The Pose® Method: a biomechanical and physiological comparison with heel-toe running

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Research into endurance running performance (economy, optimal running biomechanics, and injury mechanisms) lacks a universal running technique; however, landing heel-toe identified eighty percent of runners. A new Gravitational hierarchical model of running was developed based upon a novel technique Pose® running, owing to deficiencies in the current hierarchical model (Hay and Reid, 1988) on the interaction of forces involved in running. A major deficiency in the current hierarchical model is viewing gravity as only active during flight. In contrast, the Gravitational hierarchical model defines a gravitational torque as the motive force in running. Ground reaction force is not a motive force but operates according to Newton's third law. The ground can only propel a runner forward via muscle activity, but leg and hip extensor muscles have consistently proven to be silent during leg extension. High Achilles tendon forces at terminal stance suggest the elastic recoil creates a re-bound effect in the vertical direction only, thus reducing work against gravity. Two experienced Pose® runners were compared (study 1) with two experienced heel-toe runners using primary and secondary research variables derived from the Gravitational hierarchical model, which effectively distinguished the two techniques while establishing gravity as the motive force. For example, maximum horizontal acceleration of the centre of mass occurred before maximum horizontal ground reaction force, supporting the Gravitational hierarchical model that only a gravitational torque could create acceleration. Finally, sixteen male recreational endurance heel-toe runners (study 2 using the same primary variables as study 1) were randomly assigned into two groups where one group received a 7-hour Pose® intervention over 7-days while the other group remained as heel-toe runners. A 2 x 2 mixed factorial ANOVA where group (control vs. treatment) and trial (pre to post changes) assessed the primary research variables. Significant interactions were explored using Tukey *post hoc* tests, which found significance (Pose® runners pre-post test) for stance time (P= 0.001), centre of mass to support limb at 25 ms (P= 0.042), centre of mass displacement during stance (P = 0.001), knee flexion angular velocity during stance (P= 0.005) plus swing (P= 0.043) and stride frequency (P= 0.002). After 12-days the Pose® group's post-test time-trial (2400 m) improved by a mean of 24.7 s compared with a 3 s decrease in the heel-toe group. No significant changes pre-post test, were found for an economy run (2400 m) at 3.35 $m \cdot s^{-1}$. A preliminary prospective 3-month injury report found no injury incidence in the Pose® runners compared to six injuries in the heel-toe group. It was concluded, that the Pose® technique is a valid biomechanical technique, which improved performance, while reducing injuries. Future work should further quantify gravity's role in accelerated running by ascertaining whether the horizontal acceleration of the centre of mass also occurs before maximal horizontal ground reaction force.

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION TO THE PROBLEM

The problem of identifying and correcting errors in athletic technique is an important part of sports coaching. Technique represents the actions of internal and external forces on the human body, which determine how the parts of the human body move during a sports performance (Hay and Reid, 1988). Theories relating to technique tend to develop through coaches experimenting in a trial and error approach. In professional sport, athletes push themselves to their body's limit, which often results in injuries (van Mechelen, 1992). Dapena (1984) suggested making a biomechanical template from elite performers technique as a potential solution. Unfortunately, Dapena's method is little better than the trial and error approach, owing to a variety of elite performer's techniques. This precludes trial and error and elite-template methods of technique development as a process for long-term success. A more systematic approach is therefore advised.

Mathematical modelling is a systematic and theoretical approach to analysing sports movement. It uses physical laws that link the model of the performer and their movement (Bartlett, 1999). Mathematical equations represent certain characteristics of the sports movement creating a simplified model of the performance. The mathematical model undergoes simulation (computer modelling) and finally optimisation (finding optimum values that minimise or maximise performance outcomes). However, the complexity of this approach for running is beyond the scope of this thesis.

Hierarchical modelling is another systematic approach. Relationships between the performance criterion (desired aim of the technique) and performance parameters (key performance variables) are established using biomechanical laws (Bartlett, 1997). Development of a hierarchical model precedes data collection (Bartlett, 1997).

