participants reported being demotivated by not being able to reach the target. The target acceleration was, therefore, set at the tenth percentile of the baseline measurement and the target moved according to the performance of the participant. Participants saw the feedback together with a target on the screen. Further, participants heard a sound and felt a vibration scaled to the error. The treadmill speed was set to 95 per cent of participants' five-kilometre time-trial to create a more representative design compared to either having a fixed treadmill speed for all participants or a comfortable running speed for each participant. Finally, the importance of a single-subject analysis was highlighted, having both responders and non-responders to a biofeedback intervention aimed at reducing peak tibial acceleration.

Objective 3: Establish the reliability of peak tibial acceleration and selected kinematic and spatiotemporal parameters in describing movement patterns.

Most acceleration, kinematic, and spatiotemporal parameters showed excellent reliability. Consequently, these parameters could be used with confidence in other studies outlined in this programme of research. Exceptions were hip flexion at initial contact, knee flexion at initial contact, peak hip adduction and peak eversion excursion, for these parameters caution should be exercised. The parameters which did not show excellent reliability had a higher minimal detectable difference, suggesting that it will be harder to find a difference in these parameters for individual comparisons. The minimal detectable difference was calculated to determine the minimum amount of change, which was sufficiently greater than the measurement error and day-to-day variability for the variables of interest and could be considered as "real". This allowed for determining a magnitude of change above which the measured differences were expected to be due to genuine changes in gait rather than measurement error and day-to-day variability.

Objective 4: Investigate the learning response to a biofeedback intervention aimed to reduce tibial shock in a group of runners, with a focus on fast and slow learning responses and task automatization.

A fast learning response was found for most participants participating in the different studies in this programme of research, suggesting participants were able to reduce tibial acceleration within one session. However, though most participants found a fast learning response within the first session, it did not mean the learning response was automatized. For three participants one session was enough to find and automatize the reduction of peak tibial acceleration, other participants needed more sessions, varying from two to six sessions. However, even though participants automatized the learning response based on the Stroop-test results, participants were still able to reduce tibial acceleration in additional sessions. As a group, the participants found a significant decrease of 26 per cent in mean peak tibial acceleration comparing the retention measurement after a month to the baseline measurement. Nine out of the eleven participants showed a real effect of the two-week feedback intervention on mean peak tibial acceleration. Taken these results together, multisensory feedback was found to be meaningful in reducing the injury risk factor for nine out of the eleven participants.

Objective 5: Establish the kinematic strategies participants used in response to a biofeedback intervention aimed at reducing tibial acceleration.

Participants used several shock-absorbing mechanisms to reduce peak tibial acceleration. These different gait strategies included a change from a rear/midfoot contact to a midfoot/forefoot contact, an increase in knee flexion excursion, knee flexion at initial contact, hip adduction excursion, ankle eversion excursion, or a combination of these parameters. In the current research, changing the foot contact pattern from a rear/midfoot contact to a midfoot/forefoot contact appeared to be the most beneficial way to reduce tibial acceleration. Participants who were unable to respond to the feedback did find changes in certain gait parameters, but not in others, suggesting the right combination of parameters is important, and therefore changing one parameter might not be sufficient. Finally, participants did not only find different strategies between each other, but they also found different strategies comparing both retention measurements, suggesting the participant did not learn a specific solution to the task, but a concept for reducing tibial acceleration and were able to sense the magnitude of tibial acceleration.

7.3 Limitations

There were various limitations which could have influenced the results of this programme of research. The limitations of each study in this programme of research have been discussed in detail in the individual chapters. Therefore, the limitations will only be briefly discussed in the current section.

In the intervention study in the current programme of research, the retention measurement was taken directly after the biofeedback trial without a rest period. Previous research had a rest period of 1-2 days between the intervention and the retention measurement taken directly after the intervention measurement (Clansey et al., 2014). The retention measurement taken directly after the feedback intervention in the current programme of research might be affected by fatigue (Clansey et al., 2012; Derrick et al., 2002; Sheerin et al., 2019). However, due to the lack of a control group, it is difficult to assess how fatigue affected participants' running patterns. Previous research of Clansey et al. (2014) found no effect of six sessions of running on a treadmill in a control group on kinematic and spatiotemporal parameters. Therefore, in the current study, no effect of six sessions of running in a control group on kinematic and spatiotemporal parameters would be expected for the one-month follow-up measurement. However, the measurements taken during the sixth session as retention measurements in the current study should be interpreted with care. Due to a lack of time and resources, it was infeasible to include a control group. When possible, future research should include a control group.

In the intervention study, efforts were made to select participants with high tibial acceleration. However, the baseline value of tibial acceleration in the first session on a treadmill was lower compared to previous studies (Bowser et al., 2018; Clansey et al., 2014; Crowell & Davis, 2011). The lower baseline value of tibial acceleration could have affected the results. By having lower baseline values of mean peak tibial acceleration, there might have been a reduced capacity for change. Participants were selected based on a high tibial acceleration measured during a five-kilometre trial in the field. It could be that the acceleration in the field was not representative of measurements done in the laboratory. In a study of (Zhang, Chan, Au, An, & Cheung, 2019) participants were able to reduce tibial acceleration in laboratory settings by 28.5 per cent. These reductions transferred to up- and downhill running in the laboratory and outdoor level running. The results, however, did not translate to up and downhill running outside, suggesting running patterns do not fully translate to field-based settings. Further, mean peak tibial acceleration, controlled for speed, did not change across a marathon measured in a field-based setting (Ruder et al., 2019), while tibial acceleration did increase from the beginning to the end during treadmill runs performed in a laboratory (Clansey et al., 2012; Derrick et al., 2002; Sheerin et al., 2019). This is a potential limitation of the current study and future research should focus on the difference between measurements taken in the field and in the laboratory.

Finally, in the current study, it was aimed to relate the measurement done in the laboratory to field-based situations. Before the first biofeedback session and after the one-month follow-up, participants completed a five-kilometre time-trial. However, the measurements were inaccurate, and these data were not presented in this thesis. Biomechanics on a treadmill are comparable but not equivalent to running overground (Riley et al., 2008), therefore it is important to measure tibial acceleration in the field and see whether the results in the laboratory transfer to the field. Future research should take into account that measurement in the field might not be comparable to measurements in the laboratory and should use accurate accelerometers.

7.4 Implications of findings

The findings of the programme of research have significant implications in furthering knowledge of this research area. This programme of research showed the importance of a single-subject analysis in this area of research by finding different individual gait strategies to reduce tibial acceleration, but not finding a change in kinematic and spatiotemporal parameters as an effect of the intervention for the group. These results implicate that group analyses might mask individual results and future research on biofeedback in gait-retraining should include single-subject analysis.

Differences in shock-attenuating strategies were not only found between participants, but also within participants, comparing the retention measurement taken directly after the feedback intervention to the retention measurement taken after a month. This in combination with participants being able to reduce tibial acceleration after they automatized the task (automatization based on Stroop test results), suggested there was not one motor programme of the task (Schmidt, 1975), but several solutions could exist based on task, organism and environmental constraints (Newell, 1986). It appears participants learned the concept of reducing tibial acceleration and were able to sense the magnitude of tibial acceleration. These results implicate that future research and gait retraining could investigate individual learning responses and focus on the different strategies participants use between sessions and within sessions.

The practical implications include for runners and coaches to tail the training to individual needs. Further, the results showed that participants not only found different running patterns between participants, but also within a participant, suggesting that participants did not found one solution but understood the concept of reducing tibial acceleration and were able to sense the magnitude of tibial acceleration. For training purposes this entails that participants should not focus on learning one running strategy, but they should get an insight to the results of several strategies.

7.5 Future directions

The results of the present thesis provide a basis for future research in the area of biomechanics and injury prevention. A mapping review was performed to identify gaps in the literature on biofeedback and gait and inform more specific future reviews and/or primary research studies. Some of these points for future research were addressed in the current research, other points remain unaddressed. These unaddressed points include focusing on direct comparisons between groups of parameters and exploring feedback modes for specific gait retraining interventions. Further, researchers should seek to develop and assess the efficacy of field-based gait retraining systems using experimental designs more representative of real-life situations.

Ideally, to improve the representative design of experiments (Araújo et al., 2007) feedback should be presented in the field instead of laboratories. With the development of new feedback systems with the use of inertial measurement units (Baumgartner, Gusmer, Hollman, & Finnoff, 2019; Corzani, Ferrari, Ginis, Nieuwboer, & Chiari, 2019; Karatsidis et al., 2018; Schließmann et al., 2018) and wireless pressure sensors (He, Lippmann, Shakoor, Ferrigno, & Wimmer, 2019; Yasuda, Hayashi, Tawara, & Iwata, 2019), delivery of feedback in the field becomes more applicable. However, previous research studies have found conflicting results comparing laboratory results to field-based results (Clansey, Hanlon, Wallace, & Lake, 2012; Derrick, Dereu, & Mclean, 2002; Moore & Willy, 2019; Ruder et al., 2019; Sheerin et al., 2019). Further, it remains uncertain whether the learning is transferable from the laboratory to the field.

Therefore, future research should test the validity and repeatability of inertial measurement units in field-based settings. Based on these results, feedback could then be presented in field-based interventions.

This research found a beneficial effect of a two-week biofeedback intervention on reducing tibial acceleration. The results further implied that changing one's gait pattern to modify one risk factor (increased mean peak tibial acceleration) might impact other risk factors. Future research should investigate the occurrence of injuries after a feedback intervention based on reducing tibial acceleration; long-term follow-up measurement on injuries post-feedback are required.

This research, with a single-subject analysis, could further be expanded to different participant groups, to be able to overcome the negative effects of gait limitations. As described in section 2.2 different patient groups experience different gait limitations. While most studies gave beneficial results of biofeedback on gait-related outcome measures, some studies failed to find biofeedback to be an effective tool in improving gait outcomes (section 2.3.1). A single-subject analysis could give further insight into why individuals are able or unable to respond to the feedback. Group analysis, as performed in most biofeedback studies, might mask individual results as seen in the current research. Future research should, therefore, consider single-subject analyses in future research on gait retraining.

Finally, based on the results found in the current study, future feedback interventions should be tailored more individually. Most participants were able to respond to the feedback within one session but needed several sessions to be able to find a slow learning response. In the current programme of research, the target acceleration set for the participants was tailored to the performance of the participant and the results indicated that most participants were able to reduce tibial acceleration. Further, the number of sessions could be tailored to individual learning responses. Participants who found a decrease in mean peak tibial acceleration within this first session could be given a wireless sensor to receive feedback during their own training sessions to create a more representative design (Araújo et al., 2007). Participants who are unable to reduce tibial acceleration in that first session could receive extra laboratory sessions. Participants could then decide themselves when they want to redraw the feedback so they will become independent of the accelerometer (Winstein, 1991). Further research should define whether this increases the individual learning response.

7.6 Conclusion

The goal of this thesis was to investigate individual responses of participants to a biofeedback intervention to reduce tibial acceleration. Increased peak tibial acceleration has been related to tibial stress fractures and, therefore, reducing tibial acceleration could help preventing the injury. A feedback system and intervention study were developed with the use of several feasibility studies. In the intervention study, a decrease of 26 per cent in mean peak tibial acceleration was reported between the baseline measurements and the one-month follow-up. The current programme of research complements previous research by demonstrating gait retraining with the use of biofeedback is effective at reducing mean peak tibial acceleration, suggesting feedback may have a role in reducing the injury risk factor. Unique to the current programme of research is the use of Stroop test results to gain further insight into how many sessions were needed to automatize the task and performing individual analysis to identify differences between responders and non-responders. Eight out of eleven participants were able to automatize reductions in tibial acceleration within one to five sessions and were able to maintain a reduction in mean peak tibial acceleration up to a month after the intervention. Even though participants automatized reductions in tibial acceleration based on their Stroop test results, they found further reductions in mean peak tibial acceleration.

The results showed the importance of a single-subject analysis in this area of research by finding different individual gait strategies to reduce tibial acceleration, but not finding a change in kinematic and spatiotemporal parameters as an effect of the intervention for the group. Three of the larger responders changed their foot contact pattern from a rear/midfoot contact to a midfoot/forefoot contact. Two participants who were unable to respond to the feedback did find changes in certain gait parameters, but not in others, suggesting the right combination of parameters is important, and therefore changing one parameter might not be sufficient. Individuals further found different shock-absorbing mechanisms, when comparing the measurement taken directly after the intervention to the measurement taken after a month. This, together with finding further reductions in mean peak tibial acceleration after finding a fast learning response, suggests participants did not learn a specific solution to be able to reduce tibial acceleration but learned the concept of reducing tibial acceleration, participants were able to sense the magnitude of tibial acceleration and were able to adopt more than one shock-absorbing mechanism.

Chapter 8: References

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Chapter 9: Appendices

9.1 Appendix A: Mapping review

Title:

The use of biofeedback for gait retraining: A mapping review

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The use of biofeedback for gait retraining: a mapping review

Abstract:

Background: Biofeedback seems to be a promising tool to improve gait outcomes for both healthy individuals and patient groups. However, due to differences in study designs and outcome measurements, it remains uncertain how different forms of feedback affect gait outcomes. Therefore, the aim of this study is to review primary biomechanical literature which has used biofeedback to alter gait-related outcomes in human participants.

Methods: Medline, Cinahl, Cochrane, SPORTDiscus and Pubmed were searched from inception to December 2017 using various keywords and the following MeSHterms: biofeedback, feedback, gait, walking and running. From the included studies, sixteen different study characteristics were extracted.

Findings: In this mapping review 173 studies were included. The most common feedback mode used was visual feedback (42%, n=73) and the majority fed-back kinematic parameters (36%, n=62). The design of the studies were poor: only 8% (n=13) of the studies had both a control group and a retention test; 69% (n=120) of the studies had neither. A retention test after 6 months was performed in 3% (n=5) of the studies, feedback was faded in 9% (n=15) and feedback was given in the field rather than the laboratory in 4% (n=8) of the studies.

Interpretation: Further work on biofeedback and gait should focus on the direct comparison between different modes of feedback or feedback parameters, along with better designed and field based studies.

Keywords:

Gait; movement retraining; biofeedback; real-time feedback

1. Introduction

Patient groups with lower-limb musculoskeletal and neurological conditions experience gait limitations (Baram, 2013; James, 1992; Richards et al., 2016; Tate & Milner, 2010), such as reduced walking speed and distance (Baram, 2013; James, 1992; Richards et al., 2016; Tate & Milner, 2010). These limitations can have a major impact on patients' lives, as their daily living activities and social interactions are often affected (Baram & Miller, 2006). Other examples of gait limitations include insufficient foot clearance for patients with multiple sclerosis (Bregman et al., 2010) and stroke patients (Balaban & Tok, 2014), leading to increased risk of trips and falls, a reduced push-off power for patients with multiple sclerosis (Bregman et al., 2010) and diabetes (Mueller et al., 1994) and increased knee flexion or excessive knee extension during walking for stroke patients (Balaban & Tok, 2014) and individuals with cerebral palsy (Rodda & Graham, 2001). Healthy individuals might also display gait patterns that predispose them to chronic overuse injuries. Tibial stress injuries (Agresta & Brown, 2015) and patellofemoral pain (Cheung & Davis, 2011) are both common running injuries for which altered landing mechanics have been identified as key risk factors (Noehren et al., 2012). Such overuse injuries can cause significant disruption to training, a reduction in physical fitness as well as personal frustration (Clansey et al., 2014).

Treatment options to reduce the risk of overuse injuries in athletes and improve gait limitations in patients, range from the use of orthotic devices to surgical procedures on nerves or muscles (National Institute for Health and Care Excellence, 2013, 2016c, 2016d; Yeung & Yeung, 2001). Gait retraining, a non-invasive technique which focusses on the rehabilitation of gait by either muscle strengthening, treadmill training, neurodevelopmental techniques or intensive mobility exercises (Eng & Fang Tang, 2007), is an additional treatment option. Understanding how gait retraining may be used to benefit different patient groups or reduce the risk of overuse injuries is an important step in developing non-invasive treatment plans or prevention strategies to help improve individual outcomes.

Biofeedback makes use of electronic equipment to provide the user with additional biological information, beyond that which is naturally available to them (James, 1992; Tate & Milner, 2010). Advances in technology have made biofeedback systems more affordable and more accessible to researchers; as a result there has been an increase in the literature in this area over recent years. Research suggests biofeedback to be a promising tool used to complement gait retraining (Stanton et al., 2011; Tate & Milner, 2010) and improve outcomes among several patient groups (Baram, 2013; James, 1992; Richards et al., 2016). For instance, stroke patients decreased the number of knee hyperextensions and increased gait speed when they received feedback on their joint kinematics (Stanton et al., 2011). Biofeedback has also been found to be effective at altering gait patterns in healthy subjects (Agresta and Brown, 2015; Richards et al., 2016) and reducing injury risk factors in runners (Agresta and Brown, 2015). Agresta and Brown (2015) found in their systematic review that runners demonstrated reduced kinetic risk factors associated with tibial stress fracture when receiving feedback on their peak tibial accelerations over the course of a run. Despite this, other studies included in the review of Tate and Milner (2010) have failed to find the use of biofeedback in gait retraining to be an effective tool in improving gait outcomes. These conflicting results might be due to differences in study designs and the populations examined (Stanton et al., 2011; Tate & Milner, 2010).

It is suggested that presenting the feedback in the field results in a more representative experimental design (Brunswik, 1956; Araújo et al., 2007). A more representative experimental design provides a better representation of the behavioural setting, which could lead to more beneficial and representative results (Araújo et al., 2007). With respect to the mode of feedback, researchers have suggested that multisensory feedback is superior to separate modes (visual, auditory, sensory) of feedback, not only due to encoding the most information but also due to the reduction of cognitive load associated with the separate systems due to distribution of information processing (Sigrist et al., 2013). With respect to the feedback parameter, feedback on knowledge of results might be more beneficial then feedback on knowledge of performance (Winstein, 1991). Further, studies have suggested that gradually removing feedback over time -fading the feedback- reduces the chances of participants becoming dependent on the feedback, facilitating improved learning (Agresta and Brown, 2015; Richards et al., 2016). Moreover, long term follow-up retention tests after gait retraining are important to assess learning (Agresta and Brown, 2015; Tate and Milner, 2010). Studies in the literature differ in the choice of feedback parameters and mode of feedback given, as well as the length of any retention period, which makes it difficult to draw firm conclusions about the effectiveness of, and optimal strategies for, gait retraining interventions. Advances in technology have made biofeedback systems more affordable and more accessible to researchers; as a result, there has been a surge in the literature in this area over recent years. Therefore, a mapping review of the biofeedback for gait retraining literature is required to get a broader understanding of the studies, characterise what has been done, and to identify what areas need future research.

The aim of this study was to review primary biomechanical literature which has used biofeedback to alter gait-related outcomes in human participants. Areas of interest included the mode of feedback, which parameters were fed-back, the intervention design and the length of any retention period. We intend that this rigorous approach to evaluating the trends in the area will help to inform future research in these key areas, to help provide clarity for the use of biofeedback for gait retraining applications.

2. Methods

2.1 Research design

This study used a mapping review approach; mapping reviews give an overview of the existing published research and can be used to obtain a better insight into the literature within a particular area (Booth et al., 2016). The results can be used to identify gaps in the literature and inform more specific future reviews and/or primary research studies. A mapping review searches the literature in a systematic way, but does not exclude articles based on quality. In the current mapping review the focus was on the methods used rather than the outcome.

2.2 Data sources and search strategy

The following databases were systematically searched from inception to December 2017: Medline (via EBSCOhost Research Databases), Cinahl (via EBSCOhost Research

Databases), Cochrane, SPORTDiscus (via EBSCOhost Research Databases) and Pubmed. Searches used the following combination of MeSH terms: (biofeedback (psychology) OR feedback (sensory)) AND (gait OR walking OR running). The same terms were searched separately in: Title, Abstract and Subject/Keywords. An exception was the term feedback which was not searched in the different fields as the term is too broad and led to an unmanageable volume of results. Instead, a selection of terms was combined to make the search more specific to the area of interest: augmented feedback, real-time feedback, sensory feedback, proprioceptive feedback, vibrotactile feedback, tactile feedback, visual feedback, virtual feedback, auditory feedback and audio feedback. There were exceptions for the databases: Cinahl and SPORTDiscus, which did not have a separate MeSH term for feedback (sensory), for these databases the other MeSH terms were searched together with the separate search terms. Since there was no separate field for Keywords/Subject in Pubmed, all fields were searched in this database. Furthermore reference lists were checked from all relevant reviews that were found and additional articles were identified.

2.3 Study selection

The primary researcher (LvG) selected articles based on the relevance of the title and abstract using the following inclusion criteria: (1) feedback was given on biological information beyond what was naturally available to the participants; (2) feedback was given on one or more gait related parameters (corresponding to the categories of 'Feedback parameter' in Table 1); (3) at least one of the tasks performed in the research was gait (4) the study aimed to modify one or more gait related parameters as opposed to, for example, testing the validity of a system; (5) feedback was given in real-time; (6) measurements were performed using technology as opposed to verbal feedback; (7)

treatment did not involve a combination of biofeedback and another treatment; (8) the article was written in English and (9) the article gave sufficient information on all the items listed in Table 1. The full texts of all articles that were deemed potentially relevant were then checked by the primary researcher using the same inclusion criteria.

2.4 Data extraction of included articles

The primary researcher extracted the information of interest (Table 1) from all articles that met the inclusion criteria. When an article reported a study that covered more than one category, each category was considered separately. This could occur when more than one participant group was tested, for example healthy participants and participants who experienced a stroke, when more than one feedback mode was tested, for example one group got auditory feedback and one group got visual feedback or when different parameters were fed-back, for example one group got feedback on knee angle while another group got feedback on knee moment. A second researcher (AB) reviewed a random sample of 10% of the articles at the start of the process to check the reliability of data extraction. Any disagreements between the researches were discussed and a consensus was sought with a third researcher (BH). This informed the final data extraction form which was used for all articles.

2.5 Study design categorisation

The final set of articles were assigned to four categories based on their research design: (A) the study had an experimental and a control group of at least ten participants per group and a retention test; (B) the study had an experimental and a control group of at least ten participants per group, but no retention test; (C) the study had no control group or a control group with less than ten persons per group and a retention test and (D) the study had no control group or a control group with less than ten persons per group and no retention test. A control group was defined as a group who received no intervention or an alternative (non-biofeedback) intervention at the same time as the experimental group received biofeedback. Ten participants per group was used as a cut off since this was recommended by Whitehead et al. (2016) for trials with a large effect size (0.8) with 90% power and two-sided 5% significance. A retention test was defined as a test after one day or longer during which participants had to walk or run without biofeedback.

Topics	**Categories**
Authors	
Journal	
Year of publication	
Number of participants	
Participant group	Healthy, runners, stroke/hemiplegia, Parkinson's, incomplete spinal cord injuries, cerebral palsy, multiple sclerosis, amputees, diabetics, knee injuries, other (included: ibromyalgia syndrome; uncompensated unilateral vestibular loss; bilateral peripheral vestibular loss/areflexia; different neurological gait disorders; out patients referred to a geriatric falls and balance clinic; inpatient rehabilitation program; asymptomatic participants; orthopaedic surgery; chronic ankle instability; hip arthroplasty with trochanteric osteotomy; idiopathic bilateral peripheral neuropath and Charcot-marie-tooth-disease; toe walking and Parkinson or stroke; spina bifida; lower extremity disabilities)
Mode of feedback	Visual, auditory, sensory, visual-auditory, visual-sensory, auditory-sensory, multisensory which is a combination of visual, auditory and sensory feedback
Feedback parameter	**Spatiotemporal** (included: stride width and symmetry, step length, stride length and symmetry, stance time, swing time, temporal symmetry in stance), **kinematic** (included: ankle, knee, hip, pelvis and trunk joint angles, foot contact angle, shank angle, foot progression angle, toe-out in stance phase, knee distance, minimum toe clearance, peak tibial acceleration, anterior-posterior and medial-

	lateral position of the subject's trunk, trunk sway and angular velocity), **kinetic** (included: ground reaction force, average loading rate, torque, pressure of the heel, pressure of the foot, centre of pressure, centre of mass, weight bearing, knee medial tibiofemoral contact force, peak vertical force on the cane during gait and human-machine interaction forces), **muscle activation, physiological** (included: heart rate, ventilation, VO2 and lower extremity temperature), **combination**
Feedback system	Force sensors fixed on participants, force plates fixed in place, optical motion capture system, motion capture system and force plates fixed in place, inertial measurement unit, electromyography systems, other (included: video camera, green screen; two sensors who have to be close to each other; electrogoniometer; position transducer; ultrasound; electrode to measure brain waves; biofeedback unit stabilizer, P pressure of muscles; Lokomat system (exoskeleton); Cycle-ergometer; heart rate monitor; thermal feedback system; motion capture and accelerometers; force plates and inertial sensors; EMG, 3D kinematics and instrumented treadmill, infrared, SPLnFFT Noise Meter)
Feedback in the laboratory or in the field	Laboratory, field, combination
Number of sessions	1, 2-5, 6-10, 11-20, >20, continuously wearing the device
Frequency of training	1 session, daily, twice a day, once a week, 2 times a week, 2-3 a week, 3 times a week, 4 times a week, 5 times a week, continuously wearing the device, unknown
Fading of the feedback	Yes, no
Retention test and if so, after what time	None, < 1 week, ≥ 1 week, ≥4 weeks, ≥ 3 months, ≥ 6 months
Test with or without feedback	With, without
Feedback on gait or another task	Feedback on gait, feedback on gait and another task
Outcome	Beneficial, no difference between an experimental and a control group or between a pre- and post-test, negative, no inferential statistics

Table 1. The fields that were extracted and in the second column the categories that were found for each field.

3. Results

3.1 Search results

1316 articles were identified in Medline, 392 in Cinahl, 333 in Cochrane, 303 in SPORTDiscus and 1769 in Pubmed (Fig 1). After removing duplicates a total of 2165 articles were checked for relevance based on the title and abstract and 1674 articles were excluded. The full text of the remaining 491 articles was checked against the inclusion criteria and 143 articles were identified as relevant to the review. Five additional articles from the reference lists of the reviews identified were also included. Details of all articles included in this review (n=148) can be found in the supplementary material. These articles included a total of 173 studies, since some articles reported more than one study.

3.2 Overview of study characteristics

3.2.1 Year of publication

There has been an increase in published studies over recent years (Fig 2), with most studies published in 2016 (n=26) and 2017 (n=20). When considering older studies from 1977 until 1994, participants only received auditory feedback or a combination of auditory and visual feedback. Sensory feedback was first reported in 1994 and multimodal feedback was not reported until 2010. The use of motion capture systems in combination with biofeedback for gait was first reported in 2010.

3.2.2 Participant groups

A total of 2479 participants, across the 173 studies, were included - with a mean of 15.5 (range: 1-240) participants per study. Groups included healthy participants, runners (healthy or injured) and participants with various gait disorders, numbers and percentages are depicted above the groups in the figure (Table 1, Fig 3).

3.2.3 Feedback mode

A range of feedback modes and combinations of modes were used within the included studies (Table 1, Fig 4). The most common mode of feedback used was visual.

3.2.4 Feedback parameter

A range of feedback parameters were used in the included studies (Table 1, Fig 5). Kinematic parameters were most frequently fed-back.

3.2.5 Feedback system

A variety of feedback systems (Table 1) were used to provide biofeedback to participants. Force sensors fixed to the participants feet or shoes were most frequently used (28%, n=49), followed by optical motion capture systems (15%, n=26), inertial measurement units (15%, n=25), motion capture in combination with force platforms (11%, n=19), force platforms alone (9%, n=16) and electromyography systems (9%, n=15). Other approaches were adopted in 13% (n=23) of the included studies.

3.2.6 Laboratory or field based studies

Ninety six percent (n=165) of the included studies were performed in a laboratory, 2% (n=4) in the field and the remaining 2% (n=4) used feedback given in both field and laboratory settings.

3.2.7 Training strategy and retention

More than half of all studies (53%, n=92) reported only one gait retraining session in which the participants received biofeedback. Three percent (n=5) of the studies reported 2-5 sessions, 20% (n=34) 6-10 session, 16% (n=27) 11-20 sessions while only 6% (n=11) gave the participants more than 20 sessions of feedback. In two percent (n=4) of cases participants were constantly wearing the device for the duration of the intervention. .

When studies included several sessions, most studies included 3 training sessions per week (n=24, 14%), 11% (n=19) included two sessions a week and 6% (n=11) of the studies reported up to 5 sessions a week. Three percent (n=5) of the studies included one training session a week, 3% (n=5) included four sessions a week, 2% (n=3) of the studies had daily training sessions, 1% of the studies included 2-3 training sessions a week (n=2) and 1% of the studies included training sessions twice a day (n=2). In 2% (n=4) of the studies participants wore the devices continuously in the field. Four percent (n=6) of the studies did not report the frequency of the feedback sessions.

Only 9% (n=15) of the studies faded the feedback over the course of the gait retraining intervention. In nine of these studies the task duration increased over time and the duration of the feedback decreased. The other six articles did not increase task duration, but did progressively decrease the feedback. Decreasing the feedback was done by giving alternating blocks of feedback and blocks of no feedback. In 10% (n=18) of the studies feedback was given on gait in combination with another task, such as a postural balance task.

Forty four percent (n=76) of the studies had no retention test, so the re-test was completed while participants were still receiving biofeedback. Thirty-two percent (n=55) had a retention test within a week of the intervention finishing, 8% (n=15) completed a retention test after more than a week and within 4 weeks, 10% (n=17) after 4 weeks and within 3 months, 3% (n=5) after 3 months and within 6 months, while only 3% (n=5) completed a retention test 6 months or more after the intervention finished.

3.3 Outcomes

Sixty eight percent (n=118) of the studies reported beneficial outcomes related to one or more gait parameters, 20% (n=34) reported no difference between the experimental and control groups and/or pre- and post- test outcomes and 12% (n=21) did not report inferential statistics. Negative effects of biofeedback on gait parameters were not reported in any studies.

3.4 Study design categories

Based on the study design categories outlined in the methods, only 8% (n=13) of all studies were in category A, 8% (n=14) in category B, 15% (n=26) in category C with the remaining studies (69%, n=120) categorized as group D. Since all studies in category A had an experimental and a control group of at least ten participants and a retention test, these studies were considered in further detail.

Research in category A used a range of participant groups (Table 2) with the majority of studies using visual feedback (n=5, S25, S328, S50, S105, S122) followed by a combination of visual and auditory (n=4, S24, S33, S96-1, S96-2), auditory (n=3, S61, S77, S101) feedback and one article using multisensory feedback (S94).

Most of these studies (S24, S33, S38, S94, S96-1, S96-2, S101, S122) provided feedback on kinematic parameters. Seven of the studies in this category (S24, S61, S77, S96-1, S96-2, S101, S122) reported 18 feedback sessions or more while 2 studies (S38, S105) used only a single feedback session. Two studies (S24, S25) faded the feedback given and only one study (S61) gave feedback in the field. Only 4 (S25, S33, S96-2, S101) of the 13 (31%) studies reported beneficial effects of gait retraining on their selected outcome variable. In 6 (S50, S38, S61, S94, S96-1, S122) of the studies a significant difference was reported between the baseline and retention tests, but no significant difference was reported between the experimental and the control groups. The remaining studies (S24, S105, S77) reported no difference between baseline and retention tests or between groups.

Author	Year	Participant group	Number of parti-cipants	Mode of feedback	Feedback parameter	Feedback system	Training time	Fa-ding	Retention	Study outcomes	Feedback on gait	Lab or field
Carpinella S24	2017	Parkinsons disease	Exp: 17 Con: 20	Visual and auditory	Combination of kinematic variables	Six inertial sensors	20 sessions, 45 minutes each, 3 times a week	Yes	1 month post training	No difference: No pre-post differences for walking speed. Significant differences were found for balance measurements.	Yes	Lab
Chan S25	2017	Novice runners	Exp: 166 con: 154	Visual	Vertical ground-reaction force signal	Instrumented treadmill	8 sessions, 4 times a week for 2 weeks	Yes	12 months post training	Beneficial: Both significant differences between baseline and retention test and between the experimental and control group.	Yes	Lab
Clansey S33	2014	Recreational rearfoot striking male runners	Exp: 12 Con: 10	Visual and auditory	Peak tibial axial accelerations	A tri-axial accelerometer	6 sessions, 2 times a week for 3 weeks	No	1 month post training	Beneficial: Both significant differences between baseline and retention test and between the experimental and control group.	Yes	Lab
Creaby S38	2016	Healthy male runners	Exp: 11 Con: 11	Visual	Peak tibial axial accelerations	A tri-axial accelerometer	1 session, 10 min	No	1 week post training	No difference: No between-group differences	Yes	Lab
Drużbicki S50	2016	Stroke	Exp: 25 Con: 25	Visual	Step length	Instrumented treadmill	10 sessions, 5 times a week for 2 weeks	No	6 months post training	No difference: No between-group differences	Yes	Lab
Ginis S61	2016	Patients with Parkinson's disease	Exp: 22 Con: 18	Auditory	Cadence, stride length, symmetry and gait speed	CuPiD smartphone application, inertial measurement units	18 sessions, 3 times a week for six weeks	No	4 weeks post training	No difference: No between-group differences	Yes	Field

Table 2. Key data extracted from the studies in category A. References can be found in the supplement. Exp = experimental, Con = control.

Author	Year	Participant group	Number of parti-cipants	Mode of feedback	Feedback parameter	Feedback system	Training time	Fa-ding	Retention	Study outcomes	Feedback on gait	Lab or field
Hurkmans S77	2012	Total hip arthroplasty with trochanteric osteotomy	Exp: 18 Con: 20	Auditory	Peak vertical force for each footstep	Insole pressure system, Pedalert system	Once per day during the entire hospital stay (6-8 weeks)	No	3 weeks post training	No difference: No between-group differences and no difference between the different retention tests	Yes	Lab
Lim S94	2016	Healthy older adults	Exp: 18 Con: 18	Multisensory	Trunk sway	SwayStarTM d gyroscopes	6 sessions, 3 times a week for 2 weeks	No	1 month post training	No difference: No between-group differences	Yes and balance tasks	Lab
Mandel S96	1990 (1)	Hemiparetic stroke patients	Exp: 13 Con: 11	Visual and auditory	Muscle activation of pretibial and calf muscle	Electromyography system	24 sessions, frequency unknown	No	3 months post training	No difference: No between-group differences	Yes and sitting, standing walking	Lab
Mandel S96	1990 (2)	Hemiparetic stroke patients	Exp: 13 Con: 11	Visual and auditory	Ankle position	Electrogoniometer	24 sessions, frequency unknown	No	3 months post training	Beneficial: Both significant differences between baseline and retention test and between the experimental and control group.	Yes and sitting, long sitting, standing and walking	Lab
Morris S101	1992	Patients with genu recurvatum following stroke	Exp: 13 Con: 13	Auditory	Peak amplitude of knee hyperextension	Electrogoniometer	20 session, 5 times a week for 4 weeks	No	4 weeks post training	Beneficial: Both significant differences between baseline and retention test and between the experimental and control group.	Yes	Lab
Oude Lansink S105	2017	Healthy participants	Exp: 13 Con: 11	Visual	Step width	Motion capture system	1 session, 1 min feedback	No	7-10 days post training	No difference, no effect of the treatment	Yes	Lab
Segal S122	2015	Patients with knee osteoarthritis	Exp: 19 Con: 19	Visual	Different kinematic trunk pelvic	Motion capture system	24 sessions, twice a week for 3 months	No	12 months post training	No difference: No between-group differences	Yes	Lab

Table 2 continued. Key data extracted from the studies in category A. References can be found in the supplement. Exp = experimental, Con =

4. Discussion

The aim of this study was to review primary biomechanical literature which has used biofeedback to alter gait-related outcomes in human participants. A total of 173 relevant studies were identified. Visual feedback was the most commonly used mode and feedback on kinematic parameters was most commonly used. The vast majority of studies were performed in a laboratory and reported only one feedback session, did not fade the feedback given and had no retention test. Sixty-nine percent of all studies suggested some beneficial effects of biofeedback on gait outcomes with no significant negative effects reported, however this percentage of beneficial results was lower in studies that both included a control group and a retention test (Category A articles).

Visual feedback was given most frequently in the studies included in this mapping review. In a systematic review on injured and healthy runners, different modes of feedback were found to be effective in reducing variables related to ground reaction forces, but no mode of feedback was identified as being superior (Agresta & Brown, 2015). This is important since some modes of feedback such as auditory and sensory may be more practicable for use in field-based biofeedback systems. It has previously been suggested that multisensory is superior to separate modes of feedback, not only due to presenting the most information but also due to the reduction of cognitive load associated with the separate systems due to distribution of information processing (Sigrist et al., 2013). Some of the included studies in this mapping review directly compared different feedback modes. Hirokawa and Matsumura (1989) and Shin and Chung (2017) found the best gait-related outcomes when using combined visual and auditory feedback, compared to each mode separately. However, it should be noted that different modes of feedback were used for different parameters: visual feedback for step length and auditory feedback for step duration. A study comparing visual, sensory and combined visual and sensory feedback on stride length in participants with incomplete spinal cord injury, found combined visual and sensory feedback to give significantly better results than the two modes presented separately (Yen et al., 2014). In this mapping review, multisensory feedback was only reported in 4% (n=6) of the studies. Future research on the effectiveness of different modes of feedback is therefore needed to help establish optimum feedback strategies for gait retraining applications within different populations. This suggestion supports previous research which has identified the need for research studies which directly compare different modes of feedback to further our knowledge in this area (Agresta & Brown, 2015, Sienko et al., 2017).

Kinematic variables were most frequently fed-back in the studies included in this mapping review. A previous systematic review on gait retraining found biofeedback of kinematic, kinetic and spatiotemporal parameters to show more promise than feedback on muscle activity, resulting in moderate to large short-term treatment effects in different patient groups (Tate & Milner, 2010). Feedback on muscle activity might be less effective since this mode of feedback focusses towards knowledge of performance. By moving away from knowledge of results and moving more towards knowledge of performance the learning response might be reduced (Winstein, 1991). Some studies included in this review support the suggestion that feedback on muscle activation results in smaller effects than feedback on other parameters. Franz et al. (2014) found that feedback on ground reaction forces (kinetic parameters) increased propulsive ground reaction forces and gastrocnemius muscle activity during push-off, while feedback on muscle activity only had no effect on the same gait related outcomes. In another study, feedback on muscle activity of the pretibial and calf muscles had no effect on walking speed, while feedback on ankle angle during heel-off and swing through (kinematic parameter) had a beneficial effect on the same gait related outcome (Mandel et al., 1990). However, a direct comparison between kinetic and kinematic parameters has not been reported in gait related studies, therefore it remains uncertain which group of variables may offer the best outcomes. A direct comparison between the different groups of parameters is needed to provide more insight into which parameter might be most effective at improving gait related outcomes.

Only 4 of the 173 studies gave feedback in the field, with a further 4 studies giving a combination of laboratory and field based training. Even though two previous reviews concluded that field based systems should be considered (Richards et al., 2016; Shull, Jirattigalachote, Hunt, Cutkosky, & Delp, 2014), to date the vast majority of published research is confined to laboratory settings. Presenting feedback in the field may facilitate the trend for healthcare to move away from a clinical model to a self-care model supported by technology (McCullagh et al., 2010), and it would also improve the representative design of experiments (Araújo et al., 2007). However, presenting feedback in the field does have some practical implementation issues. For example, visual feedback could be shown on a screen in the laboratory, but this would not be easily possible in the field. Auditory and sensory feedbacks are therefore easier to facilitate in field based settings.

Future research should also focus on the design of feedback interventions. Over half of the included studies reported one feedback training session. Since beneficial outcomes could be related to the duration of the intervention (Adamovich et al., 2009; Agresta & Brown, 2015), both the duration and number of sessions required for effective retraining should be explored. These findings are supported by a review of Gordt et al. (2017) on the effects of feedback of wearable sensor data on balance, gait and functional performance in both healthy and patient populations. These authors concluded that future randomised controlled trials should be designed with adequate intervention periods to enhance learning. In the current mapping review, only fifteen of the included studies used a faded feedback approach within their intervention. By gradually removing feedback over time, it is suggested that participants do not become dependent on the feedback, facilitating improved learning (Winstein, 1991). The majority of studies in this review had no retention test or a short term retention test within a week of the intervention finishing. Establishing the long term retention of any gait related changes represents a crucial step in prescribing gait retraining interventions as an effective alternate to existing treatment options (Agresta and Brown, 2015; Gordt et al. 2017, Stanton et al., 2017; Tate and Milner, 2010). Further, only thirteen studies combined having a retention test with having a control group. Of those thirteen studies, eleven studies reported beneficial effects of gait retraining when comparing baseline values to the retention values, four studies found significant differences between experimental and control groups. Therefore, the use of biofeedback shows promising results, since it has the same or a better effect compared to existing interventions, without the need for a health practitioner, or several trips to the clinic if field based feedback could be applied. However, at present there is a lack of well-designed studies that have established the long term efficacy of biofeedback for use in gait retraining interventions. Therefore, future work should focus on higher quality study designs, with a special focus on assessing the long term effects of any interventions.

This review has some limitations that are noteworthy: we used a selection of terms combined with feedback (as stated in the methods, section 2.2), since feedback is too broad as a term and would therefore have led to too many results. By using a selection of terms instead of feedback, there is a possibility that we missed some articles. However, we covered the area which we were interested in by a wide selection of terms and we further searched the reference list of reviews we found as well to make sure no articles were missed. Another limitation is the risk of publication bias, which might inflate the number of beneficial effects reported for the main outcome. Publication bias could mean that studies are less likely to be published when they have not found beneficial results. By choosing a mapping review instead of a systematic review we chose not to assess quality, assessing of the quality could have reduced the publication bias. However, in the current review the focus was on assessing the body of literature on the use of biofeedback to alter gait-related outcomes and the methods used; for this a mapping review was the most appropriate approach.

5. Conclusion

There is a growing body of research on the use of biofeedback in gait retaining. This mapping review has identified several areas within the current body of research that warrant further work. Future research should focus on direct comparisons between groups of parameters and feedback modes for specific gait retraining applications. Furthermore, researchers should seek to produce high quality well designed studies that explore the fading of feedback, the appropriate number of sessions as well as include a control group as assessing the long-term benefits of any intervention. Finally, researchers should seek to develop and assess the efficacy of field-based gait retraining systems using experimental designs more representative of real life situations.

Declarations of interest statement:

Declarations of interest: none

Acknowledgements:

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Fig 1. Flow diagram of search strategy

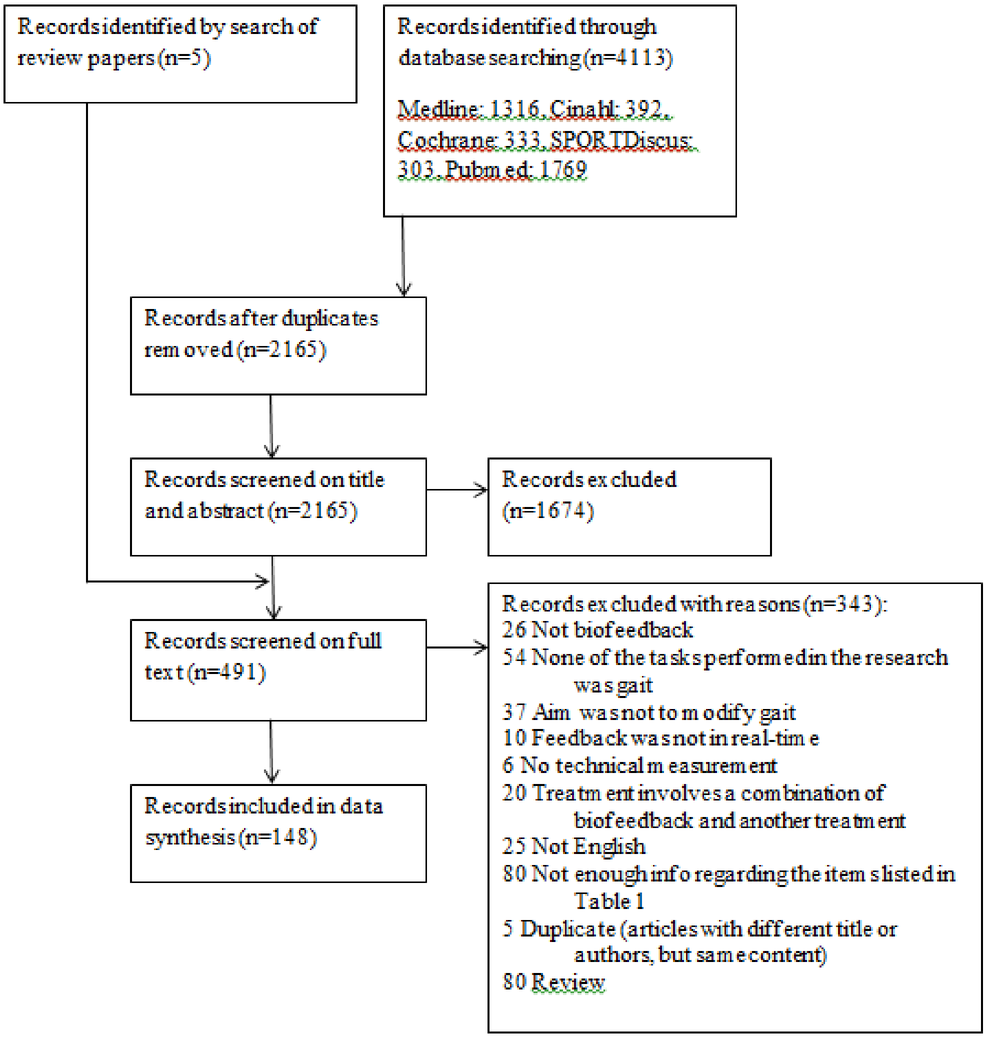


Fig 2. Number of studies published each year

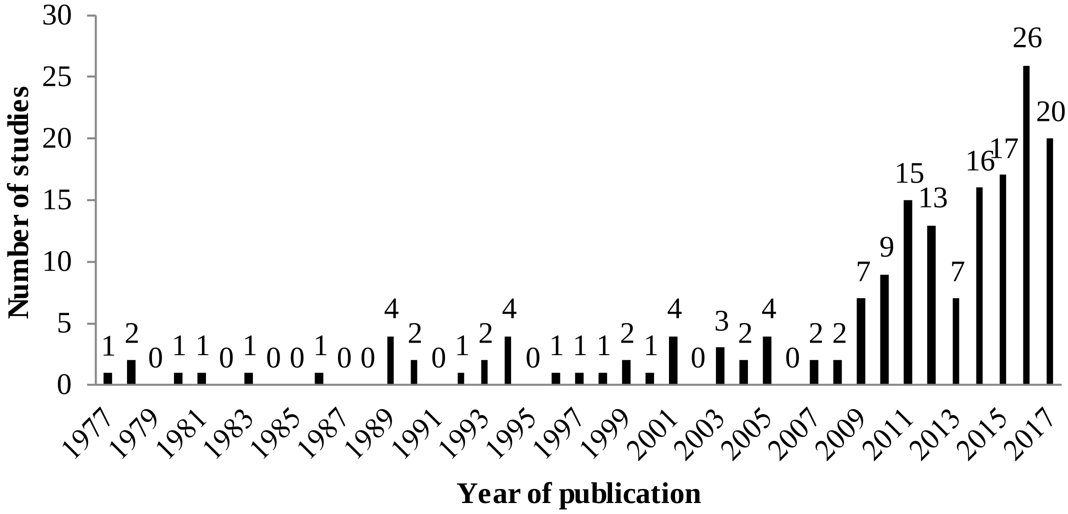


Fig 3. The number of studies published for each participant group

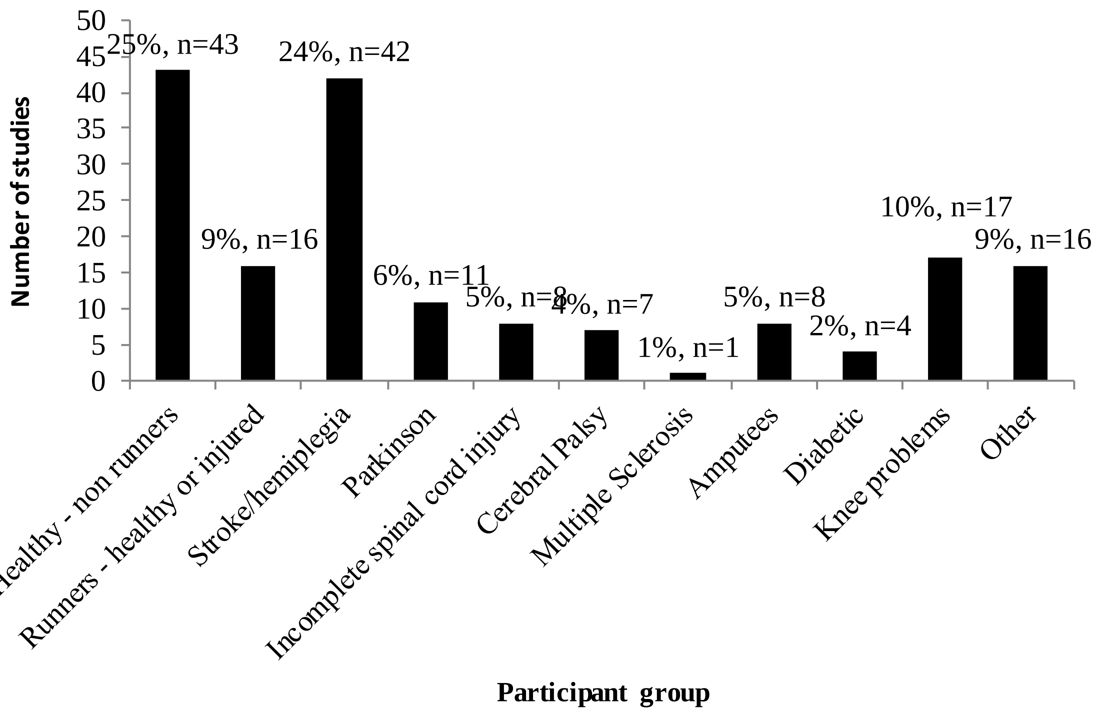


Fig 4. The number of studies published for each mode of feedback

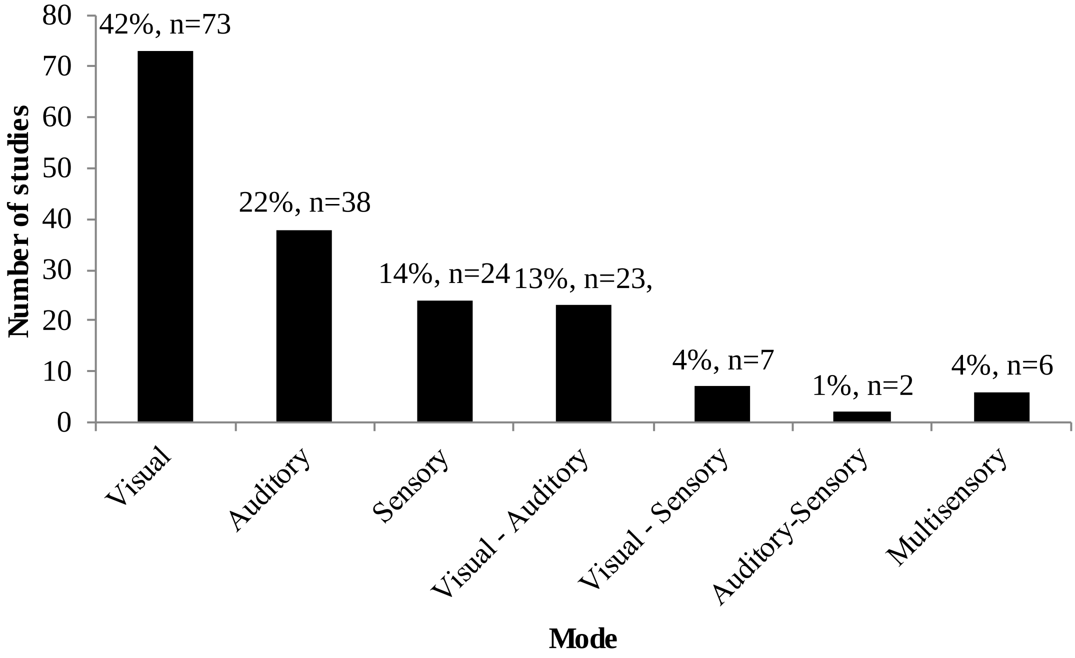
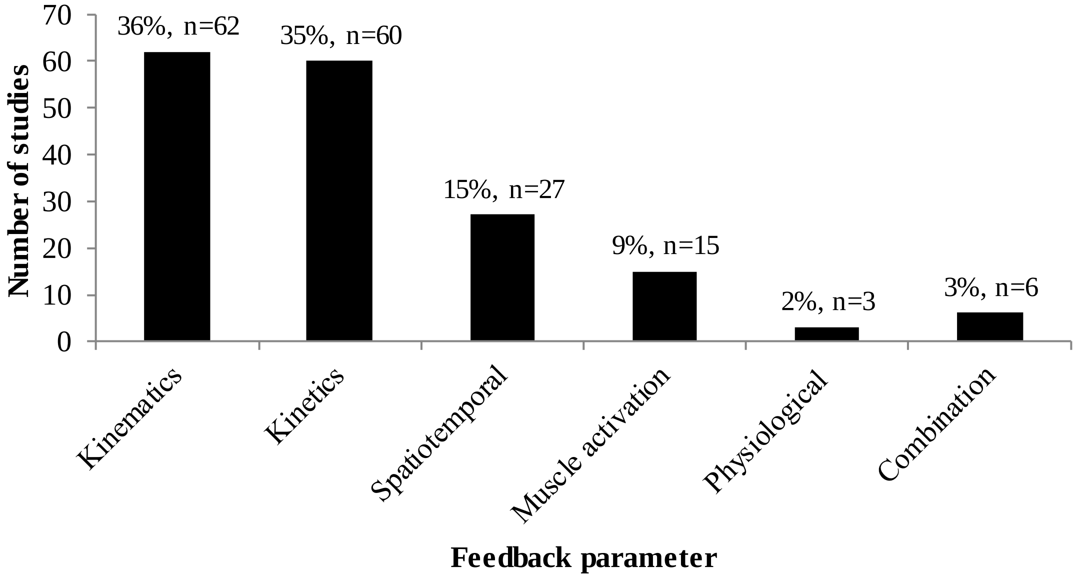


Fig 5. The numbers of studies published for each parameter which was fed-back



9.2 Appendix B: Validity of cropped time from time-trial data

To assess the validity of the cropped time described in section 3.2.3, the reliability between the calculated time and official times recorded during the five-kilometre time trial for the participants was calculated. The times of these cropped data sets were compared to the official times, based on 137 participants (Appendix C) with the use of the intraclass correlation coefficient (ICC(2,1)) estimates and their 95% confidence intervals using SPSS version 24 (SPSS Inc, Chicago, IL), based on a single rater, absolute agreement, two-way random-effects model. A single rater measurement was chosen, since a single measurement will be the basis of the actual measurement (Koo & Li, 2016). Further, an absolute agreement was chosen instead of consistency, since there was an interest in the absolute difference of the measurements and not the relative (Field, 2014; Koo & Li, 2016; Weir, 2005). A two-way model was chosen, since every subject was rated by every time calculation (McGraw & Wong, 1996). Finally, a random-effects model was chosen, because measurements taken are a sample from the population and, therefore, generalizable to other participants as well (Field, 2014). Values less than 0.5, between 0.5 and 0.75, between 0.75 and 0.9, and greater than 0.9 indicated respectively poor, moderate, good and excellent reliability (Koo & Li, 2016). The time calculated from the data had an excellent agreement with the official parkrun times, with 95% confidence intervals ranging from good to excellent agreement (ICC = 0.92, 95% CI = 0.87-0.95) across participants.

The ICC is prone to several constraints as described in section 3.2.4. Therefore, a paired samples *t*-test, a Bland-Altman plot, calculation of the limits of agreement (LOA) and Pearson's correlation between the absolute difference and the mean of the two methods were calculated as well. Based on the paired samples *t*-test a significant difference was found between the two measurements ($p<0.001$), with the official parkrun time being longer than the calculated time. This was, however, expected, since the five-kilometre time trial has a mass start, people starting in the back will, therefore, start running later and are likely to walk the first steps. Further, if participants had a really low mean peak tibial acceleration (below 3 g) the sensor would not start measuring until the participant went above the threshold, this could have caused the measured time to be shorter than the official parkrun time. Considering the wireless sensors were used to define participants with an increased mean peak tibial acceleration, it was acceptable for participants with a lower mean peak tibial acceleration to have missing running data, since they will not be included in the intervention study.

The Bland-Altman plot can be found in Figure 9.1, the mean ± 95% limits of agreement were 0.72 ± 3.91. The correlation between the absolute difference and the mean of the two methods was 0.308 and significant ($p<0.001$). From these results, it could be concluded that higher means resulted in higher differences between the two measurement methods and, therefore, heteroscedasticity was suspected. However, this was expected as well due to the same reason a systematic error was found. People who took more time were more likely to start in the back of the queue and did, therefore, not actually start running at the signal of a run director.

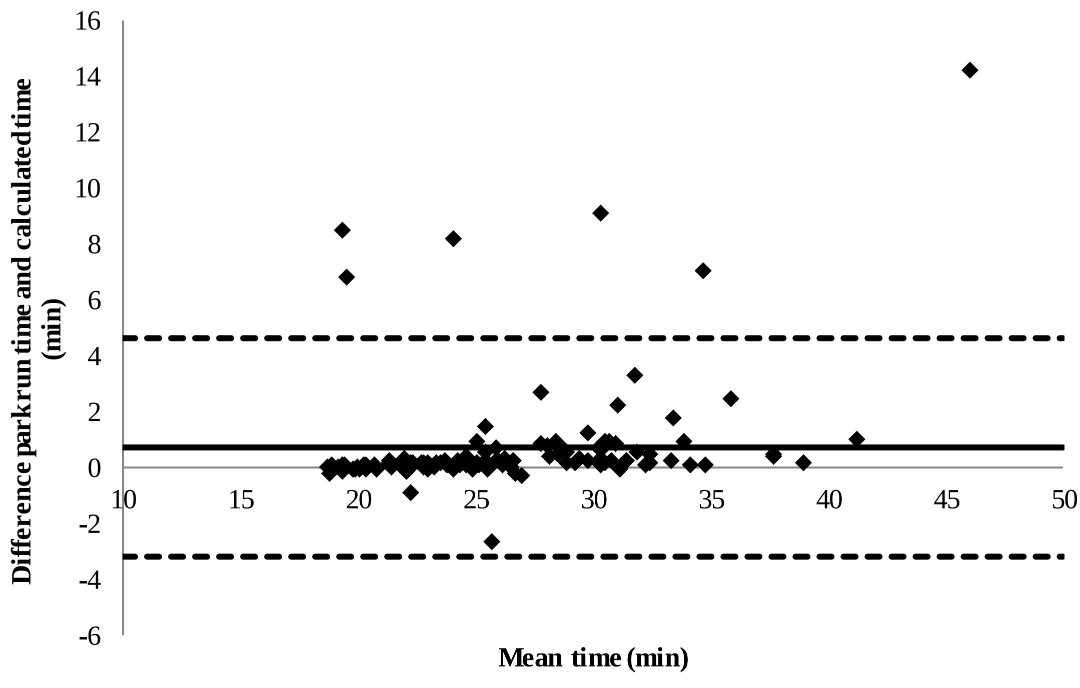


Figure 9.1. Bland-Altman plots and limit of agreement for the times based on the official timing and calculated from the data.

9.3 Appendix C: Selection of participants for tibial acceleration intervention

9.3.1 Introduction

Runners who participated in the intervention study (further described in chapter 6) were selected based on increased mean peak tibial acceleration from a five-kilometre time trial. Participants with an increased tibial acceleration are at a higher risk of injury (section 2.5.5). Therefore, reducing tibial acceleration could reduce the prevalence of this injury. Further, during the feasibility studies (further explained in section 5.2, 5.3, 5.4, and 5.5) it was noticed that participants who started with a tibial acceleration below 5 g and decreased further to mean values below 3 g, produced unorthodox running patterns. These unorthodox running patterns, such as speed walking or excessive knee and hip flexion were difficult for participants to maintain. It was, therefore, decided to only include participants with a high peak tibial acceleration for the intervention study (Chapter 6). To be able to measure a high number of participants, a local parkrun was used as a fixed five-kilometre time trial to measure participants' tibial acceleration. parkrun is a weekly, free, five-kilometre timed event and takes place all over the world ("parkrun," 2019). The aim of this study was to identify participants with higher tibial acceleration.

9.3.2 Methods

Participants

Following institutional and parkrun Research Board ethical approval (Appendix R and S), a total of 137 participants were recruited and measured. Participants were recruited through social media and asked to come to parkrun and run like they normally would do, with the addition of a small sensor. The measurements for this particular research took place at Endcliffe Park, Sheffield over several weeks, where every Saturday the event starts at 9.00 am. The event at Endcliffe Park consists of two laps in which the first half of each lap is uphill and the second half of the lap is downhill. It is important to note that parkrun is an inclusive event, so people can run or walk the course at their own pace. Along with participants being recruited through social media, participants were recruited on-site as well. Participants were given a participant information sheet (Appendix T) and after agreeing to participate, they signed an informed consent form (Appendix U) and filled in a questionnaire on how much they run, past and current injuries, and height and weight (Appendix V). Due to malfunctioning of the sensors, complete data sets were collected for 133 participants (66 female, 67 male; 38.5 ± 12 years; stature: 1.70 ± 0.09 m; body mass: 69.2 ± 12.2 kg). Data on stature and body mass were collected through questionnaires. Not all participants completed all questions, therefore, the age, stature, and body mass data are based on respectively 131, 129 and 127 participants. Based on the information of 131 participants, participants ran 19.7 ± 15.2 km on average a week, 124 participants ran at least once a week and 7 participants ran less than once a week.

Study design and equipment

A tri-axial accelerometer (RunScribe version 2, Scribe Labs, California, USA) was attached to the anteromedial aspect of the right tibia, five centimetres above the medial malleolus (Barnes, Wheat and Milner, 2011) with double-sided tape and wrapped up with cohesive bandage (see Figure 9.2). Participants were asked to run the five-kilometre time-trial like they normally would and hand the sensor back after the run.

Outcome measures and data analysis

The acceleration signal was filtered with a 400th order Hamming band-pass filter with lower and upper cut-off frequencies of 8 and 60 Hz, respectively (for more information on the sensor and filters see section 3.2). After the offset was removed, steps which were considered as walking were removed (section 3.2.3). The main outcome measurement for this study was the mean peak tibial acceleration for each runner. Based on the mean tibial acceleration the participants were sorted from low mean peak tibial acceleration to high mean peak tibial acceleration. The official parkrun times were used to define the time participants took to complete the course.

Figure 9.2 Runner during the five-kilometre time trial, the sensor is located under the blue bandage on the right leg. Used with permission of George Carman.

9.3.3 Results

Mean peak tibial acceleration for all participants was: 9.12 ± 2.8 g with a range of 2.39 g to 15.92 g. Times varied from 18 minutes and 42 seconds to 53 minutes and 13 seconds, with a mean of 26 minutes and 35 seconds ± 5 minutes and 8 seconds.

9.3.4 Discussion and conclusion

The aim of this study was to select participants with high tibial acceleration. It should be noted that the values that were found in the current study for peak tibial acceleration were relatively high when compared to studies done in a laboratory on a runway at respectively 3.5 m/s or 3.7 m/s (Davis et al., 2004; Milner et al., 2006). In the current study, a mean tibial acceleration of 9.12 g was found, while in a prospective study (Davis et al., 2004) a mean value of 4.73 g was found for participants who did not sustain a tibial stress fracture and 9.06 g for participants who did sustain a tibial stress fracture. Similar values were found in a retrospective study by Milner et al. (2006), respectively 5.81 ± 1.66 g and 7.70 ± 3.21 g. Taking those numbers into account, more than half of the participants of the current study could be at risk of sustaining a tibial stress fracture. However, the current study was recorded outside on tarmac and the running surface can affect the impact of the running, with a more compliant surface leading to lower peak pressures (Hollis et al., 2019; Tessutti, Ribeiro, Trombini-Souza, & Sacco, 2012; Tessutti, Trombini-Souza, Ribeiro, Nunes, & Sacco, 2010). In a study by Hollis et al. (2019) participants were asked to run at a slow and fast speed on a track surface and they found mean values of respectively 9.9 ± 1.8 g and 10.7 ± 1.1 g. Further, Ruder et al. (2019) found a mean tibial acceleration of 10.19 ± 3.40 g over a marathon, which are more in line with our results. Tibial acceleration values in the current study were relatively high compared to tibial acceleration measured in the lab. More research is needed to define the differences in peak tibial acceleration between measurements done in the laboratory and the field. For the current study, the absolute value was of less importance since there was an interested for participants with the highest mean peak tibial acceleration.

9.4 Appendix D: Institutional ethical approval intervention study

Exploring different types of biofeedback and strategies participants use to reduce tibial acceleration

Ethics Review ID: ER6565173
Workflow Status: Application Approved
Type of Ethics Review Template: Very low risk human participants studies

Primary Researcher / Principal Investigator

Linda Van Gelder (Health and Wellbeing)

Converis Project Application::
Q1. Is this project: ii) Doctoral research

Director of Studies

Ben Heller
(Health and Wellbeing)

Q4. Proposed Start Date of Data Collection: 14/05/2018
Q5. Proposed End Date of Data Collection : 31/10/2018

Q6. Will the research involve any of the following:
i) Participants under 5 years old: No
ii) Pregnant women: No
iii) 5000 or more participants: No
iv) Research being conducted in an overseas country: No
Q7. If overseas, specify the location:
Q8. Is the research externally funded?: No
Q9. Will the research be conducted with partners and subcontractors?: No
Is another UK HEI the lead partner?: No
Q10. Does the research involve one or more of the following?
i. Patients recruited because of their past or present use of the NHS or Social Care: No
ii. Relatives/carers of patients recruited because of their past or present use of the NHS or Social Care: No
iii. Access to data, organs, or other bodily material of past or present NHS patients: No
iv. Foetal material and IVF involving NHS patients: No
v. The recently dead in NHS premises: No
vi. Participants who are unable to provide informed consent due to their incapacity even if the project is not health related: No
vii. Prisoners or others within the criminal justice system recruited for health-related research: No
viii. Prisoners or others within the criminal justice system recruited for non-health-related research:
No

ix. Police, court officials or others within the criminal justice system: No

Q11. Category of academic discipline: Physical Sciences and Engineering
Q12. Methodology: Quantitative

P2 - Project Outline

Q1. General overview of study: The objectives of this study are to investigate the effect of providing feedback to explore a range of tibial acceleration compared to decreasing tibial acceleration and to investigate the difference in strategies participants use to change their gait patterns. Tibial stress fractures are common overuse injuries among runners. Tibial stress fractures can cause significant disruption
to training, a reduction in physical fitness as well as increased psychological distress. Increased tibial acceleration is related to tibial stress fractures and could therefore be an important risk factor for injury. One way to decrease tibial accelerations within runners is by providing them with biofeedback. In previous studies participants were asked to decrease tibial acceleration with the use of biofeedback. We however believe an increased learning effect can be achieved by not only asking the participants to reduce in tibial acceleration but also to increase in tibial acceleration, so they can explore the relation between movement pattern and outcome better. To test this hypothesis we will compare the outcome of two groups, one will receive feedback to decrease in tibial acceleration and one to explore tibial acceleration. We would further like to investigate the different strategies participants use to change their gait patterns. In an earlier study responders as well as non-responders to tibial acceleration feedback were found. In a study who focused on change in running patterns to biofeedback changes were found in the ankle joint angles, but no changes
were found in the hip or knee joint angles. In a pilot study we did earlier we noticed different participants had different strategies in changing their running pattern to biofeedback. These different strategies might cancel each other out, if you take the mean over a group. Therefore we will perform a single subject analysis.

Q2. Background to the study and scientific rationale (if you have already written a research proposal,e.g. for a funder, you can upload that instead of completing this section).: The objectives of this study are to investigate the effect of providing feedback to explore a range of tibial acceleration compared to decreasing tibial acceleration and to investigate the difference in strategies participants use to change their gait patterns. Tibial stress fractures are common overuse injuries among runners [1]. Tibial stress fractures can cause significant disruption to training, a reduction in physical fitness as well as increased psychological distress [2]. An earlier prospective study [3] suggests that increased tibial acceleration during the loading phase in running is related to tibial stress fractures and could therefore be an important risk factor for injury. In this prospective study the relationship between the incidence of tibial stress fractures and measures of loading including tibial acceleration in competitive women runners was examined. In their study, Davis et al. [3] found five participants who sustained a tibial stress fracture or a tibial stress reaction, the precursor for tibial stress fractures. These participants had increased values of peak tibial acceleration (9.06 g) compared to the five controls (4.73 g). Milner et al. [4] compared 20 female runners with a history of tibial stress fractures to 20 participants who did not in a prospective study. They found that participants in the group who did have a history of tibial stress fractures run with a mean peak tibial acceleration of 7.7g (SD=3.21) compared to a mean of 5.81g (SD=1.66) in the group who did not have an history of tibial stress fractures. Therefore increased values of tibial acceleration being associated with tibial stress fractures found in the prospective study of Davis et al. [3] were confirmed by a retrospective study of Milner et al. [4]. To overcome the negative impacts of tibial stress fractures, a decrease in tibial acceleration could reduce the prevalence of this injury, since tibial acceleration is related to tibial stress fractures. One way to decrease tibial accelerations within runners is by providing them with biofeedback [5-10]. Different studies found decreased tibial accelerations after participants received feedback on this
parameter until a month after the intervention [5, 7]. In these different studies participants were asked to run on a treadmill while receiving different modes of feedback. In all of these studies participants were asked to decrease tibial acceleration. We however believe an increased learning effect can be achieved by not only asking the participants to reduce in tibial shock but also to increase in tibial shock, so they can explore the relations between movement patterns and movement outcomes better. To test this hypothesis we will compare the outcome of two groups, one will receive feedback to decrease in tibial acceleration and one group will receive feedback to explore the relation between their movement pattern and tibial acceleration. Even

though participant groups are able to reduce tibial acceleration [5-10], individual differences exist [8]. In a study of Crowell et al. [8] responders as well as non-responders to tibial acceleration feedback were found. We are therefore interested in how different participants change their running pattern according to the feedback. In a study of Clansey et al. [5] changes were found in the ankle joint angels, but no changes were found in either the hip or knee joint angles. In a pilot study we did earlier [11] we noticed different participants had different strategies in changing their running pattern to biofeedback. These different strategies might cancel each other out, if you take the mean over a group. Therefore we will perform a single subject analysis to see whether we can find different strategies and whether certain strategies might benefit participants more. References [1] K.L. Bennell, S. a Malcolm, S. a Thomas, J.D. Wark, P.D. Brukner, The incidence and distribution of stress fractures in competitive track and field athletes. A twelve- month prospective study., Am. J. Sports Med. 24 (1995) 211–7. doi:10.1177/036354659602400217. [2]
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Davis, Biomechanical factors associated with tibial stress fracture in female runners, Med. Sci. Sports Exerc. 38 (2006) 323–328. doi:10.1249/01.mss.0000183477.75808.92. [5] A.C. Clansey, M. Hanlon, E.S. Wallace,
A. Nevill, M.J. Lake, Influence of Tibial shock feedback training on impact loading and running economy, Med. Sci. Sports Exerc. 46 (2014) 973–981. doi:10.1249/MSS.0000000000000182. [6] M.W. Creaby, M.M. Franettovich Smith, Retraining running gait to reduce tibial loads with clinician or accelerometry guided feedback, J. Sci. Med. Sport. 19 (2016) 288–292. doi:10.1016/j.jsams.2015.05.003. [7] H.P. Crowell,
I.S. Davis, Gait retraining to reduce lower extremity loading in runners, Clin. Biomech. 26 (2011) 78–83. doi:10.1016/j.clinbiomech.2010.09.003. [8] H.P. Crowell, C.E. Milner, J. Hamill, I.S. Davis, Reducing impact loading during running with the use of real-time visual feedback., J. Orthop. Sports Phys. Ther. 40 (2010) 206–213. doi:10.2519/jospt.2010.3166. [9] M. Gray, E; Sweeney, M; Creaby,M; Smith, Gait retraining using visual and verbal feedback in runners, 30Th Annu. Conf. Biomech. Sport. (2012) 262–263. [10] C.M. Wood,
K. Kipp, Use of audio biofeedback to reduce tibial impact accelerations during running, J. Biomech. 47 (2014) 1739–1741. doi:10.1016/j.jbiomech.2014.03.008.

Q3. Is your topic of a sensitive/contentious nature or could your funder be considered controversial?: No

Q4. Are you likely to be generating potentially security-sensitive data that might need particularly secure storage?: No

Q5. Has the scientific/scholarly basis of this research been approved, for example by Research Degrees Sub-committee or an external funding body?: NA e.g. there is no relevant committee governing this work

Q6. Main research questions: 1. What is the effect of different forms of feedback in reducing tibial acceleration? 2. What is the difference in strategies participants use to change their gait patterns and how relates this to their ability to decrease tibial acceleration?

Q7. Summary of methods including proposed data analyses: Participants will be asked to run parkrun with a sensor two times and they will be asked to come to the laboratory seven times. The first measurement will take place at parkrun. When the participants come for the first measurement at parkrun we will ask them to complete an informed consent. When the informed consent is completed we will attach a runscribe (accelerometer) to the tibia and ask the participants to run parkrun like they normally would do. The sensitive axis of the runscribe will be visually aligned with the long axis of the right tibia. The accelerometer will be attached with double sided tape to the antero-medial aspect of the right tibia, five centimeter above the medial malleolus. We will further use cohesive bandage to secure the runscribes. The data will be processed in custom programs written in Matlab (Mathworks, Natick, MA, USA, R2016a). From the peak tibial acceleration signal the peaks will be found and averaged within each participant. The same measurement at parkrun will be done after a month after the intervention. We choose this moment since from earlier research it seemed that a significant difference is seen after a month after the treatment, but that the decrease in tibial acceleration was more immediate after the treatment [1-2]. That would mean that if we would find a result after a month it is likely that there was also a result after two weeks. Further, we are more interested in the long-term retention effect compared to the short-term retention effect. The first six of the seven laboratory sessions will take place within two weeks, which involves participants coming to the university three times a week. The seventh session will take place after a month after the sixth session. In the first, sixth and seventh laboratory session kinematic and kinetic values will be measured. Before participants start running, mass and height measurements will be taken and markers will be placed on the participant according to a fixed marker template. Further participants will be wearing a heart rate monitor and an accelerometer of which the sensitive axis is visually aligned with the long axis of the right tibia. The accelerometer is mounted on a small piece of themoplastic (total mass: 1.65 g) which is attached with double sided tape to the antero-medial aspect of the right tibia, five centimeter above the medial malleolus [3]. The accelerometer is connected via a wire to a PCB signal conditioner (PCB Piezotronics, Stevenage, UK, model: 480E09; gain = 10) and sampled at 1000 Hz. Accelerometer data will only be measured during the trials on the treadmill. The makers will be tracked with a motion capture system (MAC) during the running trials. In all session in the laboratory the running speed will be fixed and based on the speed participants run during parkrun. The first, sixth and seventh session will involve a warming-up of six minutes on the treadmill, six minutes are needed to familiarize to running on the treadmill [4], and followed by ten over ground running trials to be able to do measurements with the force plate. Five correct trials, trials in which the force plate is hit correctly, for each foot will be recorded. After the over ground trials a baseline recording will be done on the treadmill. In the first and sixth session a biofeedback session will be included as well. In the first session this will be after the baseline measurements and in the final session this will before the baseline measurements. The feedback session (session one until six) will be given different for different groups. The first group will be asked to reduce tibial acceleration and the second group will be encouraged to explore different tibial acceleration levels. Feedback of the first group will partly be based on the research which is done by Crowell and Davis [2]. Feedback will be given on tibial acceleration to reduce peak tibial acceleration. Based on pilot tests we did, we will add a few changes to the work of Crowell and Davis [2]. First, participants will be running at the speed based on their average five kilometre speed instead of a self-selected speed. Since tibial acceleration is related to running speed, a self-selected comfortable running speed is unlikely to reach the parkrun running speed and therefore mean tibial acceleration is likely to be decreased when compared to field based situations. This is what was we found in earlier pilot studies as well. Also by pushing people to their boundaries, they have less degrees of freedom to their availability to change. Further we will have to adjust the number of session from eight to six due to practical reasons. Six sessions should be enough, since previous studies have suggested that running styles can successfully retrained in short time periods, i.e. five to seven training session. We will however fade the feedback according to the principles of the study of Crowell end Davis [2]. So the run time will be gradually improved from 15-30 minutes (Session 1: 15 min, session 2: 18min, session 3: 21 min, session 4: 24 min, session 5: 27 min, session 6: 30 min). The feedback will progressively be removed over the last four sessions. During the last four sessions, one third of the feedback will be provided at the beginning of each session, one third in the middle, and one third at the end. By the last session, runners will be provided 1 min of feedback in the beginning, one in the middle and one in the end of the session. Further to keep participants motivated a changing target will be used instead of a fixed target. Finally, instead of only visual or auditory feedback a combination of the three modes of feedback will be used, since that is expected to give better results. Participants will be told that feedback is given on tibial acceleration but no further instruction will be given on what the possible strategies are to change tibial acceleration. Participants can therefore explore their own movement strategies. The second group will be encouraged to explore different tibial acceleration levels. We expect an increased learning effect can be achieved by not only asking the participants to reduce in tibial shock but also to increase in tibial shock, so they can explore the relation between movement pattern and outcome better. Further the same protocol will be applied as the other group: the running speed will be based on their average five kilometre speed, participants will receive six feedback sessions and participants will receive multisensory feedback. And also in this group participants will be told that feedback is given on tibial acceleration but no further instruction will be given on what the possible strategies are to change tibial acceleration. Participants can therefore explore their own movement strategies. All data collected from the laboratory trials will be processed in Matlab. To receive a better insight

in whether the second group which receives feedback to explore different tibial acceleration levels performs better compared to the first group who receives feedback only to reduce tibial acceleration a mixed Mixed-Model Anova will be performed. In this comparison we will mainly focus on the tibial acceleration measures done in the lab as well as in the field. To receive a better insight in how different participants change their running pattern according to the feedback we will perform a single-subject analysis on all kinematic and kinetic data [5]. In this analysis we will mainly focus on how the feedback sessions compare to the baseline condition and what strategies participants use to change their running pattern. Since participants are expected to respond differently to feedback, a typical statistical analysis of group data might mask individual changes. Therefore, a single-subject analysis will be used to characterise the change in running pattern for each participant individually [5]. We will check whether this change in running pattern will remain over time. References [1] A.C. Clansey, M. Hanlon, E.S. Wallace, A. Nevill, M.J. Lake, Influence of Tibial shock feedback training on impact loading and running economy, Med. Sci. Sports Exerc. 46 (2014) 973–981. doi:10.1249/MSS.0000000000000182. [2] H.P. Crowell, I.S. Davis,
Gait retraining to reduce lower extremity loading in runners, Clin. Biomech. 26 (2011) 78–83. doi:10.1016/ j.clinbiomech.2010.09.003. [3] Barnes, A.; Wheat, J.; Milner, C.E. Fore- and Rearfoot Kinematics in High- and Low-Arched Individuals during Running. Foot Ankle Int. 2011, 32, 710–716, doi:10.3113/FAI.2011.0710.
[4] V. Lavcanska, N.F. Taylor, A.G. Schache, Familiarization to treadmill running in young unimpaired adults, Hum. Mov. Sci. 24 (2005) 544–557. doi:10.1016/j.humov.2005.08.001 [5] Bates, B.T. Single-subject methodology: An alternative approach. Med. Sci. Sports Exerc. 1996, 28, 631–638.

P3 - Research with Human Participants

Q1. Does the research involve human participants?: Yes
Q2. Will any of the participants be vulnerable?: No
Q3. Is this a clinical trial?: Yes
If yes, will the placebo group receive a treatment plan after the study? If N/A tick no.: No
Q4. Are drugs, placebos or other substances (e.g. food substances, vitamins) to be administered to the study participants or will the study involve invasive, intrusive or potentially harmful procedures of any kind?: No
Q5. Will tissue samples (including blood) be obtained from participants?: No
Q6. Is pain or more than mild discomfort likely to result from the study?: No
Q7. Will the study involve prolonged testing (activities likely to increase the risk of repetitive strain injury)?: No
Q8. Is there any reasonable and foreseeable risk of physical or emotional harm to any of the participants?: No
Q9. Will anyone be taking part without giving their informed consent?: No
Q10. Is it covert research?: No
Q11. Will the research output allow identification of any individual who has not given their express consent to be identified?: No
Q12. Where data is collected from human participants, outline the nature of the data, details of anonymisation, storage and disposal procedures if these are required (300 - 750): Tibial acceleration during parkrun will be measured in the field using runscribes. The data of these runscribes will be stored on a password protected laptop. In this research participants further will be asked to run on a treadmill and overground in a lab based setting. From the treadmill trials tibial acceleration and MAC data will be recorded and stored on a laptop. From the overground trails forceplate and MAC data will be collected and stored on a computer. For each participant a measurement log will be made in which height, weight and date of birth are noted together with the recorded acceleration trial names. The data will be anonymised by using a code on the measurement log instead of the name. The code will relate to one name of one participant which could be found in a separate password protected document. All digital data will be stored in a confidential folder on the Q-drive which can only be reached by the contributing researchers. The data will be processed on a password protected laptop from the university. The data will be processed with the use of programs including LabView, Matlab and SPSS. Non-digital data will be protected and stored in a locked cabinet in Chestnut Court S003 on collegiate campus. All data will only be used for academic purposes. The data will be kept

confidentiality for three years (duration of program of research) after publication. No access to the data will be granted without approval from a member of the team or the participants.

P4 - Research in Organisations

Q1. Will the research involve working with an external organisation or using data/material from an external organisation?: No

P5 - Research with Products and Artefacts

Q1. Will the research involve working with copyrighted documents, films, broadcasts, photographs, artworks, designs, products, programmes, databases, networks, processes, existing datasets or secure data?: No

P7 - Health and Safety Risk Assessment

Q1. Will the proposed data collection take place only on campus?
: No
Q2. Are there any potential risks to your health and wellbeing associated with either (a) the venue where the research will take place and/or (b) the research topic itself?: None that I am aware of
Q3. Will there be any potential health and safety risks for participants (e.g. lab studies)? If so a Health and Safety Risk Assessment should be uploaded to P8.: Yes
Q4. Where else will the data collection take place? (Tick as many venues as apply)Researcher's Residence: false

Participant's Residence: false
Education Establishment: false
Other e.g. business/voluntary organisation, public venue: true
Outside UK: false
Q5. How will you travel to and from the data collection venue?: On foot
Q6. Please outline how you will ensure your personal safety when travelling to and from the data collection venue.: Part of the study will be done at Endcliff park, which is next to my house so it will be a short walk. Further, other people will be around at Saturday 9am in the park.
Q7. If you are carrying out research off-campus, you must ensure that each time you go out to collect data you ensure that someone you trust knows where you are going (without breaching the confidentiality of your participants), how you are getting there (preferably including your travel route), when you expect to get back, and what to do should you not return at the specified time. (See Lone Working Guidelines). Please outline here the procedure you propose using to do this.: I will tell my partner when I will be measuring. He lives next to the park and might join to help. I further will tell him when I am supposed to be finished.
Q8. How will you ensure your own personal safety whilst at the research venue, (including on campus where there may be hazards relating to your study)?: There will be a lot of people at the venue, including first-aiders. On campus there will always be a second person in the building. During out of office hours that second person will be in the room.

P8 - Attachments

Are you uploading any recruitment materials (e.g. posters, letters, etc.)?: Yes
Are you uploading a participant information sheet?: Yes
Are you uploading a participant consent form?: Yes
Are you uploading details of measures to be used (e.g. questionnaires, etc.)?: Non Applicable
Are you uploading an outline interview schedule/focus group schedule?: Non Applicable
Are you uploading debriefing materials?: Non Applicable
Are you uploading a Risk Assessment Form?: Yes
Are you uploading a Serious Adverse Events Assessment (required for Clinical Trials and Interventions)?: Non Applicable
Are you uploading a Data Management Plan?: Yes
Upload:

Data Management Plan.docx
Participant Informed Consent Form - Researchers Copy.docx
Letter participants results.docx
Project Health and Safety Asssessment.docx Participant Information Sheet.docx

P9 - Adherence to SHU Policy and Procedures

Primary Researcher / PI Sign-off:
I can confirm that I have read the Sheffield Hallam University Research Ethics Policy and Procedures: true
I can confirm that I agree to abide by its principles: true
Date of PI Sign-off: 19/04/2018

Director of Studies Sign-off:

I confirm that this research will conform to the principles outlined in the Sheffield Hallam University Research Ethics policy: true
I can confirm that this application is accurate to the best of my knowledge: true
Date of submission and supervisor sign-off: 08/05/2018

Director of Studies Sign-off

Ben Heller

P12 - Post Approval Amendments

Amendment 1

Title of Amendment 1: Focus no longer on different learning theories but on the way participants change
their running pattern
Details of Amendment 1: Instead of two groups with two different forms of feedback we will only measure one group. For this study the focus is no longer on different learning theories but on the way participants change their running pattern. The one group that will remain (lower target) will still get the same feedback as provided in this ethics approval. With one difference, since participants will be asked to run at 95% of their parkrun speed, we will ask them to run for a max of 20 minutes instead of 30 minutes. This is so we can make the running sustainable for all participants. The feedback will still be faded.
Date of Amendment 1: 27/05/2018
In my judgement amendment 1 should be:: Amendment Approved
Reason for amendment 1 decision (if applicable): approved
Date of Amendment Outcome 1: 31/05/2018

Amendment 2

Title of Amendment 2: Stroop test
Details of Amendment 2: We would further like to add a Stroop test to measure the cognitive demand on the participants while they are learning to use the biofeedback. At the end of each session in the lab we will ask participants to run two extra minutes without feedback, the first minute will be without the Stroop test and the second will be with the Stroop test.
Date of Amendment 2: 27/05/2018
In my judgement amendment 2 should be:: Amendment Approved
Reason for amendment 2 decision (if applicable): approved
Date of Amendment Outcome 2: 31/05/2018

Amendment 3

Title of Amendment 3: Change of Participant Information Sheet
Details of Amendment 3: Changed the participant information sheet to reflect the legal changes from GDPR. We further included the new protocol.
Date of Amendment 3: 27/05/2018

Upload:
Participant Information Sheet New.docx
In my judgement amendment 3 should be:: Amendment Approved
Reason for amendment 3 decision (if applicable): approved
Date of Amendment Outcome 3: 31/05/2018

9.5 Appendix E: Joint coordinate systems

Hip, knee and ankle joint coordinate system angles (Grood & Suntay, 1983) were calculated in Visual 3D (C-Motion Inc., Germantown, USA). First, orthogonal segment coordinate systems for each segment were calculated using data from the static trials. To be able to make the joint coordinate systems as close to anatomical rotations as possible, the segment coordinate systems were defined separately for each joint. Because our main interest was in the flexion angle of the different joints, the first axis was defined as the flexion axis of the proximal (reference) segment, the third axis as the longitudinal axis of the distal segment (target) and the second (floating) axis was the cross-product of the third by first axis (Cole, Nigg, Ronsky, & Yeadon, 1993). Because both the thigh and the shank function as proximal, as well as a distal segment, respectively knee and hip for the thigh and ankle and knee for the shank, different segment coordinate systems were calculated for each joint. The different segment and joint coordinate systems can be found on the following pages.

The pelvis and thigh coordinate systems to calculate the hip joint coordinate system (Figure 9.4) are given in Figure 9.3

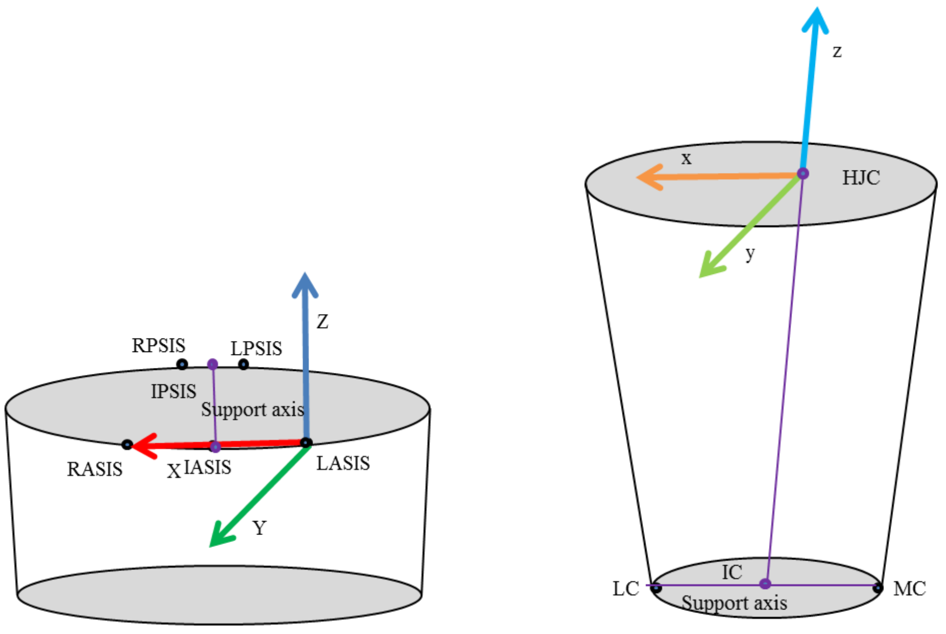


Figure 9.3

Left: the definition for the pelvis coordinate systems to calculate the hip joint coordinate system, where:
Origin: Left anterior superior iliac spine (LASIS)
X-axis: line passing through the left (LASIS) and right (RASIS) anterior superior iliac spine with positive direction to the right
Support axis: line passing through midpoint (IASIS) of the left (LASIS) and right (RASIS) anterior superior iliac spines and midpoint (IPSIS) of the left (LPSIS) and right (RPSIS) posterior superior iliac spines, with positive direction forwards
Z-axis: cross-product of the X-axis and the support axis
Y-axis: cross-product of Z-axis and X-axis

Right: the definition for the thigh coordinate systems to calculate the hip joint coordinate system, where:
Origin: Functional hip centre (HJC)
z-axis: line passing through origin and midpoint (IC) between lateral (LC) and medial (MC) condyles, with positive direction proximal
Support axis: line passing through the lateral (LC) and medial condyles (MC) with positive direction to the right
y-axis: cross-product of z-axis and support axis
x-axis: cross-product of y-axis and z-axis

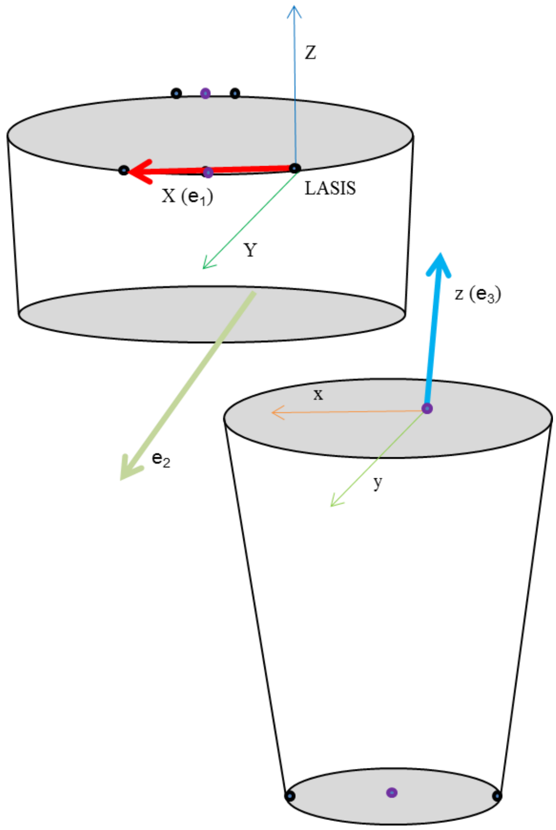


Figure 9.4 The hip joint coordinate system, where:
e_1: X-axis of pelvis coordinate system, flexion-extension axis
e_2: the floating axis, cross-product of z-axis and the X-axis, abduction/adduction axis
e_3: z-axis of the thigh coordinate system, axial rotation axis

The thigh and shank coordinate systems to calculate the knee joint coordinate system (Figure 9.6) are given in Figure 9.5.

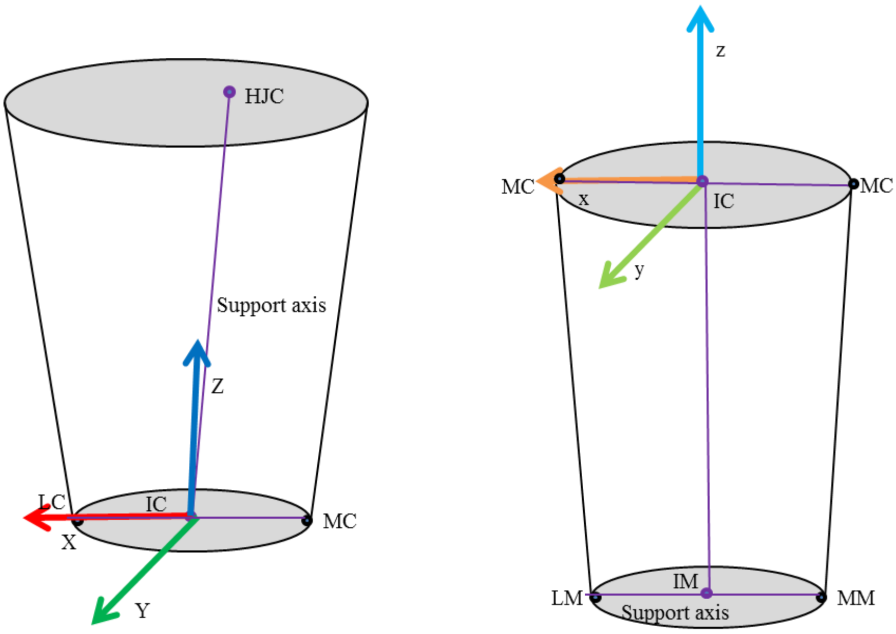


Figure 9.5

Left: the definition for the thigh coordinate systems to calculate the knee joint coordinate system, where:
Origin: midpoint (IC) in between lateral (LC) and medial (MC) condyles
X-axis: line passing through the lateral (LC) and medial (MC) condyles with positive direction to the right
Support axis: line passing through origin and hip joint centre (HJC), with positive direction proximal
Y-axis: cross-product of support axis and X-axis
Z-axis: cross-product of X-axis and Y-axis

Right: the definition of the shank coordinate system to calculate the knee joint coordinate system, where:
Origin: midpoint (IC) between lateral (LC) and medial (MC) condyles
z-axis: line passing through origin and midpoint (IM) between the lateral (LM) and medial (MM) malleoli, with positive direction proximal
Support axis: line passing through the lateral (LM) and medial (MM) malleoli with positive direction to the right
y-axis: cross-product of z-axis and support
x-axis: cross-product of y-axis and z-axis

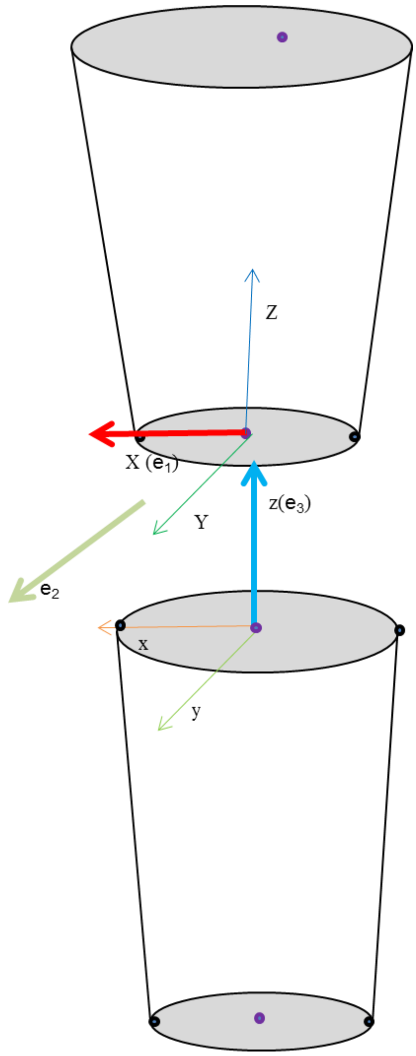


Figure 9.6 The knee joint coordinate system, where:
e1: X-axis of thigh coordinate system, flexion-extension axis
e2: the floating axis, cross-product of z-axis and the X-axis, abduction/adduction axis
e3: z-axis of the shank coordinate system, axial rotation axis

The shank and foot segment coordinate systems to calculate the ankle joint coordinate system (Figure 9.8) are given in Figure 9.7.

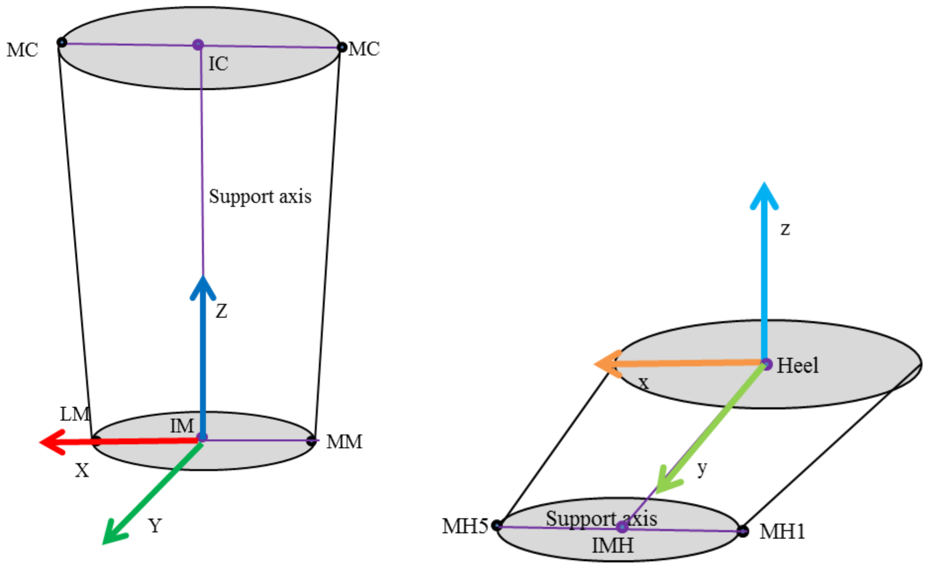


Figure 9.7

Left: the definition for the shank coordinate system to calculate the ankle joint coordinate system, where:
Origin: midpoint (IM) between lateral (LM) and medial (MM) malleoli
X-axis: line passing through the lateral (LM) and medial (MM) malleoli with positive direction to the right
Support axis: line passing origin and through midpoint (IC) between lateral (LC) and medial (MC) condyle, with positive direction proximal
Y-axis: cross-product of support axis and X-axis
Z-axis: cross-product of X-axis and Y-axis

Right: the definition for the foot coordinate system to calculate the ankle joint coordinate system, where:
Origin: heel marker
y-axis: line passing through heel and the midpoint (IMH) between the first (MH1) and fifth (MH5) metatarsal head
Support axis: line passing through the first (MH1) and fifth (MH5) metatarsal head, pointing towards the right.
z-axis: cross-product of support axis and y-axis
x-axis: cross-product of y-axis and z-axis

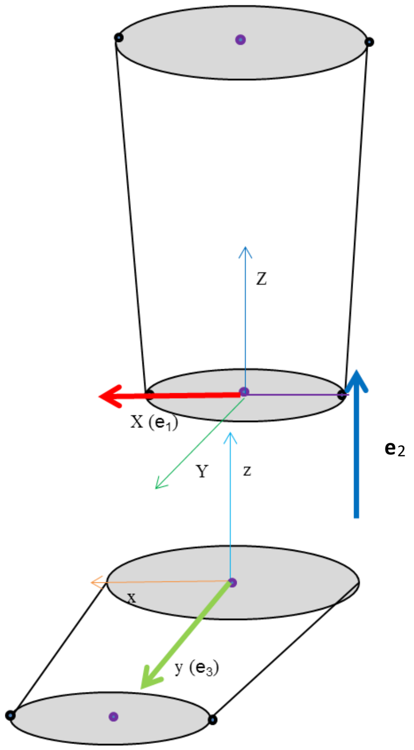


Figure 9.8The ankle joint coordinate system, where:
e_1=X-axis of shank coordinate system - flexion-extension axis
e_2 = the floating axis, cross-product of X-axis and the y-axis, internal/external rotation
e_3 = y-axis of the foot coordinate system, inversion/eversion

9.6 Appendix F: Cut-off frequency for filter for marker data

A residual analysis was performed to define the cut-off frequency for the filter for the marker data. The residual analysis consisted of filtering the data at cut-off frequencies ranging from 0.5 Hz to 50 Hz in 0.1 Hz increments. The residual between each set of filtered data and the original signal was subsequently calculated and plotted against the cut-off frequency. The maximum feasible frequency was based on the seventh harmonic of the fundamental frequency (Winter, 2009). The fundamental frequency of running was expected to be at 3 Hz (180 steps per minute), which made the maximum feasible frequency expected to be above 21 Hz. One harmonic is seen as the multiple of the fundamental frequency and it is expected that 99.7 per cent of the signal power is found in the first seven harmonics. Above the seventh harmonic there is still some signal power, but it will mainly be noise. A regression line was fitted from the approximate maximum feasible frequency (25 Hz) to the maximum cut-off frequency used (50 Hz) to determine the intercept. The optimal cut-off frequency was chosen as the cut-off frequency corresponding to the point where the residual equalled or exceeded the intercept. For the data in this programme of research, this was 22 Hz for all markers for a second-order, single pass, Butterworth filter. However, to prevent a phase distortion, the filtered data had been filtered again in the reverse direction to create a two-pass, zero-phase shift filter. A zero-phase filter doubles the order of the filter and changes the cut-off frequency of the filter as well. Since a second order, single-pass Butterworth filter was used the double filter became a fourth order Butterworth filter. The actual cut-off frequency, corresponding to the zero-phase Butterworth filter was calculated with the following formulas based on Winter (2009) :

$$f_{cor} = \frac{f_s * tan^{-1}(C * (\tan \frac{\pi * C_f}{f_s}))}{\pi} \tag{3}$$

where f_s was the sampling frequency and C_f was the cut-off frequency of the single pass filter, C was calculated by the following formula:

$$C = (2^{\frac{1}{2n}} - 1)^{0.25} \tag{4}$$

where n was the number of passes, which gave C a value of 8.022 for a Butterworth double-pass filter. The actual cut-off frequency based on these formulas was 18 Hz.

For displacement data, the optimal frequency is a frequency in where the signal distortion is equal to the residual noise (Winter, 2009) as shown above. However, the motion capture data are not only used for displacement data, but the acceleration values are also calculated from the heel and first and fifth metatarsal heads markers along the z-axis to define initial contact in the gait cycle (see paragraph 3.3.5). The optimal cut-off frequency, $f_{c,2}$, for acceleration data is different and can be calculated by the following formula according to Yu et al. (1999):

$$f_{c,2} = 0.06\ f_s - 0.000022\ {f_s}^2 + 5.95/\varepsilon \qquad (5)$$

where f_s is the sampling frequency and ε the relative mean residual calculated as:

$$\varepsilon = \sqrt{\frac{\sum_{n=0}^{N}(x_n - x'_n)^2}{\sum_{n=0}^{N}(x_n - \bar{x})^2} \times\ 100\%} \qquad (6)$$

where x is the raw signal, N was the length of the raw signal, x'_n was the filtered data with the optimal cut-off frequency and $\bar{x}$ was the mean of x_n. Using the above equations an optimal frequency of 14 Hz was found for the acceleration along the z-axis for all the markers.

9.7 Appendix G: Formulas ANOVA

The F-statistic value in a one-way ANOVA is calculated as follow (Field, 2009):

$$F = \frac{MS_M}{MS_R} \tag{1}$$

with MS_M being the model mean-squares (formula 2) and MS_R being the residual mean-squares (formula 4).

$$MS_M = \frac{SS_M}{df_M} \tag{2}$$

with SS_M being the model sum of squares (formula 3) and df_M the model degrees of freedom defined as the number of groups minus 1.

$$SS_M = \sum n_k (\bar{x}_k - \bar{x}_{grand})^2 \tag{3}$$

with n_k being the number of participants within a group, $\bar{x}_k$ the mean of a group and $\bar{x}_{grand}$ being the total mean of all data.

$$MS_R = \frac{SS_R}{df_R} \tag{4}$$

with SS_R being the residual sum of squares (formula 5) and df_R the degrees of freedom defined as total sample size minus the number of groups.

$$SS_R = \sum (x_{ik} - \bar{x}_k)^2 \tag{5}$$

with x_{ik} being a person within each group and $\bar{x}_k$ the mean of a group.

9.8 Appendix H: Institutional ethical approval for reliability study

Reliability and minimal detectable change values for spatiotemporal, kinematic and tibial acceleration values in healthy runners.

Ethics Review ID: ER13561446

Workflow Status: Application Approved

Type of Ethics Review Template: All other research with human participants

Primary Researcher / Principal Investigator

Linda van Gelder

(Health and Wellbeing)

Converis Project Application::

Q1. Is this project: ii) Doctoral research

Director of Studies

Ben Heller
(Health and Wellbeing)

Q4. Proposed Start Date of Data Collection: 01/04/2019

Q5. Proposed End Date of Data Collection : 30/04/2019

Q6. Will the research involve any of the following:

i) Participants under 5 years old: No
ii) Pregnant women: No
iii) 5000 or more participants: No
iv) Research being conducted in an overseas country: No
Q7. If overseas, specify the location:

Q8. Is the research externally funded?: No
Q9. Will the research be conducted with partners and subcontractors?: No

Q10. Does the research involve one or more of the following?

i. Patients recruited because of their past or present use of the NHS or Social Care: No

ii. Relatives/carers of patients recruited because of their past or present use of the NHS or Social Care: No
iii. Access to data, organs, or other bodily material of past or present NHS patients: No
iv. Foetal material and IVF involving NHS patients: No
v. The recently dead in NHS premises: No
vi. Participants who are unable to provide informed consent due to their incapacity even if the project is not health related: No
vii. Prisoners or others within the criminal justice system recruited for health-related research: No
viii. Prisoners or others within the criminal justice system recruited for non-health-related research: No
ix. Police, court officials or others within the criminal justice system: No

Q11. Category of academic discipline: Physical Sciences and Engineering

Q12. Methodology: Quantitative

P2 - Project Outline

Q1. General overview of study: The objective of this study is to investigate the reliability and minimal detectable change values for spatiotemporal, kinematic and tibial acceleration values in healthy runners. The results of this study will inform another study which investigates the effect of providing feedback to decrease tibial acceleration and to investigate the difference in strategies participants use to change their gait patterns. The results of the current study could be used for other future studies which use the same systems as well. Reliability is associated with the true differences that can exist between participants or measurements, while the systematic and random sources of error are accounted for by the measurement error. The minimal detectable change value provides information on the amount of change which is sufficiently greater than the measurement error for the variable of interest. With the use of this value, an observed change between assessments can be checked for whether the value found was a true effect of the intervention or whether it was a result of a measurement error.

Q2. Background to the study and scientific rationale (if you have already written a research proposal, e.g. for a funder, you can upload that instead of completing this section).: The objective of this study is to investigate the reliability and minimal detectable change values for spatiotemporal, kinematic and tibial acceleration values in healthy runners. The results of this study will inform another study which investigates the effect of providing feedback to decrease tibial acceleration and to investigate the difference in strategies participants use to change their gait patterns. Tibial stress fractures are common overuse injuries among runners [1]. Tibial stress fractures can cause significant disruption to training, a reduction in physical fitness as well as increased psychological distress [2]. An earlier prospective study [3] suggests that increased tibial acceleration during the loading phase in running is related to tibial stress fractures and could, therefore, be an important risk factor for injury. In this prospective study, the relationship between the incidence of tibial stress fractures and measures of loading including tibial acceleration in competitive women runners was examined. In their study, Davis et al. [3] found five participants who sustained a tibial stress fracture or a tibial stress reaction, the precursor for tibial stress fractures. These participants had increased values of peak tibial acceleration (9.06 g) compared to the five controls (4.73 g). Milner et al. [4] compared 20 female runners with a history of tibial stress fractures to 20 participants who did not in a retrospective study. They found that participants in the group who did have a history of tibial stress fractures run with a mean peak tibial acceleration of 7.7g (SD=3.21) compared to a mean of 5.81g (SD=1.66) in the group who did not have a history of tibial stress fractures. Therefore increased values of tibial acceleration being associated with tibial stress fractures found in the prospective study of Davis et al. [3] were confirmed by a retrospective study of Milner et al. [4]. To overcome the negative impacts of tibial stress fractures, a decrease in tibial acceleration could reduce the prevalence of this injury, since tibial acceleration is related to tibial stress fractures. One way to decrease tibial accelerations within runners is by providing them with biofeedback [5-10]. Different studies found decreased tibial accelerations after participants received feedback on this parameter until a month after the intervention [5, 7]. In these different studies, participants were asked to run on a treadmill while receiving different modes of feedback. In all of these studies, participants were asked to decrease tibial acceleration. Even though participant groups are able to reduce tibial acceleration [5-10], individual differences exist [8]. In a study of Crowell et al. [8] responders as well as non-responders to tibial acceleration feedback were found. We are therefore interested in how different participants change their running pattern according to the feedback. In a study by Clansey et al. [5] changes were found in the ankle joint angles, but no changes were found in either the hip or knee joint angles. In a pilot study we did earlier [11] we noticed different participants had different strategies in changing their running pattern to biofeedback. These different strategies might cancel each other out if you take the mean over a group. To understand the differences we find in the study described above, the current study will be performed to define the reliability and the minimal detectable change. Reliability is associated with the true differences that can exist between participants or measurements, while the systematic and random sources of error are accounted for by the measurement error [12]. The minimal detectable change value provides information on the amount of change which is sufficiently greater than the measurement error for the variable of interest. With the use of this value, an observed change between assessments can be checked for whether the value found was a true effect of the intervention or whether it was a result of a measurement error [13].

References

[1] K.L. Bennell, S. a Malcolm, S. a Thomas, J.D. Wark, P.D. Brukner, The incidence and distribution of stress fractures in competitive track and field athletes. A twelve-month prospective study., Am. J. Sports Med. 24 (1995) 211–7. doi:10.1177/036354659602400217. [2] A.C. Clansey, M. Hanlon, E.S. Wallace, A. Nevill, M.J. Lake, Influence of Tibial shock feedback training on impact loading and running economy, Med. Sci. Sports Exerc. 46 (2014) 973–981. doi:10.1249/MSS.0000000000000182. [3] I. Davis, C.E. Milner, J. Hamill, Does Increased Loading During Running Lead to Tibial Stress Fractures? A Prospective Study, Med. Sci. Sport. Exerc. 36 (2004) S58. doi:http://dx.doi.org/10.1097/00005768-200405001-00271. [4] C.E. Milner, R. Ferber, C.D. Pollard, J. Hamill, I.S. Davis, Biomechanical factors associated with tibial stress fracture in female runners, Med. Sci. Sports Exerc. 38 (2006) 323–328. doi:10.1249/01.mss.0000183477.75808.92.

[5] A.C. Clansey, M. Hanlon, E.S. Wallace, A. Nevill, M.J. Lake, Influence of Tibial shock feedback training on impact loading and running economy, Med. Sci. Sports Exerc. 46 (2014) 973–981. doi:10.1249/ MSS.0000000000000182. [6] M.W. Creaby, M.M. Franettovich Smith, Retraining running gait to reduce tibial loads with clinician or accelerometry guided feedback, J. Sci. Med. Sport. 19 (2016) 288–292. doi:10.1016/j.jsams.2015.05.003. [7] H.P. Crowell, I.S. Davis, Gait retraining to reduce lower extremity loading in runners, Clin. Biomech. 26 (2011) 78–83. doi:10.1016/j.clinbiomech.2010.09.003. [8] H.P. Crowell, C.E. Milner, J. Hamill, I.S. Davis, Reducing impact loading during running with the use of real-time visual feedback., J. Orthop. Sports Phys. Ther. 40 (2010) 206–213. doi:10.2519/jospt.2010.3166. [9] M. Gray, E; Sweeney, M; Creaby,M; Smith, Gait retraining using visual and verbal feedback in runners, 30Th Annu. Conf. Biomech. Sport. (2012) 262–263. [10] C.M. Wood, K. Kipp, Use of audio biofeedback to reduce tibial impact accelerations during running, J. Biomech. 47 (2014) 1739–1741. doi:10.1016/j.jbiomech.2014.03.008.

[11] van Gelder, L. M. A.; Barnes, A.; Wheat, J.S.; Heller, B.W., Characterizing the Learning Effect in Response to Biofeedback Aimed at Reducing Tibial Acceleration during Running. Proceedings (2018), 2, 200. [12] Mokkink, L., Terwee, C., Knol, D., Stratford, P., Alonso, J., Patrick, D., Bouter, L., de Vet, H., 2006. Protocol of the COSMIN study: COnsensus-based Standards for the selection of health Measurement INstruments. BMC Med. Res. Methodol. 6, 2. https://doi.org/10.1186/1471-2288-6-2 [13] de Vet, H.C., Terwee, C.B., Ostelo, R.W., Beckerman, H., Knol, D.L., Bouter, L.M., 2006. Minimal

changes in health status questionnaires: distinction between minimally detectable change and minimally important change. Health Qual. Life Outcomes 4, 54. https://doi.org/10.1186/1477-7525-4-54

Q3. Is your topic of a sensitive/contentious nature or could your funder be considered controversial?: No

Q4. Are you likely to be generating potentially security-sensitive data that might need particularly secure storage?: No

Q5. Has the scientific/scholarly basis of this research been approved, for example by Research Degrees Sub-committee or an external funding body?: NA e.g. there is no relevant committee governing this work

Q6. Main research questions: What is the reliability and minimal detectable change values for spatiotemporal, kinematic and tibial acceleration values in healthy runners?

Q7. Summary of methods including proposed data analyses: Participants will be asked to come to the laboratory twice. The first time they come to the lab they will be asked to complete informed consent. The second measurement will take place a week after the first measurement. In both sessions spatiotemporal, kinematic and tibial acceleration values will be measured. Before participants start running, mass and height measurements will be taken and markers will be placed on the participant according to a fixed marker template. Participants will be wearing an accelerometer of which the sensitive axis is visually aligned with the long axis of the right tibia. The accelerometer is mounted on a small piece of thermoplastic (total mass: 1.65 g) which is attached with double sided tape to the anteromedial aspect of the right tibia, five centimetres above the medial malleolus [1]. The accelerometer is connected via a wire to a PCB signal conditioner (PCB Piezotronics, Stevenage, UK, model: 480E09; gain = 10) and sampled at 1000 Hz. Accelerometer data will only be measured during the trials on the treadmill. The makers will be tracked with a motion capture system (MAC). Kinematic data will be collected using a 14-camera optoelectronic motion capture system (10 x Raptor model and 2 x Eagle model, Motion Analysis Corporation, Santa Rosa, CA, USA) sampling at 240 Hz. The cameras will be placed optimally around the capture volume with a length of 2.250 meters, which covered the length of the treadmill, a width of 0.75 meters, which covered the width of the treadmill and a height of 1.5 meters, which included the legs and pelvis of the participants. The positive x-axis will be directed mediolateral, pointing to the lateral part of the right leg; the positive y-axis will be directed anterior, while the positive z-axis will be directed from distal to proximal. During the sessions, participants will be asked to do a six-minute warm-up, six minutes are needed to familiarize to running on the treadmill [2], which will be followed by 2 minutes of data collection. Participants will be running at 95% of their most recent parkrun time. All data collected from the laboratory trials will be processed in Cortex, Visual 3D and Matlab. Reliability will be calculated with the use of an intraclass correlation coefficient and minimal detectable change values will be calculated with the use of the following formula: MDC= SEM * 1.96 * #2 [3]. SEM was calculated using the equation: SD * # (1-ICC), where SD is the pooled variance.

References [1] Barnes, A.; Wheat, J.; Milner, C.E. Fore- and Rearfoot Kinematics in High- and Low-Arched Individuals during Running. Foot Ankle Int. 2011, 32, 710–716, doi:10.3113/FAI.2011.0710. [2] V. Lavcanska, N.F. Taylor, A.G. Schache, Familiarization to treadmill running in young unimpaired adults, Hum. Mov. Sci. 24 (2005) 544–557. doi:10.1016/j.humov.2005.08.001 [3] Wilken, J.M., Rodriguez, K.M., Brawner, M., Darter, B.J., 2012. Reliability and minimal detectible change values for gait kinematics and kinetics in healthy adults. Gait Posture 35, 301–307. https://doi.org/10.1016/j.gaitpost.2011.09.105

P3 - Research with Human Participants

Q1. Does the research involve human participants?: Yes

Q2. Will any of the participants be vulnerable?: No
Q3. Is this a clinical trial?: No
If yes, will the placebo group receive a treatment plan after the study? If N/A tick no.: No
Q4. Are drugs, placebos or other substances (e.g. food substances, vitamins) to be administered to the study participants or will the study involve invasive, intrusive or potentially harmful procedures of any kind?: No
Q5. Will tissue samples (including blood) be obtained from participants?: No
Q6. Is pain or more than mild discomfort likely to result from the study?: No
Q7. Will the study involve prolonged testing (activities likely to increase the risk of repetitive strain injury)?: No
Q8. Is there any reasonable and foreseeable risk of physical or emotional harm to any of the participants?: No
Q9. Will anyone be taking part without giving their informed consent?: No
Q10. Is it covert research?: No
Q11. Will the research output allow identification of any individual who has not given their express consent to be identified?: No
Q12. Where data is collected from human participants, outline the nature of the data, details of anonymisation, storage and disposal procedures if these are required (300 - 750): Tibial acceleration and MAC data will be recorded and stored on a password protected laptop. For each participant, a measurement log will be made in which height, weight and date of birth are noted together with the recorded acceleration trial names. The data will be anonymised by using a code on the measurement log instead of the name. The code will relate to one name of one participant which could be found in a separate password protected document. All digital data will be stored in a confidential folder on the Q-drive, which can only be reached by the contributing researchers. The data will be processed on a password protected laptop from the university. The data will be processed with the use of programs including LabView, Matlab, Cortex, Visual 3D and SPSS. Non-digital data will be protected and stored in a locked cabinet in Chestnut Court S003 on Collegiate campus. All data will only be used for academic purposes. The data will be kept confidential for three years (duration of the program of research) after publication. No access to the data will be granted without approval from a member of the team or the participants.

P4 - Research in Organisations

Q1. Will the research involve working with an external organisation or using data/material from an external organisation?: No

P5 - Research with Products and Artefacts

Q1. Will the research involve working with copyrighted documents, films, broadcasts, photographs, artworks, designs, products, programmes, databases, networks, processes, existing datasets or secure data?: No

P6 - Human Participants - Extended

Q1. Describe the arrangements for recruiting, selecting/sampling and briefing potential participants.: For this study, we are looking at recruiting 10 participants. This sample size might differ since reliability testing is unbiased to sample size (Weir 2005). All participants must be aged 18 years or above, and be without any current injuries or other conditions that could affect their running. Letter and participant information sheet can be found on tab 8. Weir, J.P., 2005. Quantifying Test-Retest Reliability Using the Intraclass Correlation Coefficient and the SEM. J. Strength Cond. Res. 19, 231. https:// doi.org/10.1519/15184.1
Q2. Indicate the activities participants will be involved in.: Participants will be asked to come to the lab twice and during each session they will be asked to do a six-minute progressive warm-up, followed by 2 minutes of data collection. Participants will be running at 95% of their parkrun speed during the data collection.
Q3. What is the potential for participants to benefit from participation in the research?: The outcomes of this study will be used to inform further research on how to improve running. Participants could further get an insight into their current running pattern.
Q4. Describe any possible negative consequences of participation in the research along with the ways in which these consequences will be limited: Risks are: - participants could be allergic to the tape that will be used. Participants will be specifically asked about allergies before participating. If they find out during the run they can stop and take the sensor off. - Risk of tripping over on the treadmill caused by a missed step. When participants run on the treadmill, there will be a treadmill safety key which can stop the treadmill immediately if the runner slips or feels uncomfortable by pulling out the connection to the treadmill control panel. Participants can also press the emergency button to stop the treadmill. The treadmill has supports fitted on one side which will prevent participants from getting hurt if they slip on the treadmill, and will prevent them from falling off. Further participants will have a warmup so they will be able to get familiar with the treadmill. Risk of discomfort such as feeling tired, hot, pain caused by running. Participants are allowed to redraw from the study at any time. A pre-test medical questionnaire is used to identify risk factors and exclude at-risk participants from the study. A fan will be available for hot conditions. Water and paper tissues will be available to all participants. Participants will further do a warmup to reduce the chances of muscle injury.
Q5. Describe the arrangements for obtaining participants' consent.: Information sheet and informed consent are attached at tab 8.
Q6. Describe how participants will be made aware of their right to withdraw from the research.: Text in participant information sheet: "What if I want to leave the study before the end? You are under no obligation to take part in this study. If you do decide to participate but wish to leave before the study is complete, you are free to withdraw at any time, without prejudice and without having to provide a reason. No disadvantage will arise from any decision to participate or not. If you decide to leave the study, you may also request for your data to be removed. If you have any concerns, queries or want to discuss your participation after your involvement within the study please don't hesitate to contact the principal researcher (details at end). " Text at informed consent form: "3. I understand that I am free to withdraw from the study at any time, 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. "
Q7. If your project requires that you work with vulnerable participants describe how you will implement safeguarding procedures during data collection: We will not be working with vulnerable participants
Q8. If Disclosure and Barring Service (DBS) checks are required, please supply details: Not applicable **Q9. Describe the arrangements for debriefing the participants.:** If participants agree they will be informed of their own results and the study results
Q10. Describe the arrangements for ensuring participant confidentiality. This should include details of:: Data will be anonymised by using a code on the measurement log instead of the name. The code will relate to one name of one participant which could be

found in a separate document.
Q11. Are there any conflicts of interest in you undertaking this research?: No

Q12. What are the expected outcomes, impacts and benefits of the research?: The objective of this study is to investigate the reliability and minimal detectable change values for spatiotemporal, kinematic and tibial acceleration values in healthy runners. We expect good to excellent reliability based on earlier studies (Barnes, 2011; Ferber et al., 2002; McGinley et al., 2009). The results of this study will inform another study which investigates the effect of providing feedback to decrease tibial acceleration and to investigate the difference in strategies participants use to change their gait patterns. The results of the current study could be used for other future studies which use the same systems as well. Barnes, A., 2011. Forefoot-rearfoot kinematics as risk factors for tibial stress injuries. Sheffield Hallam University.
Ferber, R., McClay Davis, I., Williams, D.S., Laughton, C., 2002. A comparison of within- and between- day reliability of discrete 3D lower extremity variables in runners. J. Orthop. Res. 20, 1139–1145. https:// doi.org/10.1016/S0736-0266(02)00077-3 McGinley, J.L., Baker, R., Wolfe, R., Morris, M.E., 2009. The reliability of three-dimensional kinematic gait measurements: A systematic review. Gait Posture 29, 360–369. https://doi.org/10.1016/j.gaitpost.2008.09.003
Q13. Please give details of any plans for dissemination of the results of the research.: The data will be stored confidentially for at least 3 years after collection. Data will be written up into the thesis and preferable also as an article. See Data Management Plan for more information.

P7 - Health and Safety Risk Assessment

Q1. Will the proposed data collection take place only on campus?: Yes

Q2. Are there any potential risks to your health and wellbeing associated with either (a) the venue where the research will take place and/or (b) the research topic itself?: None that I am aware of
Q3. Will there be any potential health and safety risks for participants (e.g. lab studies)? If so a Health and Safety Risk Assessment should be uploaded to P8.: Yes
Q4. Where else will the data collection take place? (Tick as many venues as apply)Researcher's Residence: false
Participant's Residence: false
Education Establishment: false
Other e.g. business/voluntary organisation, public venue: false
Outside UK: false
Q8. How will you ensure your own personal safety whilst at the research venue, (including on campus where there may be hazards relating to your study)?: There will always be a second person in the building.

P8 - Attachments

Are you uploading any recruitment materials (e.g. posters, letters, etc.)?: Yes
Are you uploading a participant information sheet?: Yes
Are you uploading a participant consent form?: Yes
Are you uploading details of measures to be used (e.g. questionnaires, etc.)?: Non Applicable
Are you uploading an outline interview schedule/focus group schedule?: Non Applicable

Are you uploading debriefing materials?: Non Applicable
Are you uploading a Risk Assessment Form?: Yes
Are you uploading a Serious Adverse Events Assessment (required for Clinical Trials and Interventions)?: Non Applicable
Are you uploading a Data Management Plan?: Yes

Upload:
Data Management Plan.docx Letter participants.docx
Participant Informed Consent Form - Researchers Copy.docx
Project Health and Safety Asssessment.docx Participant Information Sheet New.docx

P9 - Adherence to SHU Policy and Procedures

Primary Researcher / PI Sign-off:

I can confirm that I have read the Sheffield Hallam University Research Ethics Policy and Procedures: true
I can confirm that I agree to abide by its principles: true
Date of PI Sign-off: 19/03/2019

Director of Studies Sign-off:

I confirm that this research will conform to the principles outlined in the Sheffield Hallam University Research Ethics policy: true
I can confirm that this application is accurate to the best of my knowledge: true

Director of Studies' Comments: This is a small extension study on top of Linda's main PhD study to assess day-to-day variability of measurement.
Date of submission and supervisor sign-off: 21/03/2019

Director of Studies Sign-off

Ben Heller

P10 - Review

Comments collated by Lead Reviewer (Or FREC if escalated): Approved
Final Decision to be completed by Lead Reviewer (or FREC if escalated): Approved
Date of Final Decision: 04/04/2019

P12 - Post Approval Amendments

Amendment 1

In my judgement amendment 1 should be:: Select Amendment Outcome

Amendment 2

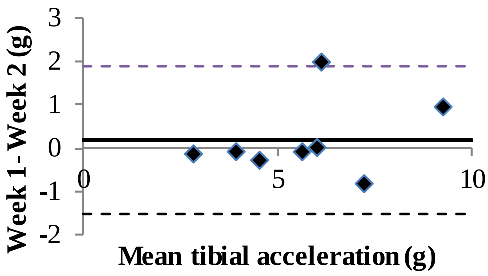
In my judgement amendment 2 should be:: Select Amendment Outcome

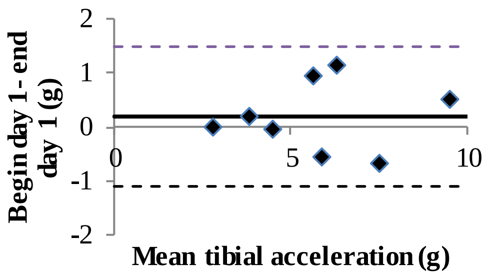
Amendment 3

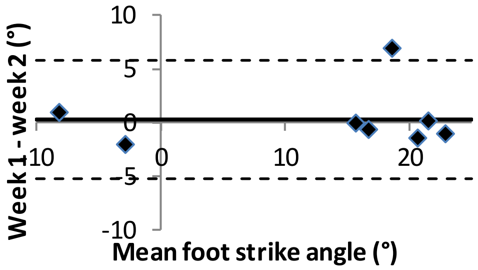
In my judgement amendment 3 should be:: Select Amendment Outcome

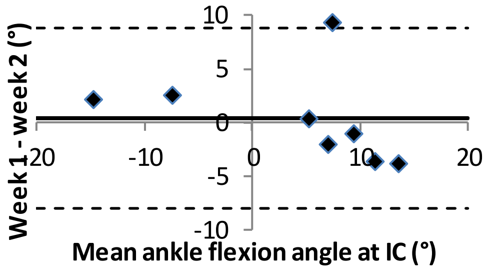
9.9 Appendix I: Bland-Altman plots

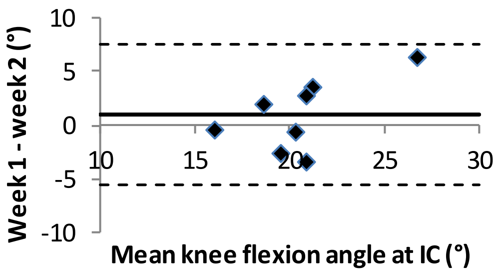
Bland-Altman plot and limit of agreement for the different variables. Variable described on x-axis.

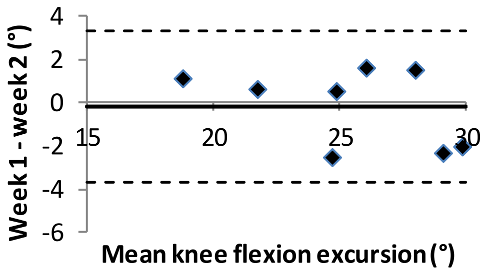


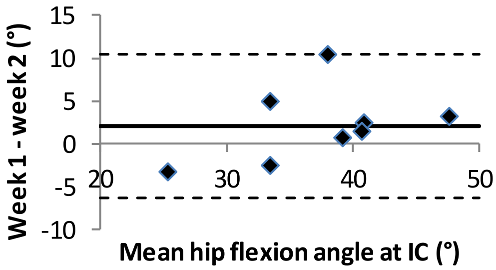


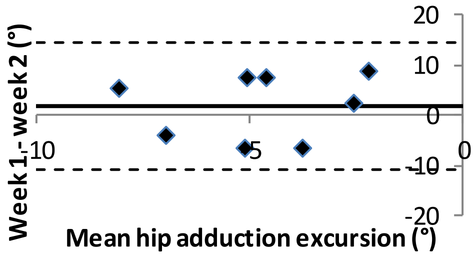


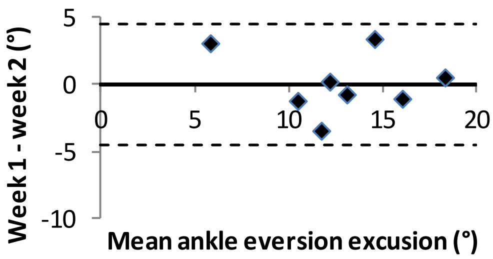


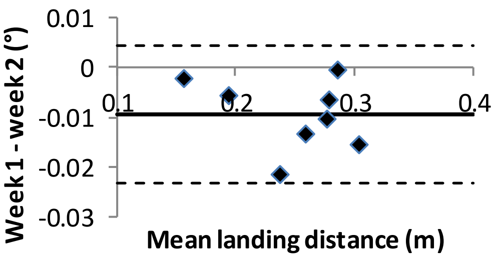


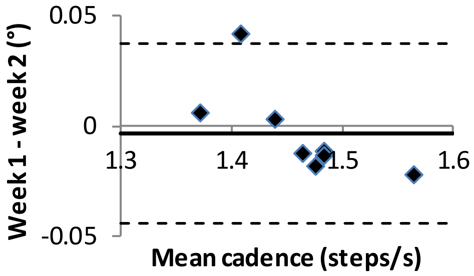


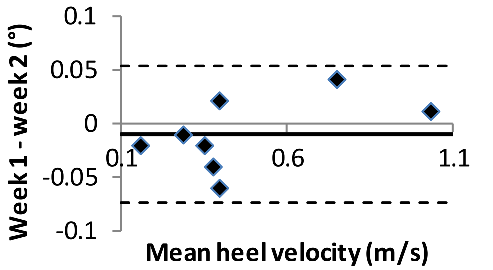


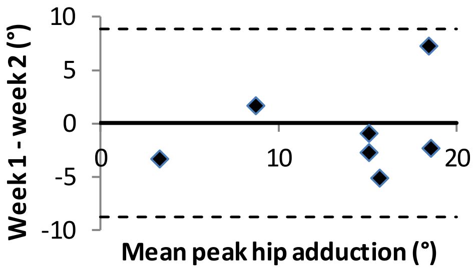


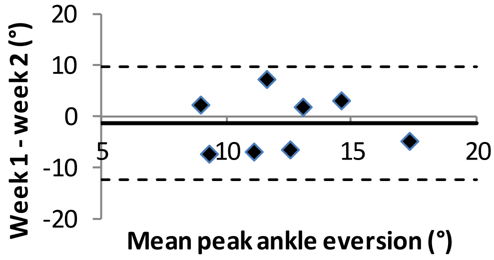





0.05
0
-0.05
1.3
1.4
1.5
1.6
Week 1 - week 2 (°)
Mean cadence (steps/s)


0.1
0.05
0
-0.05
-0.1
0.1
0.6
1.1
Week 1 - week 2 (°)
Mean heel velocity (m/s)


10
5
0
-5
-10
0
10
20
Week 1 - week 2 (°)
Mean peak hip adduction (°)


20
10
0
-10
-20
5
10
15
20
Week 1 - week 2 (°)
Mean peak ankle eversion (°)

9.10 Appendix J: Institutional ethical approval, exploratory study

Sheffield Hallam University

RESEARCH ETHICS CHECKLIST (SHUREC1)

This form is designed to help staff and postgraduate research students to complete an ethical scrutiny of proposed research. The SHU Research Ethics Policy should be consulted before completing the form.

Answering the questions below will help you decide whether your proposed research requires ethical review by a Faculty Research Ethics Committee (FREC). In cases of uncertainty, members of the FREC can be approached for advice.

Please note: staff based in University central departments should submit to the University Ethics Committee (SHUREC) for review and advice.

The final responsibility for ensuring that ethical research practices are followed rests with the supervisor for student research and with the principal investigator for staff research projects.

Note that students and staff are responsible for making suitable arrangements for keeping data secure and, if relevant, for keeping the identity of participants anonymous. They are also responsible for following SHU guidelines about data encryption and research data management.

The form also enables the University and Faculty to keep a record confirming that research conducted has been subjected to ethical scrutiny.

- For postgraduate research student projects, the form should be completed by the student and counter-signed by the supervisor, and kept as a record showing that ethical scrutiny has occurred. Students should retain a copy for inclusion in their thesis, and staff should keep a copy in the student file.
- For staff research, the form should be completed and kept by the principal investigator.

Please note if it may be necessary to conduct a health and safety risk assessment for the proposed research. Further information can be obtained from the Faculty Safety Co-ordinator.

General Details

Name of principal investigator or postgraduate research student	Linda van Gelder
SHU email address	l.v.gelder@shu.ac.uk
Name of supervisors	Ben Heller, Andrew Barnes, Jonathan Wheat

email address	hwbbh@exchange.shu.ac.uk, hwbab@exchange.shu.ac.uk,
Title of proposed research	The effect of learning while using feedback to reduce impact loading in running
Proposed start date	15th May 2017
Proposed end date	31st July 2017
Brief outline of research to include, rationale & aims (500 - 750 words).	In this pilot study we would like to receive a better insight into different aspects of learning while providing participants with biofeedback on tibial accelerations to decrease their tibial shock. Increased tibial accelerations which are a measure for tibial shock are related to tibial stress fractures (I. Davis et al., 2004). Tibial stress fractures are common overuse injuries among runners (Bennell et al., 1995) and can cause disruption to training, a reduction in physical fitness as well as increased personal frustration (Clansey et al., 2014). To overcome these negative impacts, a decrease in tibial acceleration could reduce the prevalence of this injury, since tibial acceleration is related to tibial stress fractures. One way to decrease tibial accelerations within runners is by providing them with biofeedback (Clansey et al., 2014; Creaby & Franettovich Smith, 2016; Crowell & Davis, 2011; Crowell et al., 2010; Gray et al., 2012; Wood & Kipp, 2014). Different studies found decreased tibial accelerations after participants received feedback on this parameter. In the different studies participants were asked to run on a treadmill while receiving different modes of feedback, either visual feedback, auditory feedback or a combination of these. These modes of feedback all decreased tibial shock. Visual feedback decreased tibial acceleration by: 1.64 g (Creaby & Franettovich Smith, 2016), 3.9 g (Crowell & Davis, 2011) or 0.63 g (Gray et al., 2012); auditory by: 0.6 g (Wood & Kipp, 2014) and a combination of visual and auditory by: 3.28 g (Clansey et al., 2014). However, due to the differences in characteristics of the studies these results are inappropriate to compare, therefore it remains uncertain which mode is best. A better insight into the different modes of feedback could help to inform the future development of feedback systems. With health

	care moving away from its clinical model to a self-care model (McCullagh et al., 2010) more restrictions will apply to the feedback systems. For example, systems have to be portable, which could limit the options for visual feedback, since visual feedback could be shown on a screen in the lab, but this would be more challenging in the field. Auditory and sensory feedback are therefore easier to facilitate in the field. However, there is a fundamental difference between the modes of feedback: different modes of feedback seem to have different impacts on the results depending on the task difficulty (Sigrist et al., 2013), but it remains uncertain how they compare to each other. Therefore, it is important to understand the differences between the different modes. Before we can perform a study to compare the different modes of feedback, this pilot test has to be performed to inform the methodology of such a study. At the moment it is uncertain how high peak tibial accelerations should be for participants to be able to change this parameter, how long it takes participants to learn to use the feedback and how long the learning effect lasts. In the pilot test we will ask participants to run three trials on a treadmill at their preferred running speed. Their preferred running speed will be based on the methods of Hamill et al. (Hamill et al., 1995). Participants will run on a treadmill while increasing and decreasing the speed themselves until a comfortable speed is found and participant can successfully identify the same speed (less than 0.5 m/s difference) on three successive trials. Hereafter, participants will run without receiving feedback for eight minutes, six minutes are needed to familiarize to running on the treadmill (Lavcanska et al., 2005) and the last two minutes will be used to record tibial shock data which will be used as a baseline value. Following this, participants will be asked to run again for ten minutes at their preferred speed but this time they will receive visual feedback on tibial acceleration. The multisensory feedback will consist of visual, auditory and sensory feedback. Visual feedback will be shown on a screen, together with a target line which will be at

	an healthy peak tibial acceleration value of 4.73 (I. Davis et al., 2004). If participants run with lower baseline values the target will be set at the lowest 10% percentile of their baseline values. If participants do not reach the target they will hear a sound and feel a vibration as well. Finally participants will be asked to run another ten minutes without feedback. While they run the three trials, an accelerometer will be attached to the anteromedial part of the tibia to measure tibial accelerations. The participants will be asked to return to the lab for a 6 minute warming up and a 10 minute run trial without feedback after one day and after one week to measure the learning effect. **References** [1] I. Davis, C.E. Milner, J. Hamill, Does Increased Loading During Running Lead to Tibial Stress Fractures? A Prospective Study, Med. Sci. Sport. Exerc. 36 (2004) S58. doi:http://dx.doi.org/10.1097/00005768-200405001-00271. [2] K.L. Bennell, S. a Malcolm, S. a Thomas, J.D. Wark, P.D. Brukner, The incidence and distribution of stress fractures in competitive track and field athletes. A twelve-month prospective study., Am. J. Sports Med. 24 (1995) 211–7. doi:10.1177/036354659602400217. [3] A.C. Clansey, M. Hanlon, E.S. Wallace, A. Nevill, M.J. Lake, Influence of Tibial shock feedback training on impact loading and running economy, Med. Sci. Sports Exerc. 46 (2014) 973–981. doi:10.1249/MSS.0000000000000182. [4] M.W. Creaby, M.M. Franettovich Smith, Retraining running gait to reduce tibial loads with clinician or accelerometry guided feedback, J. Sci. Med. Sport. 19 (2016) 288–292. doi:10.1016/j.jsams.2015.05.003. [5] H.P. Crowell, I.S. Davis, Gait retraining to reduce lower extremity loading in runners, Clin. Biomech. 26 (2011) 78–83. doi:10.1016/j.clinbiomech.2010.09.003. [6] H.P. Crowell, C.E. Milner, J. Hamill, I.S. Davis, Reducing impact loading during running with the use of real-time visual feedback., J. Orthop. Sports Phys. Ther. 40 (2010) 206–213. doi:10.2519/jospt.2010.3166.

	[7] M. Gray, E; Sweeney, M; Creaby,M; Smith, Gait retraining using visual and verbal feedback in runners, 30Th Annu. Conf. Biomech. Sport. (2012) 262–263. [8] C.M. Wood, K. Kipp, Use of audio biofeedback to reduce tibial impact accelerations during running, J. Biomech. 47 (2014) 1739–1741. doi:10.1016/j.jbiomech.2014.03.008. [9] P.J. McCullagh, C.D. Nugent, H. Zheng, W.P. Burns, R.J. Davies, N.D. Black, P. Wright, M.S. Hawley, C. Eccleston, S.J. Mawson, G.A. Mountain, Promoting Behaviour Change in Long Term conditions Using a Self-management Platform, in: Des. Incl. Interact., Springer, London, 2010: pp. 229–238. [10] R. Sigrist, G. Rauter, R. Riener, P. Wolf, Augmented visual, auditory, haptic, and multimodal feedback in motor learning: A review, Psychon. Bull. Rev. 20 (2013) 21–53. doi:10.3758/s13423-012-0333-8. [11] J. Hamill, T.R. Derrick, K.G. Holt, Shock attenuation and stride frequency during running, Hum. Mov. Sci. 14 (1995) 45–60. doi:10.1016/0167-9457(95)00004-C. [12] V. Lavcanska, N.F. Taylor, A.G. Schache, Familiarization to treadmill running in young unimpaired adults, Hum. Mov. Sci. 24 (2005) 544–557. doi:10.1016/j.humov.2005.08.001.
Where data is collected from human participants, outline the nature of the data, details of anonymisation, storage and disposal procedures if these are required (300 -750 words).	In this research participants will be asked to run on a treadmill. From the run trials tibial acceleration data will be recorded with a sample rate of 1000Hz and stored on a laptop. For each participant a measurement log will be made in which height, weight and date of birth are noted together with the recorded acceleration trial names. The data will be anonymised by using a code on the measurement log instead of the name. The code will relate to one name of one participant which could be found in a separate document. All digital data will be stored in a confidential folder on the Q-drive which can only be reached by the contributing researchers. The data will be processed on a password protected laptop from the university. The data will be processed with the use of programs

	including LabView, Matlab and SPSS. Non-digital data will be protected and stored in a locked cabinet in Chestnut Court S001 on collegiate campus. All data will only be used for academic purposes. The data will be kept confidentiality for three years (duration of program of research) after publication. No access to the data will be granted without approval from a member of the team or the participants.
Will the research be conducted with partners & subcontractors?	**No** (If **YES**, outline how you will ensure that their ethical policies are consistent with university policy.)

1. Health Related Research involving the NHS or Social Care / Community Care or the Criminal Justice System or with research participants unable to provide informed consent

Question		Yes/No
1.	Does the research involve? • Patients recruited because of their past or present use of the NHS or Social Care • Relatives/carers of patients recruited because of their past or present use of the NHS or Social Care • Access to data, organs or other bodily material of past or present NHS patients • Foetal material and IVF involving NHS patients • The recently dead in NHS premises • Prisoners or others within the criminal justice system recruited for health- related research* • Police, court officials, prisoners or others within the criminal justice system* • Participants who are unable to provide informed consent due to their incapacity even if the project is not health related	NO
2.	Is this a research project as opposed to service evaluation or audit? *For NHS definitions please see the following website* http://www.nres.nhs.uk/applications/is-your-project-research/	NO

If you have answered **YES** to questions **1 & 2** then you **must** seek the appropriate external approvals from the NHS, Social Care or the National Offender Management Service (NOMS) under their independent Research Governance schemes. Further information is provided below.

NHS https://www.myresearchproject.org.uk/Signin.aspx

* Prison projects may also need National Offender Management Service (NOMS) Approval and Governor's Approval and may need Ministry of Justice approval. Further guidance at:
http://www.hra.nhs.uk/research-community/applying-for-approvals/national-offender-management-service-noms/

NB FRECs provide Independent Scientific Review for NHS or SC research and initial scrutiny for ethics applications as required for university sponsorship of the research. Applicants can use the NHS proforma and submit this initially to their FREC.

2. Research with Human Participants

Question		**Yes/No**
1.	Does the research involve human participants? This includes surveys, questionnaires, observing behaviour etc. *Note* *If YES, then please answer questions 2 to 10* *If NO, please go to Section 3*	YES
2.	Will any of the participants be vulnerable? *Note* *'Vulnerable' people include children and young people, people with learning disabilities, people who may be limited by age or sickness or disability, etc. See definition*	NO
3	Are drugs, placebos or other substances (e.g. food substances, vitamins) to be administered to the study participants or will the study involve invasive, intrusive or potentially harmful procedures of any kind?	NO
4	Will tissue samples (including blood) be obtained from participants?	NO
5	Is pain or more than mild discomfort likely to result from the study?	NO
6	Will the study involve prolonged or repetitive testing?	NO
7	Is there any reasonable and foreseeable risk of physical or emotional harm to any of the participants? *Note* *Harm may be caused by distressing or intrusive interview questions, uncomfortable procedures involving the participant, invasion of privacy, topics relating to highly personal information, topics relating to illegal activity, etc.*	NO
8	Will anyone be taking part without giving their informed consent?	NO
9	Is it covert research? *Note* *'Covert research' refers to research that is conducted without the knowledge of participants.*	NO
10	Will the research output allow identification of any individual who has not given their express consent to be identified?	NO

If you answered **YES only** to question **1,** you must complete the box below and submit the signed form to the FREC for registration and scrutiny.

Data Handling
Where data is collected from human participants, outline the nature of the data, details of anonymisation, storage and disposal procedures if these are required (300 -750 words). See above

If you have answered **YES** to any of the other questions you are **required** to submit a SHUREC2A (or 2B) to the FREC. If you answered **YES** to question **8** and participants cannot provide informed consent due to their incapacity you must obtain the appropriate approvals from the NHS research governance system.

3. Research in Organisations

Question		**Yes/No**
1	Will the research involve working with/within an organisation (e.g. school, business, charity, museum, government department, international agency, etc.)?	NO
2	If you answered YES to question 1, do you have granted access to conduct the research? *If YES, students please show evidence to your supervisor. PI should retain safely.*	
3	If you answered NO to question 2, is it because: A. you have not yet asked B. you have asked and not yet received an answer C. you have asked and been refused access.	NA
Note	*You will only be able to start the research when you have been granted access.*	

4. Research with Products and Artefacts

Question		**Yes/No**
1.	Will the research involve working with copyrighted documents, films, broadcasts, photographs, artworks, designs, products, programmes, databases, networks, processes, existing datasets or secure data?	NO

2. If you answered YES to question 1, are the materials you intend to use in the public domain? *Notes ‘In the public domain’ does not mean the same thing as ‘publicly accessible’.* – *Information which is 'in the public domain' is no longer protected by copyright (i.e. copyright has either expired or been waived) and can be used without permission.* – *Information which is 'publicly accessible' (e.g. TV broadcasts, websites, artworks, newspapers) is available for anyone to consult/view. It is still protected by copyright even if there is no copyright notice. In UK law, copyright protection is automatic and does not require a copyright statement, although it is always good practice to provide one. It is necessary to check the terms and conditions of use to find out exactly how the material may be reused etc.* *If you answered YES to question 1, be aware that you may need to consider other ethics codes. For example, when conducting Internet research, consult the code of the Association of Internet Researchers; for educational research, consult the Code of Ethics of the British Educational Research Association.*	
3. If you answered NO to question 2, do you have explicit permission to use these materials as data? *If YES, please show evidence to your supervisor. PI should retain permission.*	NA
4. If you answered NO to question 3, is it because: A. you have not yet asked permission B. you have asked and not yet received and answer C. you have asked and been refused access. *Note You will only be able to start the research when you have been granted permission to use the specified material.*	NA

Adherence to SHU policy and procedures

Personal statement	
I can confirm that: – I have read the Sheffield Hallam University Research Ethics Policy and Procedures – I agree to abide by its principles.	
Student / Researcher/ Principal Investigator (as applicable)	
Name: Linda van Gelder	Date: 25-05-2017
Signature:	

Supervisor or other person giving ethical sign-off	
I can confirm that completion of this form has not identified the need for ethical approval by the FREC or an NHS, Social Care or other external REC. The research will not commence until any approvals required under Sections 3 & 4 have been received.	
Name:	Date:
Signature:	
Additional Signature if required:	
Name:	Date:
Signature:	

Please ensure the following are included with this form if applicable, tick box to indicate:

	Yes	No	N/A
Research proposal if prepared previously	☐	☐	x
Any recruitment materials (e.g. posters, letters, etc.)	x	☐	☐
Participant information sheet	x	☐	☐
Participant consent form	x	☐	☐
Details of measures to be used (e.g. questionnaires, etc.)	x	☐	☐
Outline interview schedule / focus group schedule	☐	☐	x
Debriefing materials	☐	☐	x
Health and Safety Project Safety Plan for Procedures	x	☐	☐
Data Management Plan*	x	☐	

If you have not already done so, please send a copy of your Data management Plan to rdm@shu.ac.uk
It will be used to tailor support and make sure enough data storage will be available for your data.
Completed form to be sent to Relevant FREC. Contact details on the website.

9.11 Appendix K: Pre-screening questionnaire, exploratory study

Sheffield Hallam University | Centre for Sports Engineering Research

Pre-Test Medical Questionnaire

The effect of learning while using feedback to reduce impact loading in running

Participant number: ____

Date of Birth: ___________ Age: _____________Sex: _______________

Please answer the following questions by putting a circle round the appropriate response or filling in the blank.

1. How would you describe your present level of activity?
   Sedentary / Moderately active / Active / Highly active

2. How would you describe you present level of fitness?
   Unfit / Moderately fit / Trained / Highly trained

3. How would you consider your present body weight?
   Underweight / Ideal / Slightly over / Very overweight

4. How often do you run? …….. times a week

5. How many kilometres do you run during a week: ……... km

6. Smoking Habits

Smoking Habits	Are you currently a smoker?	Yes / No
	How many do you smoke	…….. per day
	Are you a previous smoker?	Yes / No
	How long is it since you stopped?	.... years
	Were you an occasional smoker?	Yes / No
		.... per day
	Were you a regular smoker?	Yes / No
		.... per day

7. Do you drink alcohol? Yes / No
   If you answered **Yes**, do you usually have?
   An occasional drink / a drink every day / more than one drink a day?

8. Have you had to consult your doctor within the last six months? Yes / No
   If you answered **Yes**, please give details………………………………….…….
   ……………………………………….………….……………….……….…………
   ……………………………………….………….……………….……….…………

9. Are you presently taking any form of medication? Yes / No
If you answered **Yes**, please give details……………………………….…….
……………………………………….……….……….……………….………….………
……………………………………….……….……….……………….………….………

10. As far as you are aware, do you suffer or have you ever suffered from:

a Diabetes?	Yes / No	**b** Asthma?	Yes / No
c Epilepsy?	Yes / No	**d** Bronchitis?	Yes / No
e *Any of heart complaint?	Yes / No	**f** Raynaud's Disease	Yes / No
g *Marfan's Syndrome?	Yes / No	**h** *Aneurysm/embolism?	Yes / No
i Anaemia	Yes / No	**j** Renal dysfunction	Yes / No

11. * Is there a history of heart disease in your family? Yes / No

12. *Do you currently have any form of muscle or joint injury? Yes / No
If you answered **Yes**, please give details……………………………….…….
……………………………………….……….……….……………….…………
……………………………………….……….……….……………….……..…..

13. Have you had to suspend your normal training in the last two weeks? Yes / No
If the answer is **Yes** please give details……………………………………….……..
……………………………………….……….……….……………….…………..……
……………………………………….……….……….……………….…………..……

14. As far as you are aware, is there anything that might prevent you from successfully completing the tests that have been outlined to you? Yes / No

---

IF THE ANSWER TO ANY OF THE ABOVE IS YES THEN:
a) Discuss the nature of the problem with the Principal Investigator.

As far as I am aware the information I have given is accurate.

Signature: ………………………………………………………………...

Date: ……/……/……

9.12 Appendix L: Informed consent, exploratory study

Sheffield Hallam University | Centre for Sports Engineering Research

Participant Informed Consent Form

STUDY: **The effect of learning while using feedback to reduce impact loading in running**

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 at any time, 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 researcher 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): ____________________________

Researcher's Signature: ____________________________

Researcher's contact details:
The Centre for Sports Engineering Research | Faculty of Health & Wellbeing | Sheffield Hallam University |11 Broomgrove Road | S10 2LX Sheffield
Email: l.v.gelder@shu.ac.uk | Tel: +44 (0)114 225 2355
Please keep your copy of the consent form and the information sheet together.

9.13 Appendix M: Measurement log

Sheffield Hallam University | Centre for Sports Engineering Research

The effect of learning while using feedback to reduce impact loading in running

Name: ____

PP number: ____

Sheffield Hallam University | Centre for Sports Engineering Research

Measurement log

The effect of learning while using feedback to reduce impact loading in running

Participant number: ____

Length: _____________________ Weight: ____________________

Mean Tibial acceleration: ______ Target : ____________________

Treadmill speed:_____________

Data

Day 1		
Trial	*Trial Name*	*Notes*
Baseline trial		
Feedback trial		
Non feedback trial		

Day 2		
Trial	*Trial Name*	*Notes*
Non feedback trial		

Day 8		
Trial	*Trial Name*	*Notes*
Non feedback trial		

Sheffield Hallam University | Centre for Sports Engineering Research

Measurement log

The effect of learning while using feedback to reduce impact loading in running

Was it easy to reach the target? If not, how did that make you feel?

____

____

Did you prefer any form of feedback?

____

____

Where did you focus on?

____

____

Do you think the feedback could be better?

____

____

Was the preferred running speed ok for you?

____

____

Any other comments?

____

____

9.14 Appendix N: Measurement log

Sheffield Hallam University | Centre for Sports Engineering Research

The effect of biofeedback on changing a running pattern, study 4

Name: ____

PP number: ____

Sheffield Hallam University | Centre for Sports Engineering Research

Measurement log

The effect of biofeedback on changing a running pattern

Participant number: ____

Length: ______________________ Weight: _____________________

Treadmill speed: _____________ Mean Tibial acceleration: ______

Target trial 2: _________________ Target trial 3: _________________

Data

Day 1		
Trial	*Trial Name*	*Notes*
Baseline trial		
Feedback trial moving target		
Feedback trial fixed target		
Non feedback trial		

Sheffield Hallam University | Centre for Sports Engineering Research

Measurement log

The effect of biofeedback on changing a running pattern

Was it easy to reach the target? If not, how did that make you feel?

____

____

Where do you think feedback was given on?

____

____

Did you prefer any form of feedback? Where did you focus on?

____

____

Do you think the feedback could be better?

____

____

Was the preferred running speed ok for you?

____

____

Any other comments?

____

____

9.15 Appendix O: Pre-screening questionnaire intervention study

Sheffield Hallam University | Centre for Sports Engineering Research

Pre-Parkrun Questionnaire

Exploring different strategies participants use to reduce tibial acceleration

Name: ______________________________ Age: _____________

Please answer the following questions by putting a circle round the appropriate response or filling in the blank.

1. How many times do you run during a typical week? ….. times a week

2. How many kilometres or miles do you run during a typical week: ....km/mi

3. Do you currently have any form of muscle or joint injury? Yes / No
   If you answered Yes, please give details ……..……………………………..
   …………………………………………………………………………………
   …………………………………………………………………………………
   …………………………………………………………………………………
   …………………………………………………………………………………

4. Do you have any previous running-related injuries? For example: stress fractures, inflamed tendons, ACL injuries, etc. Please state the type of injury, how long ago it occurred and duration. Yes / No
   If you answered Yes, please give details ……….……………………………
   ……………………………………………………..……………………...…
   ……………………………………………………..……………………...
   ……………………………………………………..…………………...
   …………………………………………………………….…………………
   …………………………………………………………………………………

5. Are you allergic to tape or cohesive bandage? Yes / No

6. As far as you are aware, is there anything that might prevent you from successfully completing the tests that have been outlined to you? Yes/No
   If you answered Yes, please give details …………………………………….
   …………………………………………………………………………………
   …………………………………………………………………………………
   …………………………………………………………………………………
   …………………………………………………………………………………
   …………………………………………………………………………………

9.16 Appendix P: Informed consent intervention study

Sheffield Hallam University | Centre for Sports Engineering Research

Participant Informed Consent Form

STUDY: **Exploring different types of biofeedback and strategies participants use to reduce tibial acceleration**

Please answer the following questions by ticking the response that applies

	YES	NO
7. I have read the Information Sheet for this study and have had details of the study explained to me.	☐	☐
8. My questions about the study have been answered to my satisfaction and I understand that I may ask further questions at any point.	☐	☐
9. I understand that I am free to withdraw from the study at any time, 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.	☐	☐
10. I agree to provide information to the researcher under the conditions of confidentiality set out in the Information Sheet.	☐	☐
11. I wish to participate in the study under the conditions set out in the Information Sheet.	☐	☐
12. 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): ___________________________________

Researcher's Signature: _______________________________________

Researcher's contact details:
The Centre for Sports Engineering Research | Faculty of Health & Wellbeing | Sheffield Hallam University |11 Broomgrove Road | S10 2LX Sheffield
Email: l.v.gelder@shu.ac.uk | Tel: +44 (0)114 225 2355

Please keep your copy of the consent form and the information sheet together.

9.17 Appendix Q: Individual learning response to a biofeedback intervention

Participant 1 showed a real decrease in mean peak tibial acceleration comparing the retention measurement to the baseline measurement for the first session (Figure 6.4), suggesting a fast learning response. In the first three sessions, a real increase in mean peak tibial acceleration was found comparing the measurement taken during the Stroop test to the retention measurement, suggesting the task (reducing tibial acceleration) was not automatized. In session 4, no increase in mean peak tibial acceleration was found comparing the measurement taken during the Stroop test to the retention measurement. This indicates that the task, reducing tibial acceleration, was automatized and a cognitive demand was no longer needed. This was confirmed by a real decrease in mean peak tibial acceleration of the baseline measurement of the fifth session, compared to the baseline measurement of the first session. In the fifth session, the participant showed a further decrease in mean peak tibial acceleration, comparing the retention measurement to the baseline measurement, suggesting the participant was still exploring different solutions. A real decrease in mean peak tibial acceleration was found from the baseline measurement of the first session to the baseline measurement of the seventh session, suggesting a slow learning effect.

Comparing the retention measurement taken directly after the intervention to the baseline measurement the shock-absorbing mechanism existed of increases in ankle plantarflexion at initial contact and cadence, and a decrease in heel velocity at initial contact (Figure 9.9, Table 9.1). An increase in ankle plantarflexion at initial contact was also found comparing the retention measurement taken after a month to the baseline measurement, but on the contrary, increases in knee flexion excursion and ankle eversion excursion were shown. Concerning parameters related to injuries, the participant found a real increase in peak hip adduction from the baseline session to the retention measurement after a month.

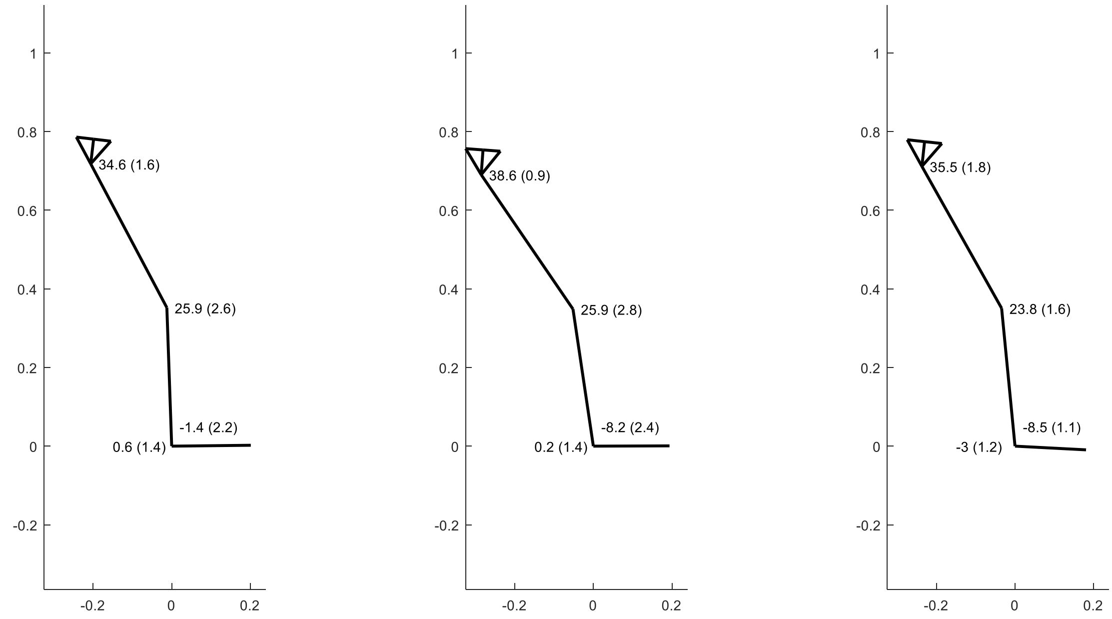


Figure 9.9 Stick figures displaying the foot contact, ankle, knee and hip angle. From left to right: baseline measurement, retention test direct after the feedback intervention, and retention test after a month.

Table 9.1 Mean and standard deviation for the parameters of interest for the different measurements.

Variable	Baseline Mean (SD)	Retention after intervention Mean (SD)	Retention after month Mean (SD)
Peak tibial acceleration (g)	6.5 (1.1)	3.2 (0.4) *	4.7 (0.6) *†
Foot strike angle (°)	0.6 (1.4)	0.2 (1.4)	-3.0 (1.3)
Ankle dorsiflexion IC (°)	-1.4 (2.2)	-8.2 (2.4) *	-8.5 (1.1) *
Knee flexion IC (°)	25.9 (2.6)	25.9 (2.9)	23.8 (1.6)
Knee flexion excursion (°)	18.2 (2.7)	17.9 (2.3)	20.2 (2.0) *†
Hip flexion IC (°)	34.6 (1.6)	38.6 (1.0)	35.5 (1.8)
Hip adduction excursion (°)	4.8 (1.0)	5.5 (1.0)	3.3 (0.8) *†
Ankle eversion excursion (°)	8.4 (3.4)	10.4 (3.2)	12.0 (1.5) *
Landing distance (m)	0.15 (0.02)	0.17 (0.01) *	0.17 (0.01) *
Cadence (steps/s)	1.46 (0.02)	1.48 (0.02) *	1.44 (0.02) †
Heel velocity IC (m/s)	0.53 (0.08)	0.43 (0.06) *	0.67 (0.06) *†
Peak hip adduction (°)	15.9 (1.3)	16.1 (1.0)	22.4 (1.2) *
Peak ankle eversion (°)	5.0 (0.9)	6.9 (0.9)	4.3 (1.2)

IC = Initial contact, SD = standard deviation, * = real difference between retention measurement and baseline measurement, † = real difference between retention measurement taken directly after the measurement and retention taken after a month, IC = initial contact

Participant 2 showed a real decrease in mean peak tibial acceleration from the baseline measurement to the retention measurement within the first session (Figure 9.10), suggesting a fast learning response. An increase in mean peak tibial acceleration comparing the measurement taken during the Stroop test to the baseline measurement was found for every session during the intervention, suggesting the reduction in mean peak tibial acceleration was not automatized in the six sessions. Comparing the baseline measurement of the fifth, sixth, and seventh session to the baseline measurement of the first session a reduction in mean peak tibial acceleration was found, suggesting a slow learning response. Taking these results together, it appears the participant was able to reduce tibial acceleration (baseline session 2, 5 and 6), but a cognitive demand was needed. In the seventh session, the mean peak tibial acceleration was remarkably lower during the baseline measurement compared to the baseline measurements of the first sixth sessions. No real increase was found in mean peak tibial acceleration during the Stroop test, compared to the baseline measurement in the seventh session, suggesting the task was automatized. These results suggest that the participant found a strategy after the feedback intervention.

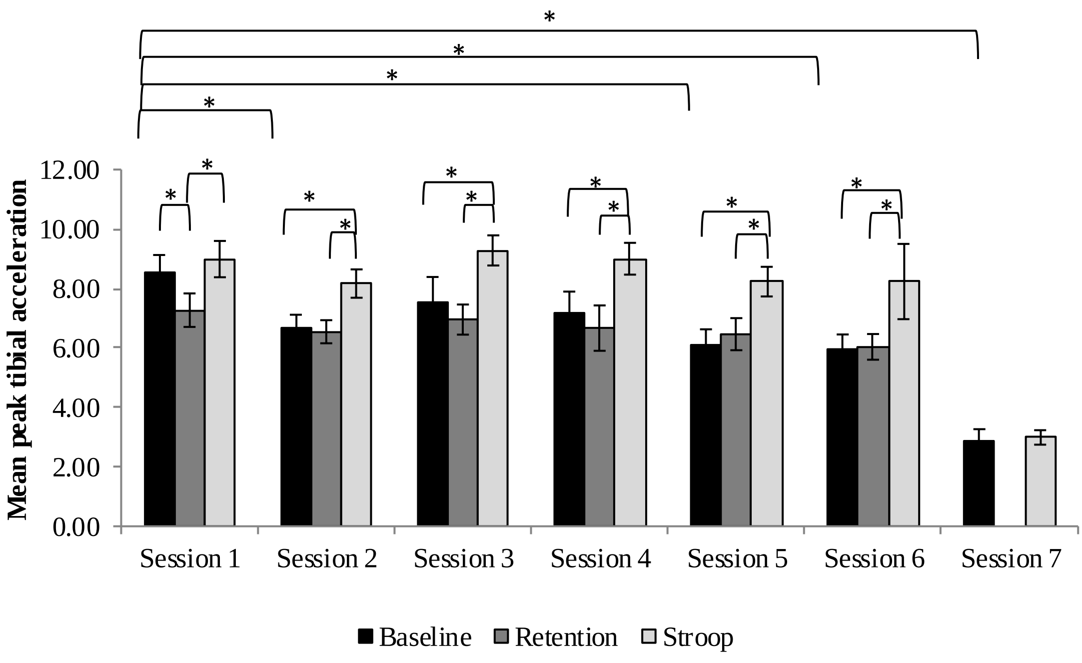


Figure 9.10 Mean peak tibial acceleration for each measurement for each session. * = real difference between measurements. Compared measurements within a session and baseline measurements of each session to the first session.

From the baseline measurement to the retention measurement taken directly after the intervention a real increase in foot strike angle was found (Figure 9.11, Table 9.2). This was accompanied by an increase in knee extension at initial contact and knee flexion excursion, and a decrease in heel velocity at initial contact. Comparing the measurement taken during the one-month retention measurement to the baseline measurement the participant went from a rearfoot to a midfoot contact pattern. This was accompanied by a real increase in knee flexion at initial contact, and a real decrease in landing distance, knee flexion excursion, and heel velocity at initial contact. Concerning parameters related to injuries, the participant found a real increase in peak ankle eversion from the baseline measurement to the retention measurement taken directly after the feedback intervention.

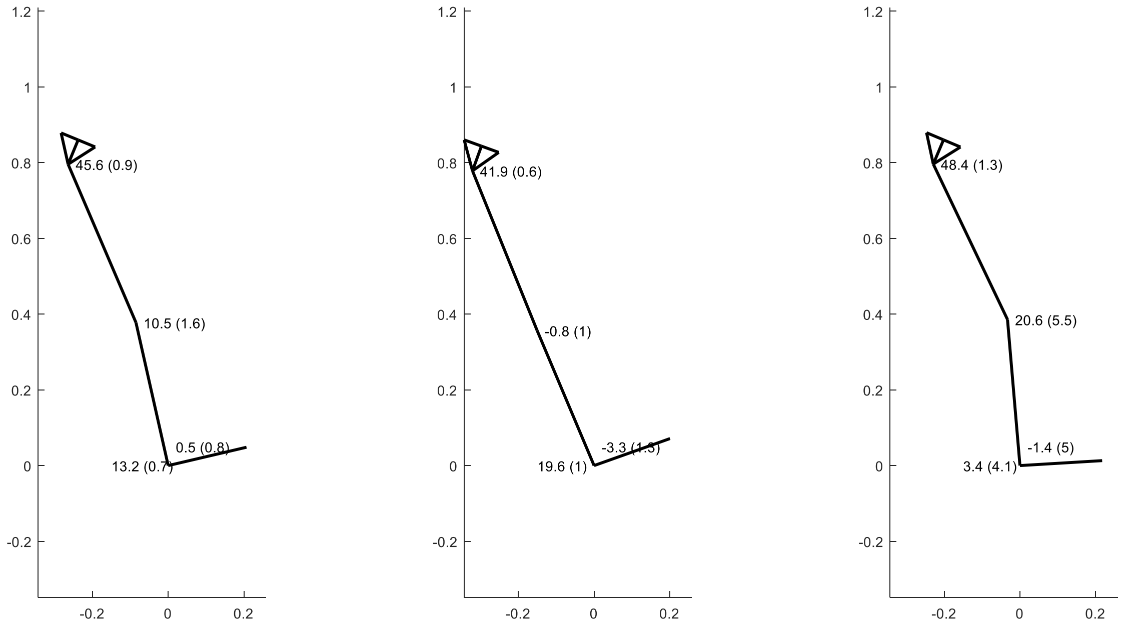


Figure 9.11 Stick figures displaying the foot contact, ankle, knee and hip angle. From left to right: baseline measurement, retention test direct after the feedback intervention, and retention test after a month.

Table 9.2 Mean and standard deviation for the parameters of interest for the different measurements.

Variable	Baseline Mean (SD)	Retention after intervention Mean (SD)	Retention after month Mean (SD)
Peak tibial acceleration (g)	8.6 (0.6)	6.0 (0.4) *	2.9 (0.4) *†
Foot strike angle (°)	13.2 (0.7)	19.6 (1.0) *	3.4 (4.1) *†
Ankle dorsiflexion IC (°)	0.5 (0.8)	-3.3 (1.3)	-1.4 (5.0)
Knee flexion IC (°)	10.5 (1.6)	-0.8 (1.0) *	20.6 (5.5) *†
Knee flexion excursion (°)	26.9 (1.6)	30.8 (1.0) *	15.7 (5.9) *†
Hip flexion IC (°)	45.6 (0.9)	41.9 (0.6)	48.4 (1.3) †
Hip adduction excursion (°)	3.5 (0.5)	4.1 (0.7)	4.3 (0.7)
Ankle eversion excursion (°)	11.3 (1.1)	10.7 (2.3)	4.3 (5.6) *†
Landing distance (m)	0.26 (0.01)	0.27 (0.01)	0.26 (0.04) *†
Cadence (steps/s)	1.48 (0.02)	1.44 (0.02) *	1.45 (0.06) *
Heel velocity IC (m/s)	0.16 (0.04)	0.07 (0.02) *	0.11 (0.09) *
Peak hip adduction (°)	13.9 (0.3)	14.2 (0.5)	20.0 (0.5)
Peak ankle eversion (°)	5.0 (0.7)	15.2 (0.6) *	11.8 (1.1)

IC = Initial contact, SD = standard deviation, * = real difference between retention measurement and baseline measurement, † = real difference between retention measurement taken directly after the measurement and retention taken after a month, IC = initial contact

Participant 3 showed a real decrease in mean peak tibial acceleration comparing the retention measurement to the baseline measurement for the first session, suggesting a fast learning response (Figure 9.12). A real increase in mean peak tibial acceleration in the measurement during the Stroop test compared to the retention measurement in the first session suggests, however, that the task (reducing tibial acceleration) was not automatized. In the second session, no real increase in mean peak tibial acceleration was found comparing the measurement taken during the Stroop test to the retention measurement, suggesting the task of reducing tibial acceleration was automatized. In session 3 and 4 a further real decrease in mean peak tibial acceleration was found in the retention measurement compared to the baseline measurement, suggesting participants were still exploring different solutions. A real decrease in mean peak tibial acceleration was found comparing the one-month follow-up measurement to the baseline measurement of the first session, suggesting a slow learning response.

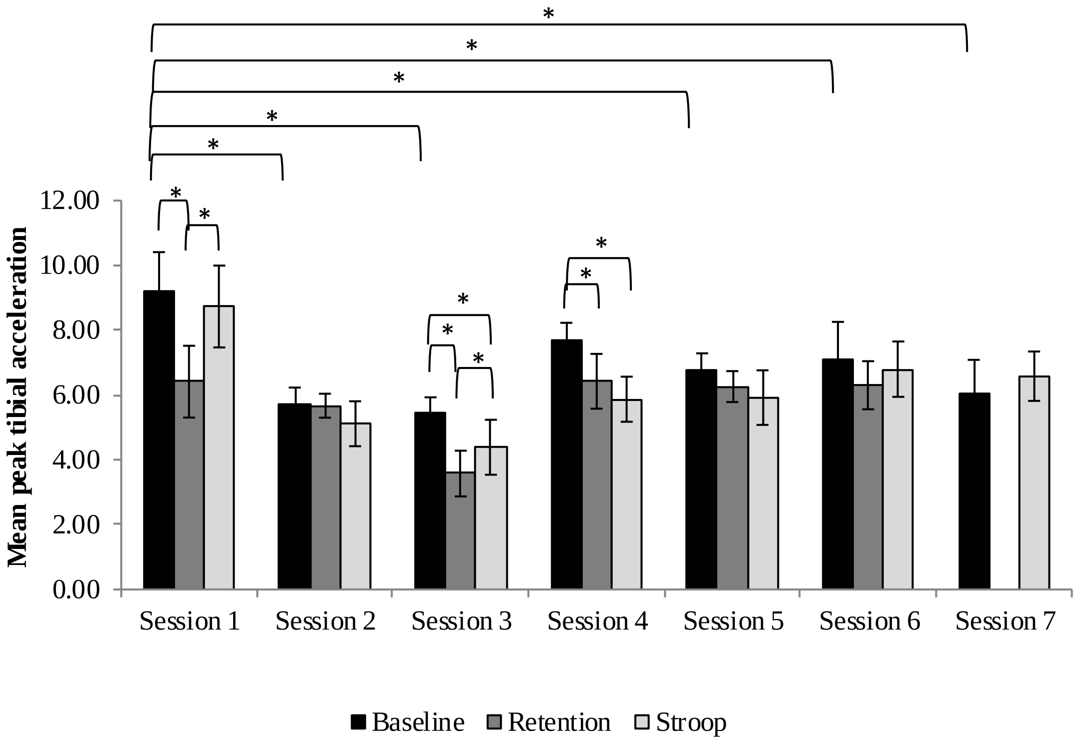


Figure 9.12 Mean peak tibial acceleration for each measurement for each session. * = real difference between measurements. Compared measurements within a session and baseline measurements of each session to the first session.

Focusing on the kinematic and spatiotemporal data, the participant used different strategies to decrease tibial acceleration when comparing both retention measurements to the baseline measurement (Figure 9.13, Table 9.3). A real decrease in heel velocity at initial contact was found for both retention measurements to the baseline measurement. However, comparing the retention measurement taken after a month to the baseline measurement a real difference was shown in knee flexion excursion. Comparing the retention measurement taken directly after the feedback intervention to the baseline measurement a real increase was shown in ankle eversion excursion, both being different shock-absorbing strategies. Concerning parameters related to injuries, the participant found a real decrease in peak hip adduction from the baseline measurement to both retention measurements. The participant further found a real increase in peak ankle eversion comparing the retention measurement taken directly after the feedback intervention to the baseline measurement.

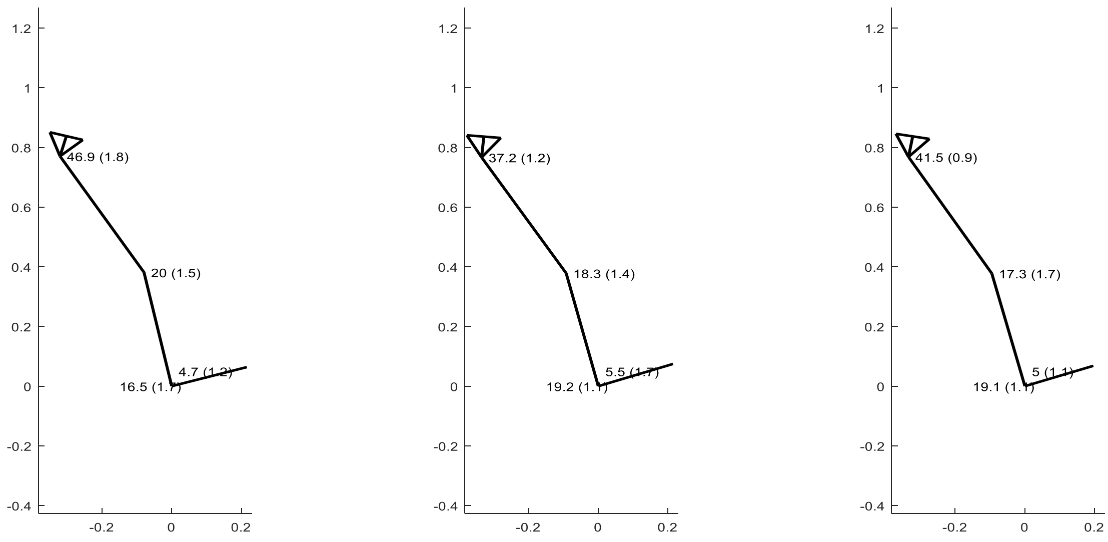


Figure 9.13 Stick figures displaying the foot contact, ankle, knee and hip angle. From left to right: baseline measurement, retention test direct after the feedback intervention, and retention test after a month.

Table 9.3 Mean and standard deviation for the parameters of interest for the different measurements.

Variable	Baseline Mean (SD)	Retention after intervention Mean (SD)	Retention after month Mean (SD)
Peak tibial acceleration (g)	9.2 (1.2)	6.3 (0.7) *	6.1 (1.0) *
Foot strike angle (°)	16.5 (1.7)	19.2 (1.1)	19.1 (1.1)
Ankle dorsiflexion IC (°)	4.7 (1.2)	5.5 (1.7)	5.0 (1.1)
Knee flexion IC (°)	20.0 (1.5)	18.3 (1.4)	17.3 (1.7)
Knee flexion excursion (°)	20.8 (1.7)	22.7 (1.4)	24.8 (1.5) *
Hip flexion IC (°)	46.9 (1.8)	37.2 (1.2) *	41.5 (0.9)
Hip adduction excursion (°)	10.9 (0.9)	5.8 (1.8) *	9.9 (0.8) †
Ankle eversion excursion (°)	11.8 (1.6)	20.4 (4.3) *	12.7 (1.2) †
Landing distance (m)	0.27 (0.01)	0.29 (0.01) *	0.29 (0.01) *
Cadence (steps/s)	1.42 (0.02)	1.41 (0.03)	1.39 (0.03) *
Heel velocity IC (m/s)	0.30 (0.06)	0.21 (0.04) *	0.22 (0.04) *
Peak hip adduction (°)	28.2 (1.1)	19.7 (0.8) *	18.6 (0.6) *
Peak ankle eversion (°)	3.7 (1.0)	11.6 (1.1) *	11.0 (0.7)

IC = Initial contact, SD = standard deviation, * = real difference between retention measurement and baseline measurement, † = real difference between retention measurement taken directly after the measurement and retention taken after a month, IC = initial contact

Participant 4 had only five feedback sessions, with the fifth feedback session missing due to malfunctioning of the system. In the first session, a real increase in mean peak tibial acceleration was found comparing the retention measurement to the baseline measurement (Figure 9.14). Compared to the baseline measurement of the first session a real increase in mean peak tibial acceleration was found for all the other baseline measurements of the other sessions. It should be noted the first baseline measurement of mean peak tibial acceleration was relatively low compared to the other participants. In conclusion, participant 4 was not able to reduce mean peak tibial acceleration, instead, an increase in mean peak tibial acceleration was found over the sessions.

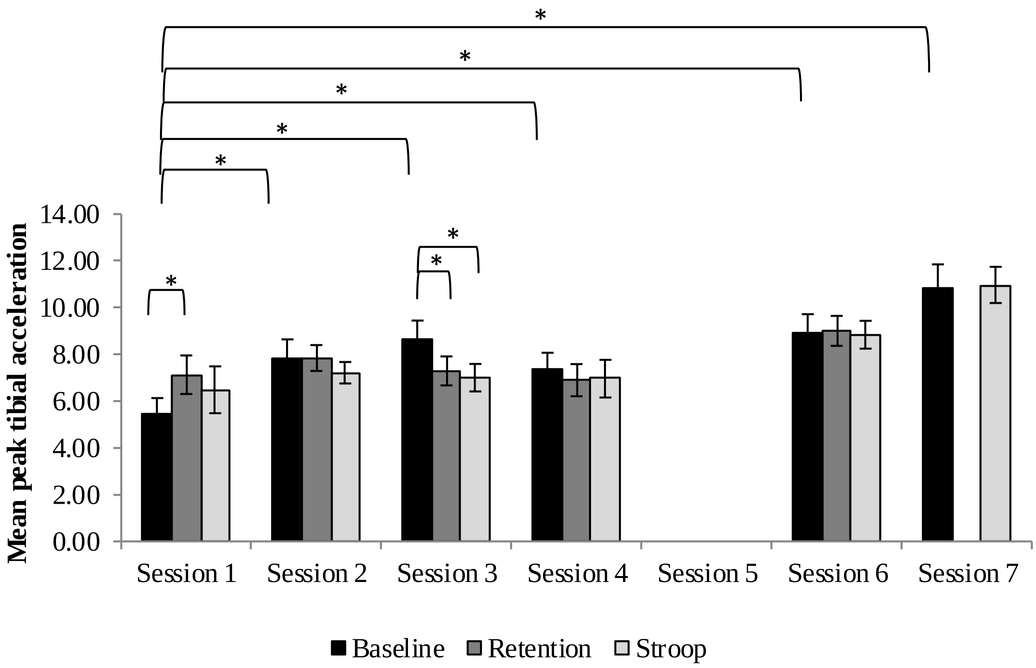


Figure 9.14 Mean peak tibial acceleration for each measurement for each session. * = real difference between measurements. Compared measurements within a session and baseline measurements of each session to the first session.

Participant 4 found a similar strategy to increase tibial acceleration at both measurements taken during the retention tests, compared to the baseline measurement. Compared to the baseline measurement, for both measurements taken during the retention tests, a real decrease was found for heel velocity at initial contact and a real increase in cadence and hip adduction excursion (Figure 9.15, Table 9.4). These differences are differences you would expect for a participant who would be able to reduce mean peak tibial acceleration, this participant, however, increased mean peak tibial acceleration over the sessions. However, though some parameters changed, others did not, an increased cadence and increased plantarflexion, which was found comparing the measurement taken during the retention test after a month to the baseline measurement, in combination with a change in foot strike angle might decrease tibial acceleration, however, no real difference in foot strike angle was found. This suggests that whether a change in parameters is beneficial could depend on the combination of parameters and is not depending on individual parameters. Concerning parameters related to injuries, the participant found a real increase in peak hip adduction from the baseline measurement to the measurement taken during the retention test taken directly after the feedback intervention. In addition, the participant found a real increase in peak ankle eversion comparing the retention measurement taken after a month to the baseline measurement.

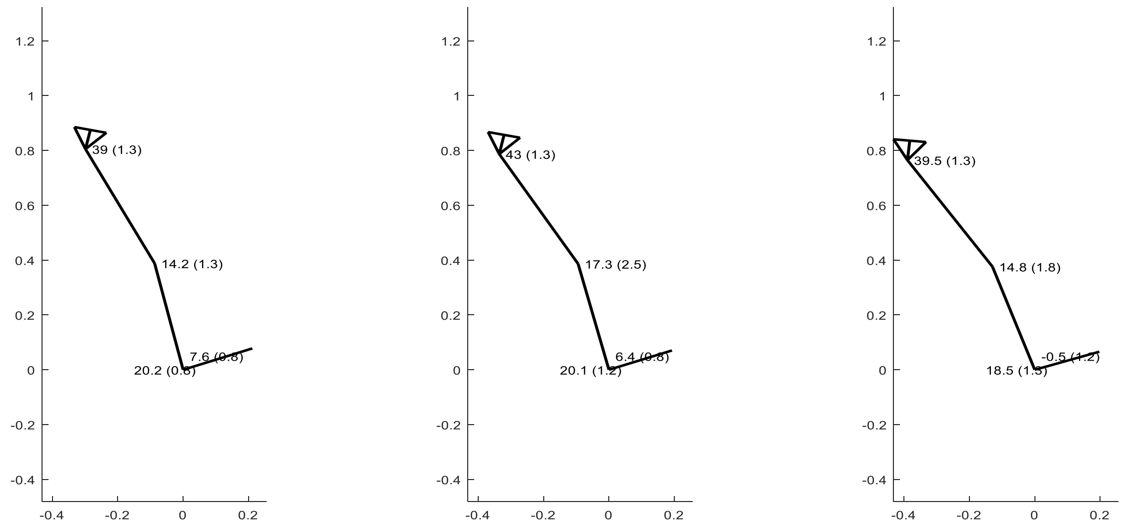


Figure 9.15 Stick figures displaying the foot contact, ankle, knee and hip angle. From left to right: baseline measurement, retention test direct after the feedback intervention, and retention test after a month

Table 9.4 Mean and standard deviation for the parameters of interest for the different measurements.

Variable	Baseline Mean (SD)	Retention after intervention Mean (SD)	Retention after month Mean (SD)
Peak tibial acceleration (g)	5.5 (0.6)	9.0 (0.6) *	10.8 (1.0) *
Foot strike angle (°)	20.2 (0.8)	20.1 (1.2)	18.5 (1.3)
Ankle dorsiflexion IC (°)	7.6 (0.8)	6.4 (0.8)	-0.5 (1.2) *†
Knee flexion IC (°)	14.2 (1.3)	17.3 (2.5)	14.8 (1.8)
Knee flexion excursion (°)	30.4 (1.6)	29.1 (2.7)	32.0 (1.7)
Hip flexion IC (°)	39.0 (1.3)	43.0 (1.3)	39.5 (1.3)
Hip adduction excursion (°)	12.6 (1.5)	17.0 (2.4) *	14.4 (1.2) *†
Ankle eversion excursion (°)	8.6 (1.8)	10.7 (1.2)	8.0 (1.4)
Landing distance (m)	0.33 (0.01)	0.33 (0.01)	0.33 (0.01)
Cadence (steps/s)	1.30 (0.07)	1.38 (0.04) *	1.33 (0.05) *†
Heel velocity IC (m/s)	0.54 (0.06)	0.38 (0.04)*	0.38 (0.06) *
Peak hip adduction (°)	13.8 (1.0)	24.2 (3.0) *	18.1 (0.8)
Peak ankle eversion (°)	8.0 (1.6)	6.9 (0.4)	16.8 (1.0) *†

IC = Initial contact, SD = standard deviation, * = real difference between retention measurement and baseline measurement, † = real difference between retention measurement taken directly after the measurement and retention taken after a month, IC = initial contact

Participant 5 had only five feedback sessions, with the fifth feedback session missing due to malfunctioning of the system. Participant 5 showed a real decrease in mean peak tibial acceleration comparing the retention measurement to the baseline measurement in the first session (Figure 9.16), suggesting a fast learning response. An increase in mean peak tibial acceleration in the measurements taken during the Stroop tests compared to the retention measurements in the first and second sessions suggested the task was not automatized. In session 3 no real increase was found comparing the mean peak tibial acceleration measured in the Stroop test to the retention test, suggesting the task was automatized in session 3. In session 4 a real decrease in mean peak tibial acceleration was found comparing the retention measurement to the baseline measurement, suggesting the participant was still exploring the different strategies. In session 6 and 7 a real increase was found in mean peak tibial acceleration comparing the measurements taken during the Stroop tests to the baseline measurements. Mean peak tibial acceleration at the baseline of the sixth session was the highest baseline value reported. The participant itself reported they competed in a race before the measurement, which might have influenced the results of this session. Between the first baseline measurement and the baseline measurement of mean peak tibial acceleration taken after a month, a real decrease was found, suggesting a slow learning response.

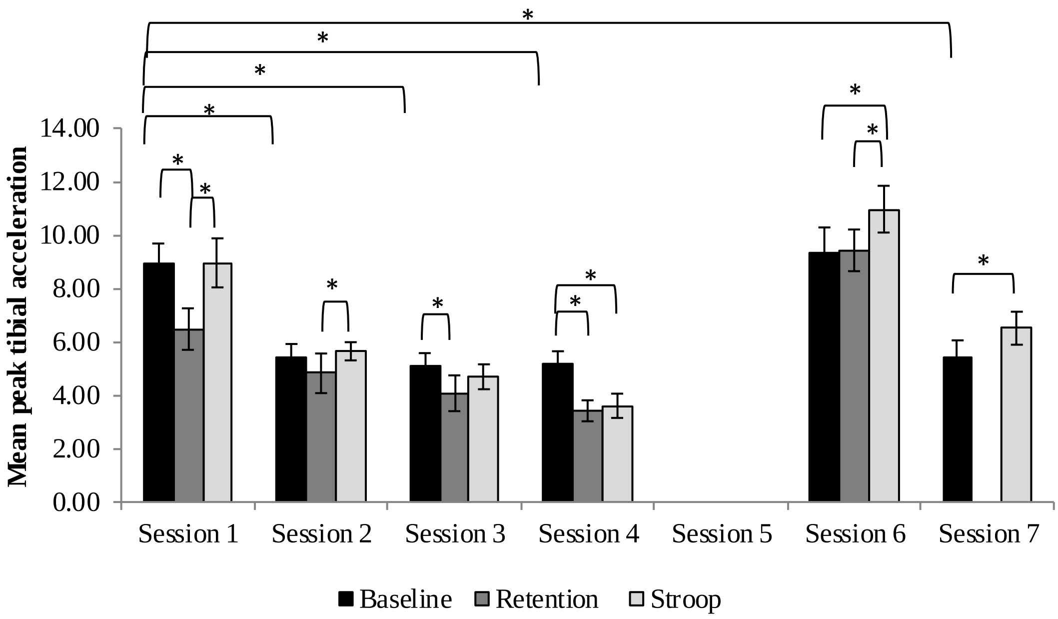


Figure 9.16 Mean peak tibial acceleration for each measurement for each session. * = real difference between measurements. Compared measurements within a session and baseline measurements of each session to the first session.

Comparing both retention measurements to the baseline measurement, the participant found a real change in their foot strike pattern, changing from contact more towards the heel to contact more towards the front of the foot. However, they stayed within the midfoot contact range (Figure 5.5, Table 8.8). This was accompanied by a real increase in knee flexion at initial contact, and hip adduction excursion, and a real decrease in landing distance, and knee flexion excursion. Comparing the retention measurement taken after a month to the baseline measurement a real increase in plantarflexion at initial contact was found, which was not found comparing the retention measurement taken directly after the feedback intervention to the baseline measurement. Concerning parameters related to injuries, the participant found a real increase in peak hip adduction from the baseline measurement to the retention measurement taken after a month.

Table 9.5 Mean and standard deviation for the parameters of interest for the different measurements.

Variable	Baseline Mean (SD)	Retention after intervention Mean (SD)	Retention after month Mean (SD)
Peak tibial acceleration (g)	8.9 (0.7)	9.4 (0.8)	5.4 (0.7) *†
Foot strike angle (°)	7.3 (1.0)	0.8 (1.1) *	-1.4 (1.1) *
Ankle dorsiflexion IC (°)	-1.3 (0.8)	-0.4 (1.4)	-7.6 (1.2) *†
Knee flexion IC (°)	18.1 (1.4)	23.9 (1.8) *	23.8 (0.9) *
Knee flexion excursion (°)	19.4 (1.9)	12.5 (2.0) *	16.0 (1.2) *†
Hip flexion IC (°)	29.5 (0.8)	28.4 (1.5)	30.4 (0.7)
Hip adduction excursion (°)	2.5 (0.7)	6.1 (1.2) *	6.0 (1.1) *
Ankle eversion excursion (°)	9.0 (1.1)	1.7 (1.6) *	5.6 (0.9) *†
Landing distance (m)	0.19 (0.01)	0.17 (0.02) *	0.16 (0.01) †*
Cadence (steps/s)	1.40 (0.03)	1.41 (0.03)	1.40 (0.03)
Heel velocity IC (m/s)	0.44 (0.05)	0.27 (0.04) *	0.44 (0.06) †
Peak hip adduction (°)	13.3 (0.9)	18.8 (1.4)	20.9 (0.9) *
Peak ankle eversion (°)	0.8 (0.6)	0.8 (0.6)	0.7 (0.4)

IC = Initial contact, SD = standard deviation, * = real difference between retention measurement and baseline measurement, † = real difference between retention measurement taken directly after the measurement and retention taken after a month, IC = initial contact

Participant 6 had only five feedback sessions, with the fifth feedback session missing due to malfunctioning of the system. Participant 6 showed a real decrease in mean peak tibial acceleration comparing the retention measurement to the baseline measurement for the first session (Figure 9.17), suggesting a fast learning response. An increase in mean peak tibial acceleration during the measurement taken during the Stroop test compared to the retention measurement suggested the task was not automatized in the first session. A decrease in mean peak tibial acceleration was found comparing the baseline measurement of session 3 to the baseline measurement of session 1. No real difference was found comparing the measurement taken during the Stroop test to the measurement taken during the retention-test, suggesting the task was automatized. The participant reduced in mean peak tibial acceleration when comparing measurements to the baseline measurement within sessions, but did not find a real difference comparing the baseline measurements of different sessions (2, 4, 5, 6) to the baseline measurement of session 1. It appears the participant needed a reminder of the feedback to be able to reduce mean peak tibial acceleration. No real difference was found comparing the retention measurement taken after one-month to the baseline measurement of the first session, suggesting no slow learning response occurred for the participant.

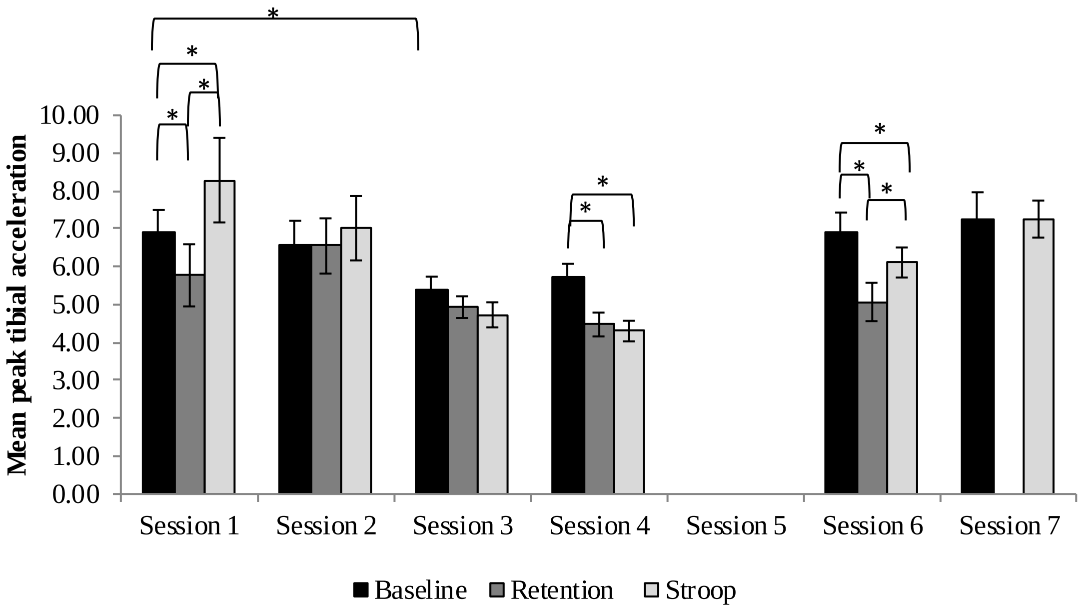


Figure 9.17 Mean peak tibial acceleration for each measurement for each session. * = real difference between measurements. Compared measurements within a session and baseline measurements of each session to the first session.

Comparing the baseline measurement to the retention measurement taken directly after the feedback intervention a real increase in flexion in the knee at initial contact, hip adduction excursion, and cadence, and a real decrease in heel velocity at initial contact were found (Figure 8.28, Table 8.9). The increases in knee flexion at initial contact and hip adduction excursion were no longer present comparing the one-month follow-up retention measurement to the baseline measurement. Concerning parameters related to injuries, no real differences were found comparing the baseline measurement to the measurements taken during the retention measurements.

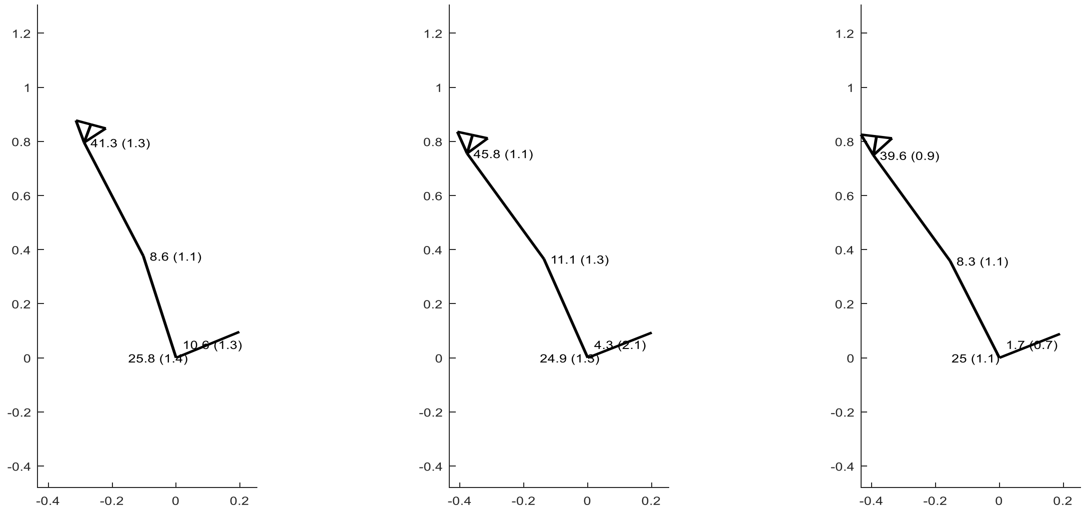


Figure 9.18 Stick figures displaying the foot contact, ankle, knee and hip angle. From left to right: baseline measurement, retention test direct after the feedback intervention, and retention test after a month.

Table 9.6 Mean and standard deviation for the parameters of interest for the different measurements.

Variable	Baseline Mean (SD)	Retention after intervention Mean (SD)	Retention after month Mean (SD)
Peak tibial acceleration (g)	6.9 (0.6)	5.1 (0.5) *	7.3 (0.7) †
Foot strike angle (°)	25.8 (1.4)	24.9 (1.3)	25.0 (1.1)
Ankle dorsiflexion IC (°)	10.6 (1.3)	4.3 (2.1) *	1.7 (0.7) *
Knee flexion IC (°)	8.6 (1.1)	11.1 (1.3) *	8.3 (1.1) †
Knee flexion excursion (°)	31.9 (1.2)	29.8 (1.1)	28.5 (1.4) *
Hip flexion IC (°)	41.3 (1.3)	45.8 (1.1)	39.6 (0.9) †
Hip adduction excursion (°)	1.8 (0.9)	5.8 (1.6) *	0.2 (0.3) *†
Ankle eversion excursion (°)	14.1 (1.7)	14.9 (4.3)	13.6 (1.2)
Landing distance (m)	0.26 (0.01)	0.27 (0.01) *	0.27 (0.01) *
Cadence (steps/s)	1.45 (0.02)	1.66 (0.08) *	1.71 (0.11) *†
Heel velocity IC (m/s)	0.39 (0.05)	0.23 (0.04) *	0.05 (0.04) *†
Peak hip adduction (°)	20.1 (1.0)	20.7 (1.0)	16.2 (1.1)
Peak ankle eversion (°)	5.2 (1.2)	1.3 (0.6)	5.8 (0.8)

IC = Initial contact, SD = standard deviation, * = real difference between retention measurement and baseline measurement, † = real difference between retention measurement taken directly after the measurement and retention taken after a month, IC = initial contact

Participant 7 had only five feedback sessions, with the fifth feedback session missing due to malfunctioning of the system. Participant 7 showed a real decrease in mean peak tibial acceleration comparing the retention measurement to the baseline measurement within the first session (Figure 9.19), suggesting a fast learning response. No real increase in mean peak tibial acceleration comparing the Stroop test to the retention measurement in the first session suggested the task was automatized. In sessions 2 and 3 a real decrease in mean peak tibial acceleration was found from the baseline measurement to the retention measurement, suggesting the participant was further exploring the task. In the sixth session, a real increase in mean peak tibial acceleration in the retention measurement and the measurement taken during the Stroop test was found compared to the baseline measurement. The data in the sixth session was, however, likely to be affected by the participant competing in a race the day before the session. A real decrease in mean peak tibial acceleration was found comparing the baseline measurement of the seventh session, to the baseline measurement of the first session, suggesting a slow learning response.

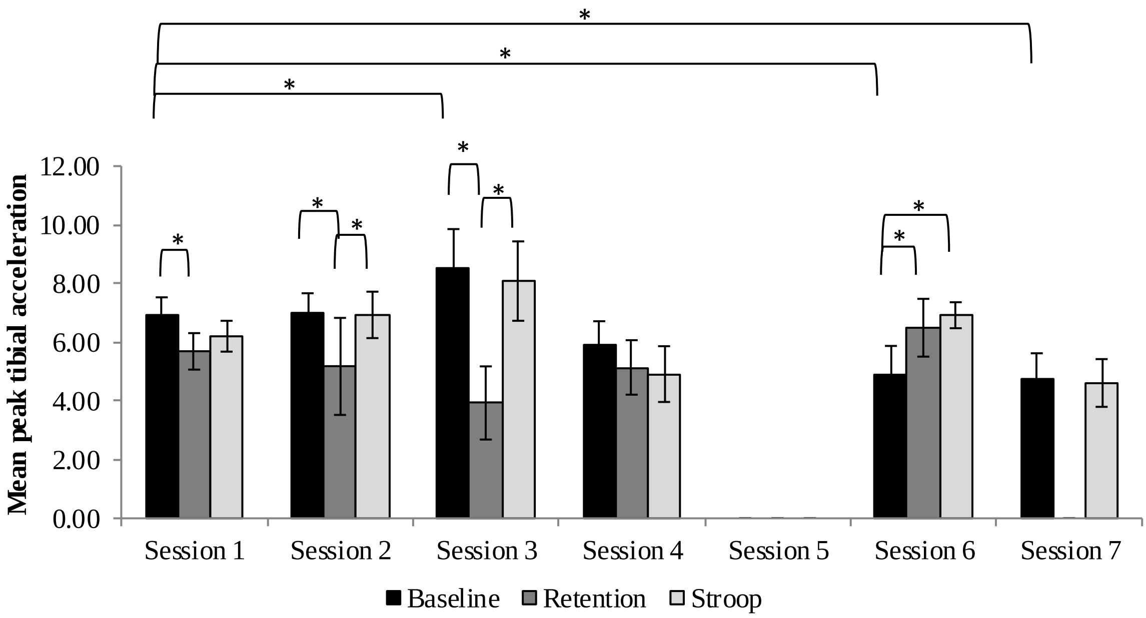


Figure 9.19 Mean peak tibial acceleration for each measurement for each session. * = real difference between measurements. Compared measurements within a session and baseline measurements of each session to the first session.

Comparing the retention measurement taken after one month to the baseline measurement the participant changed from a rearfoot contact to a midfoot contact (Figure 9.20, Table 9.7). This was accompanied by a real decrease in landing distance and knee flexion excursion, and a real increase in plantarflexion and knee flexion at initial contact and hip adduction excursion. Of these parameters, only increases in plantarflexion and hip adduction excursion were found comparing the retention measurement taken directly after the feedback intervention to the baseline measurement. Concerning parameters related to injuries, no real differences were found comparing the baseline measurement to the retention measurements in peak hip adduction or peak ankle eversion.

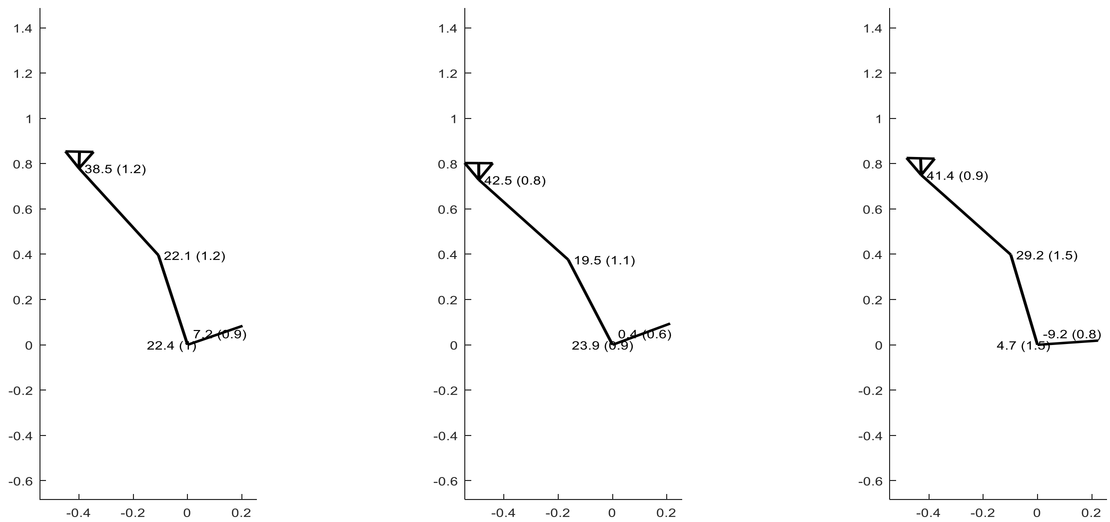


Figure 9.20 Stick figures displaying the foot contact, ankle, knee and hip angle. From left to right: baseline measurement, retention test direct after the feedback intervention, and retention test after a month.

Table 9.7 Mean and standard deviation for the parameters of interest for the different measurements.

Variable	Baseline Mean (SD)	Retention after intervention Mean (SD)	Retention after month Mean (SD)
Peak tibial acceleration (g)	6.9 (0.6)	6.5 (1.0)	4.8 (0.9) *†
Foot strike angle (°)	22.4 (1.0)	23.9 (0.9)	4.7 (1.5) *†
Ankle dorsiflexion IC (°)	7.2 (0.9)	0.4 (0.6) *	-9.2 (0.8) *†
Knee flexion IC (°)	22.1 (1.2)	19.5 (1.1)	29.2 (1.5) *†
Knee flexion excursion (°)	23.6 (1.5)	24.9 (1.1)	16.7 (1.5) *†
Hip flexion IC (°)	38.5 (1.2)	42.5 (0.8)	41.4 (0.9)
Hip adduction excursion (°)	4.8 (1.0)	8.1 (0.8) *	7.6 (0.9) *
Ankle eversion excursion (°)	12.0 (1.8)	9.5 (1.5)	14.1 (1.4) †
Landing distance (m)	0.30 (0.01)	0.30 (0.01)	0.22 (0.01) *†
Cadence (steps/s)	1.49 (0.02)	1.44 (0.01) *	1.45 (0.01) *
Heel velocity IC (m/s)	0.30 (0.06)	0.31 (0.05)	0.50 (0.06) *†
Peak hip adduction (°)	22.1 (1.6)	21.9 (1.1)	24.0 (1.2)
Peak ankle eversion (°)	2.8 (1.2)	10.4 (1.1)	0.8 (0.7) †

IC = Initial contact, SD = standard deviation, * = real difference between retention measurement and baseline measurement, † = real difference between retention measurement taken directly after the measurement and retention taken after a month, IC = initial contact

Participant 8 started with a relatively low tibial acceleration: 4.33 g (Figure 9.21). They admitted that between the measurement taken in the field and the first measurement in the lab they went to a physiotherapist, and were, therefore, likely to have changed their running pattern. They showed a real decrease in mean peak tibial acceleration comparing the retention measurement to the baseline measurement in the first session, suggesting a fast learning response. No increase in mean peak tibial acceleration during the Stroop test compared to the retention measurement in the first session suggested the task (reducing tibial acceleration) was automatized. In the second session, a further reduction in mean peak tibial acceleration was found in the retention measurement compared to the baseline measurement, suggesting the participant was further exploring the solutions. A real reduction in mean peak tibial acceleration was found comparing the baseline of the seventh session to the baseline of the first session, suggesting a slow learning response.

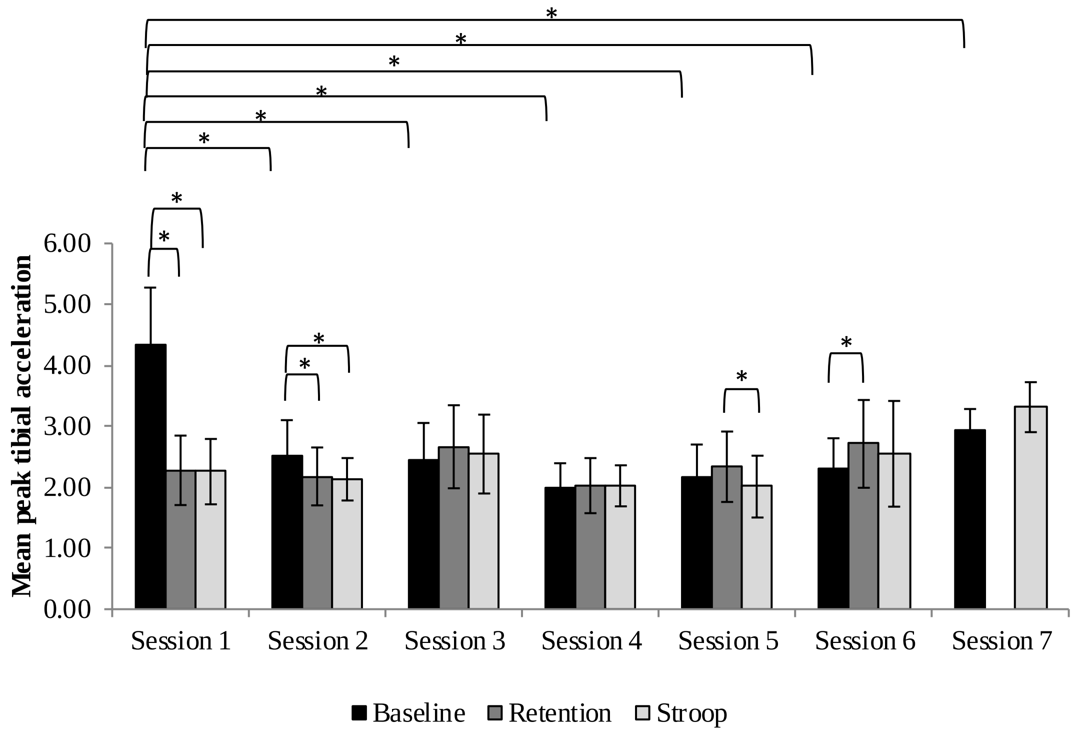


Figure 9.21 Mean peak tibial acceleration for each measurement for each session. * = real difference between measurements. Compared measurements within a session and baseline measurements of each session to the first session.

For both retention measurements, an increase was found in cadence and a decrease in heel velocity at initial contact which could be related to a decrease in mean peak tibial acceleration (Figure 9.22, Table 9.8). Further, from the baseline measurement to the retention measurement taken after a month real increases in knee flexion at initial contact and ankle eversion excursion were found. Concerning parameters related to injuries, the participant found a real increase in peak hip adduction from the baseline measurement to the retention measurement taken directly after the feedback intervention.

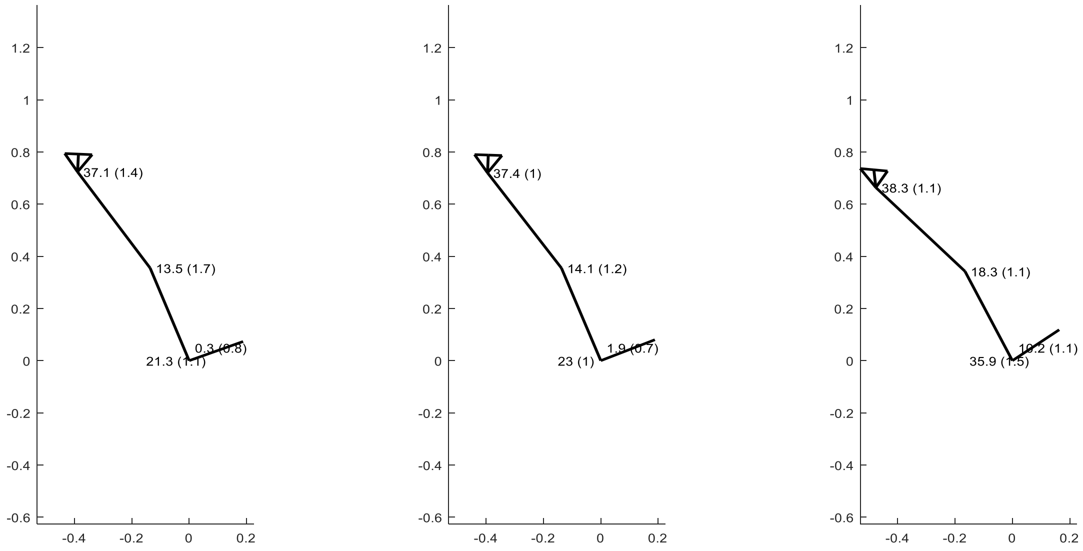


Figure 9.22 Stick figures displaying the foot contact, ankle, knee and hip angle. From left to right: baseline measurement, retention test direct after the feedback intervention, and retention test after a month.

Table 9.8 Mean and standard deviation for the parameters of interest for the different measurements.

Variable	Baseline Mean (SD)	Retention after intervention Mean (SD)	Retention after month Mean (SD)
Peak tibial acceleration (g)	4.3 (1.0)	2.8 (0.9) *	3.0 (0.5) *
Foot strike angle (°)	21.3 (1.1)	23.0 (1.0)	35.9 (1.5) *†
Ankle dorsiflexion IC (°)	0.3 (0.8)	1.9 (0.7)	10.2 (1.1) *†
Knee flexion IC (°)	13.5 (1.7)	14.1 (1.2)	18.3 (1.1) *†
Knee flexion excursion (°)	30.9 (1.6)	32.9 (1.4)	30.7 (1.4)
Hip flexion IC (°)	37.1 (1.4)	37.4 (1.0)	38.3 (1.1)
Hip adduction excursion (°)	9.3 (1.1)	7.5 (0.7) *	5.8 (1.3) *†
Ankle eversion excursion (°)	14.0 (1.0)	16.8 (1.5)	31.6 (3.9) *†
Landing distance (m)	0.26 (0.01)	0.30 (0.01) *	0.32 (0.01) *†
Cadence (steps/s)	1.40 (0.03)	1.44 (0.02) *	1.47 (0.02) *†
Heel velocity IC (m/s)	0.25 (0.03)	0.17 (0.03) *	0.11 (0.04) *†
Peak hip adduction (°)	13.9 (1.1)	22.8 (0.7) *	15.4 (0.9) †
Peak ankle eversion (°)	6.5 (0.8)	13.2 (0.8)	7.0 (1.9)

IC = Initial contact, SD = standard deviation, * = real difference between retention measurement and baseline measurement, † = real difference between retention measurement taken directly after the measurement and retention taken after a month, IC = initial contact

Participant 9 did not show a real decrease in mean peak tibial acceleration comparing the retention measurements to the baseline measurements for any of the sessions (Figure 9.23), suggesting no fast learning response was found. However, a decrease was found in mean peak tibial acceleration comparing the baseline measurement of session 3 to the baseline measurement of session 1. In session 3, no real difference was found comparing the measurement taken during the Stroop test to the retention measurement, suggesting the task was automatized. Comparing the baseline measurements of each session to the baseline measurement of the first session, a real increase in mean peak tibial acceleration was found between the second session and the first session and real decreases were found comparing the third, fourth, fifth and seventh session to the first session. So even though no fast learning response was found within a session, the participant did decrease in tibial acceleration over the several sessions, suggesting a slow learning response.

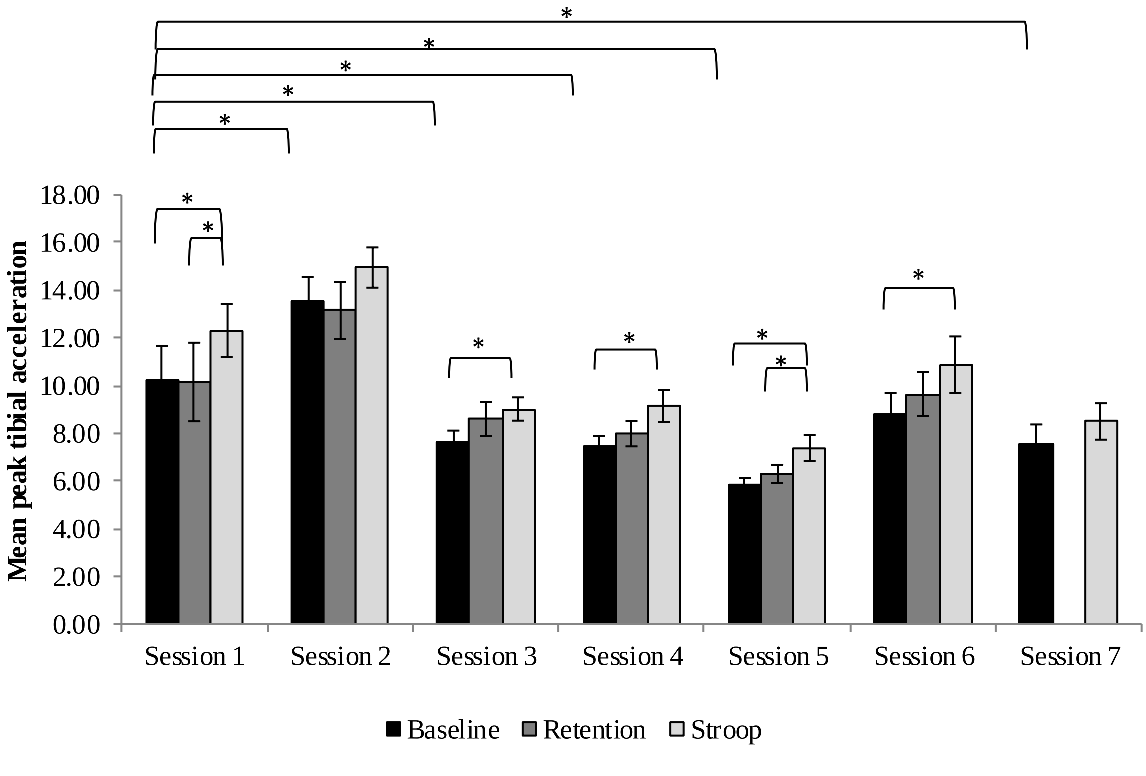


Figure 9.23 Mean peak tibial acceleration for each measurement for each session. * = real difference between measurements. Compared measurements within a session and baseline measurements of each session to the first session.

Similar changes in the running pattern were found when comparing the retention measurements to the baseline measurement (Figure 8.34, Table 8.12). These changes included a landing with a more extended leg (real increase in knee extension at initial contact and landing distance) but followed by more flexion in the knee (real increase in knee flexion excursion), a real increase in ankle eversion excursion and a real decrease in heel velocity at initial contact. The difference between the retention measurements included a decrease in landing distance and heel velocity at initial contact comparing the one-month retention measurement to the retention measurement taken directly after the feedback intervention. Concerning parameters related to injuries, the participant found a real decrease in peak hip adduction from the baseline measurement to the retention measurement taken directly after the feedback intervention.

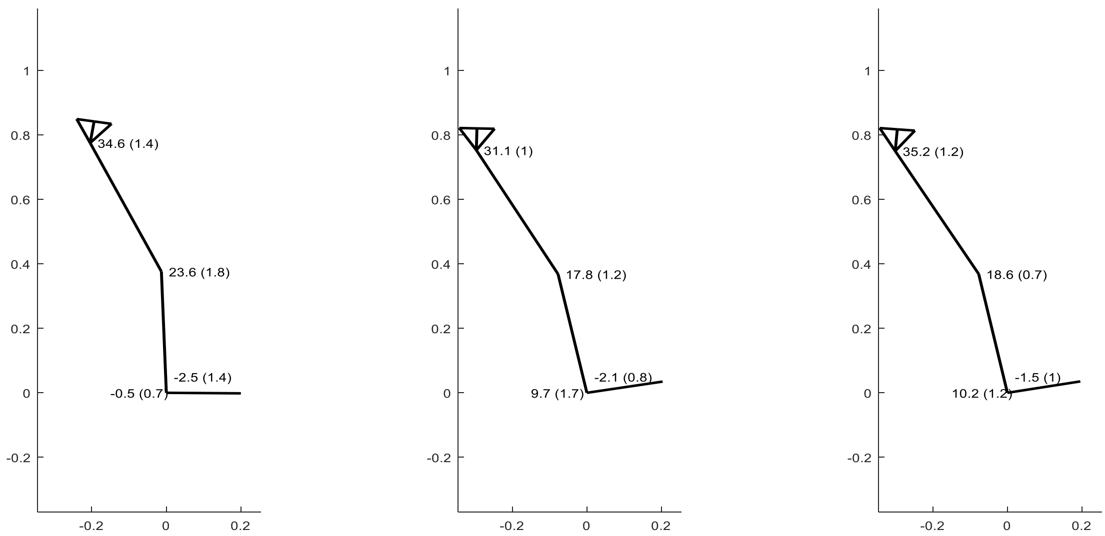


Figure 9.24 Stick figures displaying the foot contact, ankle, knee and hip angle. From left to right: baseline measurement, retention test direct after the feedback intervention, and retention test after a month.

Table 9.9 Mean and standard deviation for the parameters of interest for the different measurements.

Variable	Baseline Mean (SD)	Retention after intervention Mean (SD)	Retention after month Mean (SD)
Peak tibial acceleration (g)	10.2 (1.5)	9.7 (0.9)	7.5 (0.8) *†
Foot strike angle (°)	-0.5 (0.7)	9.7 (1.7) *	10.2 (1.2) *
Ankle dorsiflexion IC (°)	-2.5 (1.4)	-2.1 (0.8)	-1.5 (1.0)
Knee flexion IC (°)	23.6 (1.8)	17.8 (1.2) *	18.6 (0.7) *
Knee flexion excursion (°)	21.4 (1.9)	25.5 (1.5) *	24.8 (1.3) *
Hip flexion IC (°)	34.6 (1.4)	31.1 (1.0)	35.2 (1.2)
Hip adduction excursion (°)	4.5 (1.4)	3.4 (0.9)	3.1 (1.3) *
Ankle eversion excursion (°)	2.8 (1.2)	8.3 (1.7) *	7.4 (1.1) *
Landing distance (m)	0.17 (0.01)	0.23 (0.01) *	0.21 (0.01) *†
Cadence (steps/s)	1.39 (0.04)	1.41 (0.02)	1.41 (0.02) *
Heel velocity IC (m/s)	0.40 (0.09)	0.34 (0.05) *	0.29 (0.05) *†
Peak hip adduction (°)	34.4 (1.4)	29.8 (1.0)	26.8 (0.5) *
Peak ankle eversion (°)	9.2 (1.3)	1.9 (0.8)	3.8 (0.8)

IC = Initial contact, SD = standard deviation, * = real difference between retention measurement and baseline measurement, † = real difference between retention measurement taken directly after the measurement and retention taken after a month, IC = initial contact

Participant 10 showed a real decrease in mean peak tibial acceleration comparing the retention measurement to the baseline measurement within the first session (Figure 9.25), suggesting a fast learning response. Comparing the measurement taken during the Stroop test to the retention measurement in the first sessions no real increase in mean peak tibial acceleration was found, suggesting the task was automatized. In sessions 2, 4, 5, and 6, a further reduction was found in the retention measurement compared to the baseline measurement of each session, suggesting the participant was able to use the feedback to reduce tibial acceleration further. A real reduction in mean peak tibial acceleration was found comparing the baseline measurements of the seventh session the baseline measurement of the first session, suggesting a slow learning response.

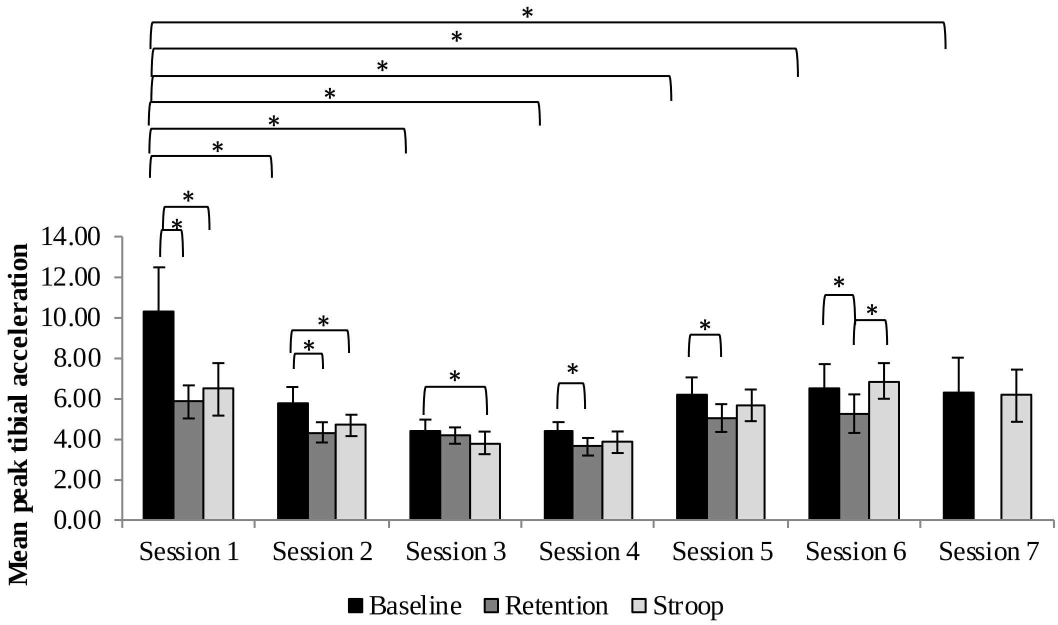


Figure 9.25 Mean peak tibial acceleration for each measurement for each session. * = real difference between measurements. Compared measurements within a session and baseline measurements of each session to the first session.

For both retention measurements, a real increase in ankle eversion excursion, hip adduction excursion, and cadence, and a real decrease in heel velocity at initial contact were found compared to the baseline measurement (Figure 8.36, Table 8.13). Concerning parameters related to injuries, the participant found a real increase in peak ankle eversion from the baseline session to the retention measurement taken directly after the feedback intervention.

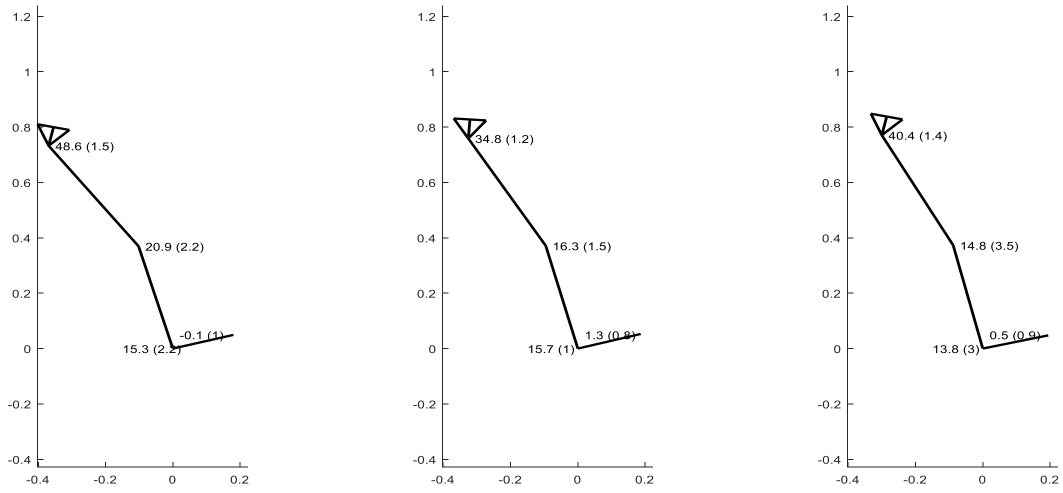


Figure 9.26 Stick figures displaying the foot contact, ankle, knee and hip angle. From left to right: baseline measurement, retention test direct after the feedback intervention, and retention test after a month.

Table 9.10 Mean and standard deviation for the parameters of interest for the different measurements.

Variable	Baseline Mean (SD)	Retention after intervention Mean (SD)	Retention after month Mean (SD)
Peak tibial acceleration (g)	10.3 (2.2)	5.3 (1.0) *	6.3 (1.7) *
Foot strike angle (°)	15.3 (2.2)	15.7 (1.0)	13.8 (3.0)
Ankle dorsiflexion IC (°)	-0.1 (1.0)	1.3 (0.8)	0.5 (0.9)
Knee flexion IC (°)	20.9 (2.2)	16.3 (1.5)	14.8 (3.5) *
Knee flexion excursion (°)	27.4 (2.8)	25.4 (1.7)	26.5 (4.3)
Hip flexion IC (°)	48.6 (1.5)	34.8 (1.2) *	40.4 (1.4) *
Hip adduction excursion (°)	3.5 (1.2)	7.9 (0.9) *	5.3 (1.1) *†
Ankle eversion excursion (°)	11.3 (1.9)	16.0 (1.4) *	17.8 (1.9) *
Landing distance (m)	0.27 (0.02)	0.28 (0.01) *	0.27 (0.02)
Cadence (steps/s)	1.35 (0.04)	1.41 (0.02) *	1.40 (0.02) *
Heel velocity IC (m/s)	0.41 (0.06)	0.33 (0.04) *	0.34 (0.08) *
Peak hip adduction (°)	18.8 (1.4)	12.8 (0.8)	15.3 (0.8)
Peak ankle eversion (°)	10.7 (0.9)	20.8 (0.7) *	13.9 (0.9)

IC = Initial contact, SD = standard deviation, * = real difference between retention measurement and baseline measurement, † = real difference between retention measurement taken directly after the measurement and retention taken after a month, IC = initial contact

Participant 11 missed the retention test and the Stroop test of the second session, due to malfunctioning of the system. During the first session, no real differences in mean peak tibial acceleration were found between the different measurements (Figure 6.7). The baseline measurements of all sessions, however, were found to have a real decrease in mean peak tibial acceleration compared to the baseline measurement of the first session, suggesting a slow learning response. In the third and fourth sessions, real increases in mean peak tibial acceleration were found comparing the measurements taken during the Stroop test to the retention measurements, suggesting the task (reducing tibial acceleration) was not automatized. In session 5, no increase in mean peak tibial acceleration was found comparing the measurement taken during the Stroop test to the retention measurement, suggesting the task was automatized.

Comparing both retention measurements to the baseline measurement a real decrease was found in heel velocity at initial contact (Figure 8.36, Table 8.14). Comparing the retention measurement taken directly after the feedback intervention to the baseline measurement a real increase in dorsiflexion and foot strike angle was found. Comparing the one-month retention to the baseline measurement, a real increase in cadence and knee flexion at initial contact was found. Concerning parameters related to injuries, the participant found a real decrease in peak hip adduction from the baseline measurement to both retention measurements. A real increase was found for peak ankle eversion, comparing the retention measurement taken after a month to the baseline measurement.

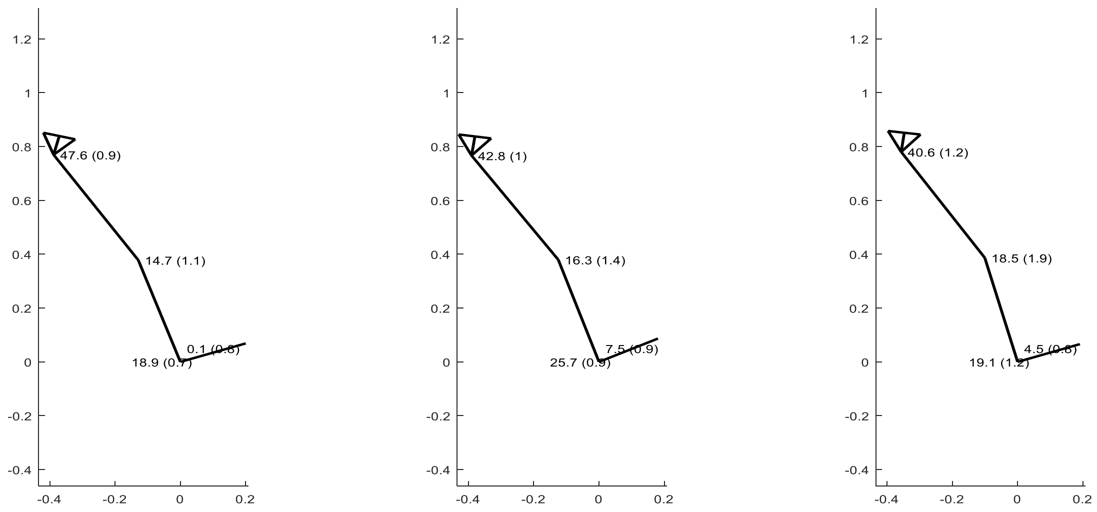


Figure 9.27 Stick figures displaying the foot contact, ankle, knee and hip angle. From left to right: baseline measurement, retention test direct after the feedback intervention, and retention test after a month.

Table 9.11 Mean and standard deviation for the parameters of interest for the different measurements.

Variable	Baseline Mean (SD)	Retention after intervention Mean (SD)	Retention after month Mean (SD)
Peak tibial acceleration (g)	8.9 (0.8)	5.9 (0.7) *	5.2 (0.6) *
Foot strike angle (°)	18.9 (0.7)	25.7 (0.9) *	19.1 (1.2) †
Ankle dorsiflexion IC (°)	0.1 (0.8)	7.5 (0.9) *	4.5 (0.8)
Knee flexion IC (°)	14.7 (1.1)	16.3 (1.4)	18.5 (1.9) *
Knee flexion excursion (°)	26.3 (1.4)	25.0 (1.5)	23.7 (1.7)
Hip flexion IC (°)	47.6 (0.9)	42.8 (1.0)	40.6 (1.2) *
Hip adduction excursion (°)	5.7 (0.9)	5.3 (0.4)	4.6 (0.9)
Ankle eversion excursion (°)	7.3 (1.6)	7.0 (2.4)	9.1 (1.9)
Landing distance (m)	0.30 (0.01)	0.33 (0.01) *	0.31 (0.01) †
Cadence (steps/s)	1.43 (0.02)	1.45 (0.01)	1.49 (0.01) *†
Heel velocity IC (m/s)	0.34 (0.05)	0.23 (0.04) *	0.25 (0.04) *
Peak hip adduction (°)	21.7 (0.9)	13.6 (0.5) *	13.9 (1.2) *
Peak ankle eversion (°)	3.4 (0.8)	8.3 (0.9)	16.1 (1.0) *†

IC = Initial contact, SD = standard deviation, * = real difference between retention measurement and baseline measurement, † = real difference between retention measurement taken directly after the measurement and retention taken after a month, IC = initial contact

9.18 Appendix R: Institutional ethical approval

Measures of tibial acceleration in runners in a field based setting

Ethics Review ID: ER5830681

Workflow Status: Application Approved

Type of Ethics Review Template: Very low risk human participants studies

Primary Researcher / Principal Investigator

Linda Van Gelder
(Health and Wellbeing)

Converis Project Application::

Q1. Is this project: ii) Doctoral research

Director of Studies

Ben Heller
(Health and Wellbeing)

Q4. Proposed Start Date of Data Collection: 13/01/2018

Q5. Proposed End Date of Data Collection : 24/02/2018

Q6. Will the research involve any of the following:

i) Participants under 5 years old: No
ii) Pregnant women: No
iii) 5000 or more participants: No
iv) Research being conducted in an overseas country: No
Q7. If overseas, specify the location:

Q8. Is the research externally funded?: No
Q9. Will the research be conducted with partners and subcontractors?: No

Is another UK HEI the lead partner?: No

Q10. Does the research involve one or more of the following?

i. Patients recruited because of their past or present use of the NHS or Social Care: No
ii. Relatives/carers of patients recruited because of their past or present use of the NHS or Social Care: No
iii. Access to data, organs, or other bodily material of past or present NHS patients: No
iv. Foetal material and IVF involving NHS patients: No
v. The recently dead in NHS premises: No
vi. Participants who are unable to provide informed consent due to their incapacity even if the project is not health related: No
vii. Prisoners or others within the criminal justice system recruited for health-related research: No
viii. Prisoners or others within the criminal justice system recruited for non-health-

related research:
No

ix. **Police, court officials or others within the criminal justice system:** No

Q11. Category of academic discipline: Physical Sciences and Engineering
Q12. Methodology: Quantitative

P2 - Project Outline

Q1. General overview of study: In this study we will ask runners at parkrun to wear an accelerometer during their run so we could receive data on peak tibial acceleration in the field. With this information we would like to get a better insight into what the average and range of peak tibial acceleration is during a fixed 5 kilometre course in the field. We would further like to receive a better insight into how these values compare to values measured in laboratory settings. Both means and range, but we would also like to compare single persons. We have a dataset of 16 participants of which tibial acceleration was measured in the laboratory; we would like to ask them to participate in parkrun as well, so we could do direct comparisons. Further from this data we hope to identify participants with increased tibial acceleration for our next study. Participants who participate in this study do not have to participate in the following study but they could be asked to do so, if we found them running with higher tibial acceleration. In the next study we would like to reduce peak tibial acceleration, since a high peak tibial acceleration is found to be correlated with tibial stress fractures. Parkrun is a five kilometre run in which times are recorded for free. The runs are organised around the world and open to everyone. We will focus on the Sheffield Hallam parkrun which has an average of 400.5 runners a week (http://www.parkrun.org.uk/sheffieldhallam/). With an average of 400.5 runners a week we should be able to find a certain amount of participants.

Q2. Background to the study and scientific rationale (if you have already written a research proposal, e.g. for a funder, you can upload that instead of completing this section).: Tibial stress fractures are common overuse injuries among runners [1]. Tibial stress fractures can cause significant disruption to training, a reduction in physical fitness as well as increased psychological distress [2]. An earlier prospective study [3] suggests that increased tibial acceleration during the loading phase in running is related to tibial stress fractures and could therefore be an important risk factor for injury. In this prospective study the relationship between the incidence of tibial stress fractures and measures of loading including tibial acceleration in competitive women runners was examined. In their study, Davis et al. [3] found 5 participants who sustained a tibial stress fracture or a tibial stress reaction, the precursor for tibial stress fractures.These participants had increased values of peak tibial acceleration (9.06g) compared to the five controls (4.73g). The values found in the prospective study of Davis et al. [3] were confirmed by a retrospective study of Milner et al. [4]. Milner et al. [4] compared 20 female runners with a history of tibial stress fractures to 20 participants who did not. They found that participants in the group who did have a history of tibial stress fractures run with a mean peak tibial acceleration of 7.7g (SD=3.21) compared to a mean of 5.81g (SD=1.66) in the group who did not have an history of tibial stress fractures. However since this is data of a retrospective study it could be that participants changed their running patterns after their injury. Both these studies [3,4] were performed in the laboratory and it might be that these mean peak tibial acceleration values could differ from values found in the field. In both studies participant ran over ground along a 23 or 25 meter runway. Where this runway will be flat, conditions in the field might differ, participants could run on uneven ground and either up or down hill. In this study we would like to receive a better insight into this difference between the laboratory and the field. Therefore we will ask runners at parkrun to wear an accelerometer during their normal parkrun run. With this information we would like to get a better insight into what the average and range of peak tibial acceleration is during a fixed 5 kilometre course in the field. We would further like to see whether there are differences in for example up and downhill running. Both means and standard deviations will be compared. We will also directly compare data from laboratory settings to field settings within participants. We have a dataset of 16 participants of which tibial acceleration was measured in the laboratory; we would like to ask them to participate in parkrun as well, so we could do direct comparisons. Further from this data we hope to identify participants with increased tibial acceleration for our next study. Participants who participate in this study do not have to participate in the following study but they could be asked to do so, if we found them running with higher tibial acceleration. In the next study we would like to reduce peak tibial acceleration with the use of biofeedback, since a high peak tibial acceleration is found to be correlated with tibial stress fractures [3]. References [1] K.L. Bennell, S. a Malcolm, S. a Thomas, J.D. Wark, P.D. Brukner, The incidence and distribution of stress fractures in competitive track and field athletes. A twelve-month prospective study., Am. J. Sports Med. 24 (1995) 211– 7. doi:10.1177/036354659602400217. [2] A.C. Clansey, M. Hanlon, E.S. Wallace, A. Nevill, M.J. Lake, Influence of Tibial shock feedback training on impact loading and running economy, Med. Sci. Sports Exerc. 46 (2014) 973–981. doi:10.1249/MSS.0000000000000182. [3] I. Davis, C.E. Milner, J. Hamill, Does Increased Loading During Running Lead to Tibial Stress Fractures? A Prospective Study, Med. Sci. Sport. Exerc. 36 (2004) S58. doi:http://dx.doi.org/10.1097/00005768-200405001-00271. [4] C.E. Milner, R. Ferber, C.D. Pollard, J. Hamill, I.S. Davis, Biomechanical factors associated with tibial stress fracture in female runners, Med. Sci. Sports Exerc. 38 (2006) 323–328. doi:10.1249/01.mss.0000183477.75808.92.

Q3. Is your topic of a sensitive/contentious nature or could your funder be considered controversial?: No

Q4. Are you likely to be generating potentially security-sensitive data that might need particularly secure storage?: No

Q5. Has the scientific/scholarly basis of this research been approved, for example by Research Degrees Sub-committee or an external funding body?: Yes

Q6. Main research questions: What is the average and range of peak tibial acceleration during running a fixed 5 kilometre course? How do measurements in the field compare to measurements of peak tibial acceleration in a lab environment? Can we identify participants with a higher tibial shock?

Q7. Summary of methods including proposed data analyses: Participants will be recruited at parkrun. We will ask for their email addresses during one day and send them the information over email. We will further send an email around and use social channels to find participants. We will ask them for the dates they will be able to come to parkrun too be measured. When the participants come for the measurement we will ask them to complete an informed consent. If runners who we did not contact before arrive early on the day so that they still have enough time read the information are willing to participate, we will give them the information and ask them to sign informed consents. When the informed consent is completed we will attach the accelerometer to the tibia and ask the participants to run parkrun like they normally would do. After they finished parkrun we will take the accelerometer back and take the data off. In the participant information sheet it will be clarified that if we find that participants run with a running pattern what could potentially cause harm we could ask them to come to the laboratory to see whether we could change their running pattern. Tibial acceleration will be measured using runscribes. The sensitive axis of the runscribe will be visually aligned with the long axis of the right tibia. The accelerometer will be attached with double sided tape to the antero-medial aspect of the right tibia, 5 cm above the medial malleolus. We will further use cohesive bandage to secure the runscribes. The data will be processed in custom programs written in Matlab (Mathworks, Natick, MA, USA, R2016a). The acceleration data will be filtered at 50 Hz with a 4th order Butterworth filter, after which the offset will be removed. From the peak tibial acceleration signal the peaks will be found and averaged within each participant. To answer the research questions the values of mean and range of peak tibial acceleration will be used. We will further ask the same participants who participated in an earlier study in the laboratory to do parkrun so we could compare the values we found in the lab to the values we found in the field. This comparison will be done using t-tests in

SPSS.

P3 - Research with Human Participants

Q1. Does the research involve human participants?: Yes
Q2. Will any of the participants be vulnerable?: No
Q3. Is this a clinical trial?: No
If yes, will the placebo group receive a treatment plan after the study? If N/A tick no.: No
Q4. Are drugs, placebos or other substances (e.g. food substances, vitamins) to be administered to the study participants or will the study involve invasive, intrusive or potentially harmful procedures of any kind?: No
Q5. Will tissue samples (including blood) be obtained from participants?: No
Q6. Is pain or more than mild discomfort likely to result from the study?: No
Q7. Will the study involve prolonged testing (activities likely to increase the risk of repetitive strain injury)?: No
Q8. Is there any reasonable and foreseeable risk of physical or emotional harm to any of the participants?: No
Q9. Will anyone be taking part without giving their informed consent?: No
Q10. Is it covert research?: No
Q11. Will the research output allow identification of any individual who has not given their express consent to be identified?: No
Q12. Where data is collected from human participants, outline the nature of the data, details of anonymisation, storage and disposal procedures if these are required (300 - 750): In this research participants will be asked to run during parkrun. During the run tibial acceleration data will be recorded with a sample rate of 500 Hz and stored on a laptop. For each participant a measurement log will be made in which the pre-medical questionnaire, height, weight and date of birth are noted together with the recorded acceleration trial name. The data will be anonymised by using a code on the measurement log instead of the name. The code will relate to one name of one participant which could be found in a separate document. All digital data will be stored in a confidential folder on the Q-drive which can only be reached by the contributing researchers. The data will be processed on a password protected laptop from the university. The data will be processed with the use of programs including Matlab and SPSS. Non-digital data will be protected and stored in a locked cabinet in Chestnut Court S003 on collegiate campus. All data will only be used for academic purposes. The data will be kept confidentiality for three years (duration of program of research) after publication. No access to the data will be granted without approval from a member of the team or the participants.

P4 - Research in Organisations

Q1. Will the research involve working with an external organisation or using data/material from an external organisation?: Yes
Q2. Do you have granted access to conduct the research?: Yes

P5 - Research with Products and Artefacts

Q1. Will the research involve working with copyrighted documents, films, broadcasts, photographs, artworks, designs, products, programmes, databases, networks, processes, existing datasets or secure data?: No

P7 - Health and Safety Risk Assessment

Q1. Will the proposed data collection take place only on campus?

: No

Q2. Are there any potential risks to your health and wellbeing associated with either (a) the venue where the research will take place and/or (b) the research topic itself?: None that I am aware of
Q3. Will there be any potential health and safety risks for participants (e.g. lab studies)? If so a Health and Safety Risk Assessment should be uploaded to P8.: Yes
Q4. Where else will the data collection take place? (Tick as many venues as apply)Researcher's Residence: false
Participant's Residence: false
Education Establishment: false
Other e.g. business/voluntary organisation, public venue: true
Outside UK: false
Q5. How will you travel to and from the data collection venue?: On foot
Q6. Please outline how you will ensure your personal safety when travelling to and from the data collection venue.: I will be going to Parkrun at Endcliff park, this park is very close to my home. so easy to reach. Further Parkrun takes place on Saturday morning at 9 am and there will be a lot of people around. **Q7. If you are carrying out research off-campus, you must ensure that each time you go out to collect data you ensure that someone you trust knows where you are going (without breaching the confidentiality of your participants), how you are getting there (preferably including your travel route), when you expect to get back, and what to do should you not return at the specified time. (See Lone Working Guidelines). Please outline here the procedure you propose using to do this.:** I will tell my partner when I will have data collection and when I expect to be finished. He lives next to the park, so it is easy for him to check up, further he sometimes does Parkrun himself, so he might be there.
Q8. How will you ensure your own personal safety whilst at the research venue, (including on campus where there may be hazards relating to your study)?: There will be a lot of people at the venue including first-aiders. I will further ask other people to help me collecting the data, so we will be with a group.

P8 - Attachments

Are you uploading any recruitment materials (e.g. posters, letters, etc.)?: Yes
Are you uploading a participant information sheet?: Yes
Are you uploading a participant consent form?: Yes
Are you uploading details of measures to be used (e.g. questionnaires, etc.)?: Yes
Are you uploading an outline interview schedule/focus group schedule?: Non Applicable
Are you uploading debriefing materials?: Non Applicable
Are you uploading a Risk Assessment Form?: Yes
Are you uploading a Serious Adverse Events Assessment (required for Clinical Trials and Interventions)?: Non Applicable
Are you uploading a Data Management Plan?: Yes

Upload:

Data Management Plan.docx
Letter.docx
Measurement log.doc
Participant Information Sheet.docx
Participant Informed Consent Form - Participants Copy.docx
Participant Informed Consent Form - Researchers Copy.docx
Pre-screening questionnaire.doc
Project Health and Safety Asssessment.docx

P9 - Adherence to SHU Policy and Procedures

Primary Researcher / PI Sign-off:

I can confirm that I have read the Sheffield Hallam University Research Ethics Policy and Procedures: true
I can confirm that I agree to abide by its principles: true
Date of PI Sign-off: 20/12/2017

Director of Studies Sign-off:

I confirm that this research will conform to the principles outlined in the Sheffield Hallam University Research Ethics policy: true
I can confirm that this application is accurate to the best of my knowledge: true
Director of Studies' Comments: I approve of this research, as long as it receives approval from the parkrun Research Board.
Date of submission and supervisor sign-off: 20/12/2017

Director of Studies Sign-off

Ben Heller

P12 - Post Approval Amendments

Amendment 1

In my judgement amendment 1 should be:: Select Amendment Outcome

Amendment 2

In my judgement amendment 2 should be:: Select Amendment Outcome

Amendment 3

In my judgement amendment 3 should be:: Select Amendment Outcome

9.19 Appendix S: Parkrun Research Board ethical approval

Certificate of approval

APPROVED

parkrun Research Board

Title of study: Measures of tibial acceleration in runners in a field based setting

Lead Investigator: Linda van Gelder (PhD Student, Sheffield Hallam Unveristy)

Other investigators: Dr Ben Heller, Dr Andy Barnes & Professor Jon Wheat (Sheffield Hallam Unveristy).

Date of approval: 31th January 2018

Valid until: 31th July 2018

Extent of approval: The researcher and their team have permission to attend the following event and offer parkrunners the opportunity to take part in his research project as outlined in the study plan: Sheffield Hallam (Endcliffe Park).

This is to certify the parkrun Research Board has approved this study to go ahead as long as the code of conduct for researchers is adhered to at all times.

Professor Steve Haake

Chair of the parkrun Research Board

Code of conduct for researchers

In conducting research associated with parkrun, researchers must:

have appropriate approvals

All studies supported by parkrun must have appropriate approvals, which may include ethical approval from an institutional ethics committee or written agreement that full ethical approval is not required. All studies must be carried out in accordance with ethical principles; potential participants must be fully informed of the study, must be given the opportunity to ask questions, and must be made aware that their participation is voluntary. It is the responsibility of researchers to ensure that participant eligibility criteria are adhered to (e.g. minimising the risk of children completing questionnaires for a study approved for adults).

liaise with event directors

If the research involves attending events in person (e.g. to collect data or recruit participants), or using social media sources linked to events for these purposes, it is essential that the event directors have agreed to this before any action is taken. The needs of the event director must be respected, and research must not interfere with the usual event procedures.

identify themselves to participants

If approaching potential participants (e.g. in person, by e-mail, via social networking sources), researchers should state their organisational affiliation, and confirm that they have approval from the parkrun Research Board.

report results to the parkrun community

Researchers must provide a summary of the study results at the earliest opportunity, to be posted on the parkrun research web page. Additional means of providing study participants with summary findings or individual results are encouraged. **A copy of any publications arising from the research must be sent to the parkrun Research Board**.

acknowledge parkrun in publications

The support of parkrun must be acknowledged in any reports or publications arising from this research. This includes help in recruiting participants, access to data, and any other support received. The contribution of parkrun participants in providing data must also be acknowledged.

agree to present results at the parkrun conference

Researchers must be willing to present the results of the research at the annual parkrun conference if invited to do so.

9.20 Appendix T: Particpant information sheet, field study

Sheffield Hallam University | Centre for Sports Engineering Research

Participant Information Sheet

Measuring running patterns in the field

You are invited to take part in a study by the Centre for Sports Engineering Research Sheffield Hallam University. This document should contain all the information you require about the study. If you have any further questions please contact the Principal Investigator using the details at the end.

The Study:
The aim of this research is to study running patterns during parkrun and to identify runners with running patterns that could potentially cause injury. You will be asked to wear a small, lightweight sensor during your normal parkrun.

Background:
People run in different running patterns, some of these patterns could cause injury. Common injuries are runner's knee, inflammations of tendons, hamstring issues, and shin splints. Tibial stress injuries are common overuse injuries among runners. Tibial stress injuries can cause significant disruption to training, a reduction in physical fitness as well as increased psychological distress. Running patterns have mainly been measured in laboratory settings, we would like to test whether we find the same kind of values during a 5 kilometre parkrun. We would further like to find people with running patterns that could potentially cause tibial stress injuries to invite to our next study, but this will be completely voluntary.

Inclusion requirements:
Every person aged 18 or above, who competes in parkrun, without current injuries or other conditions that could affect their running is able to participate.

What am I being asked to do?
During the study we will ask you to run like you would normally run parkrun, however we will attach a small sensor to the front of your right lower leg. We will attach this sensor with some double sided tape and we will further put some tape around your lower leg. After the run we would like to ask you to give the sensor back so we can analyse it.

Where will the data collection take place?
All sessions will be held in Endcliffe Park, in Sheffield, during parkrun at 9am on Saturday.

How often and for long will the data collection be?
You will be asked to come to Endcliffe Park once. You will be asked to arrive slightly early so we can attach the equipment and complete some forms. The run will be 5 kilometres and after the run we will ask you to give the device back.

How long is the study in operation?
The study will start in January and will finish in February.

How will my data be stored?
The data will be recorded and stored on a laptop. The data will be anonymised by using a code instead of your name. The code will relate to one name of one participant which could be found in a separate document. All digital data will be stored in a confidential folder which can only be accessed by the contributing researchers. The data will be processed on a password protected laptop from the university.

Non-digital data will be protected and preserved in a locked cabinet at Sheffield Hallam University. All data will only be used for academic purposes. The data will be kept confidentiality for three years after publication. No access to the data will be granted without approval from a member of the research team or you.

What is the benefit of taking part?
If we find that you run in a manner that could potentially lead to injury we will notify you (if you wish) and ask if you would like to attend our laboratory for a subsequent trial to see whether it is possible to change your running pattern with the use of biofeedback.

You will be asked whether you would like to be informed of your own results and the results of the study. If you are interested in either, you will receive the information after the study is completed.

What if I want to leave the study before the end?
You are under no obligation to take part in this study. If you do decide to participate but wish to leave before the study is complete, you are free to withdraw at any time, without prejudice and without having to provide a reason. No disadvantage will arise from any decision to participate or not. If you decide to leave the study, you may also request for your data to be removed.

If you have any concerns, queries or want to discuss your participation after your involvement within the study please don't hesitate to contact the principal investigator (details at end).

Principal Researchers

Principal Investigator Contact Details

Name:	Linda van Gelder
Department:	Centre for Sports Engineering Research
Email:	l.v.gelder@shu.ac.uk
Telephone:	0114 225 2355

Project Supervisor Contact Details:

Name:	Dr. Ben Heller
Department:	Centre for Sports Engineering Research
University Address:	Sheffield Hallam University, Faculty of Health & Wellbeing, 11 Broomgrove Road, S10 2LX Sheffield, United Kingdom
Email:	hwbbh@exchange.shu.ac.uk
Telephone:	0114 225 5764

If at any point you feel that the commitments made in this document are infringed or that your interests are otherwise being ignored, neglected or denied, you should inform Dr Nikki Jordan-Mahy, Chair of the Faculty of Health and Wellbeing Research Ethics Committee, via Sue Wallace (email: s.wallace@shu.ac.uk) who will undertake to investigate your complaint.

9.21 Appendix U: Informed consent, field study

Sheffield Hallam University | Centre for Sports Engineering Research

Participant Informed Consent Form

STUDY: **Measuring running patterns in the field**

Please answer the following questions by ticking the response that applies

	YES	NO
13. I have read the Information Sheet for this study and have had details of the study explained to me.	☐	☐
14. My questions about the study have been answered to my satisfaction and I understand that I may ask further questions at any point.	☐	☐
15. I understand that I am free to withdraw from the study at any time, 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.	☐	☐
16. I agree to provide information to the researcher under the conditions of confidentiality set out in the Information Sheet.	☐	☐
17. I wish to participate in the study under the conditions set out in the Information Sheet.	☐	☐
18. 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): ___________________________________

Researcher's Signature: _______________________________________

Researcher's contact details:
The Centre for Sports Engineering Research | Faculty of Health & Wellbeing | Sheffield Hallam University |11 Broomgrove Road | S10 2LX Sheffield
Email: l.v.gelder@shu.ac.uk | Tel: +44 (0)114 225 2355

Please keep your copy of the consent form and the information sheet together.

9.22 Appendix V: Pre-screening questionnaire, field study

Sheffield Hallam University | Centre for Sports Engineering Research

Pre-Parkrun Questionnaire

Measuring running patterns in the field

Name: ____

Age: ______________Height: _______________ Weight: _______________

Please answer the following questions by putting a circle round the appropriate response or filling in the blank.

1. How many times do you run during a typical week? …….. times a week
2. How many kilometres or miles do you run during a typical week: …….km/mi
3. Do you currently have any form of muscle or joint injury? Yes / No

   If you answered Yes, please give details………………………………………..
   ………………………………………………………………………………
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4. Do you have any previous running-related injuries? For example: stress fractures, inflamed tendons, ACL injuries, etc. Please state the type of injury, how long ago it occurred and duration. Yes / No

   If you answered Yes, please give details ………….……………………….....…
   ……………………………………………………….………………………...
   ………………………………………………………..……………………...
   ………………………………………………………..…………………...
   ..……………………………………………………………...………………
5. Are you allergic to tape or cohesive bandage? Yes / No