Following the model's development, a data collection and analysis for a large range of performers is usually completed. Finally, results from the data are assessed with respect to the hierarchical model (for example, Hay *et al.*, 1981). A hierarchical model functions as the 'gold standard' enabling variations in performance to be quantitatively measured. Hierarchical models can also evaluate individuals or small groups of athletes' technique as opposed to a large range of performers (Bartlett, 1999). This thesis aims to review an established hierarchical model for running (Hay and Reid, 1988; p. 282) while also developing a new Gravitational hierarchical model. The Gravitational hierarchical model will attempt to develop the interaction of the forces involved in running based on gravity as the motive and hierarchically leading force in running.

If force is applied as input to a biomechanical system, the system undergoes a displacement. Ensuing motion creates opposing forces, which are proportional to the displacement. An external force can be evaluated by the degree of energy needed for internal forces used in the displacement. External forces that cause displacement, which do not require large reciprocal internal forces will obviously decrease energy output (Bernstein, 1947). There are two key external forces (ignoring air resistance) involved in running: gravity and ground reaction force. Their combined effects on internal muscle force during the gait cycle need further examination (for example, Fenn, 1930 began work in this area). However, gravity's role as a constant external force in running during stance as well as flight, and its subsequent affect on muscle output is not apparent from Hay and Reid's hierarchical model.

Endurance running instead, has attempted to explore biomechanical research in three main areas. The first area is running economy, which refers to the energy cost of running (Daniels, 1985). The next area is determining an optimal biomechanical profile (Williams, 1985) and finally, it is training without injury (van Mechelen, 1995). Endurance running, including track, road, cross-country and triathlon, has many unanswered questions today from these three areas (Cavanagh, 1990; Novacheck, 1998). For example, the degree to which running biomechanics can be modified to promote a better understanding of the association between metabolic and biomechanical correlates of economy, requires further investigation (Williams and Cavanagh, 1987). Running is a fundamental movement pattern, yet the literature has not identified an optimal biomechanical profile that is universal for all runners. Injury incidence remains between

24-77% (van Mechelen, 1992; Taunton *et al.*, 2002), and this incidence rate has not changed since the 1970's running boom (Krissoff and Ferris, 1979).

Cavanagh (1990; p. 31) stated in a review of the running research literature over the last one hundred years; "*that today we are basically still trying to answer questions posed by Fischer and Fenn over 90 years ago.*" For example, Fenn (1930) suggested more economical runners might waste less energy on forward pressure on the ground.

The literature describes two main running techniques, heel-toe and forefoot ground contact. Approximately eighty percent of endurance runners are heel-toe runners, making them the predominant technique compared to twenty percent of forefoot runners (Kerr *et al.*, 1983). Therefore, heel-toe running will be used as the current norm for this thesis. Elite endurance heel-toe runners have a few biomechanical variables in common, such as increased forward trunk lean (Girardin and Roy, 1984), increased knee flexion during stance (Kerdok, *et al.*, 2002) and decreased vertical oscillation (Williams and Cavanagh, 1987). However, there are exceptions to these findings (Cavanagh and Williams, 1982), suggesting the heel-toe technique is identified predominantly by initial ground impact via the heel.

Several descriptions of 'good' running have also been suggested in the trade literature:

"*Good runners run tall, they tend not to hunch or lean. There is an economy and integrity in their form and movement. Their heads remain poised and balanced on top of their spine. They run smoothly, lightly with the brakes off, they don't pound or 'excavate' on every stride. Good runners run with awareness.*" (Alexander, 1989; p. 12).

Percy Cerutty, coach of Olympic gold medal winner Herb Elliot states:

"*The head rests loosely on the shoulders, that is, it is not held rigid. It should be capable of movement as the needs of the athlete demand. In my techniques I often test this rigidity of an athlete. Many are quite incapable of turning their heads freely on their neck and shoulders. Any rigidity here spreads right through the whole musculature. Keep the head and neck free and the rest of the moving parts will tend to be free.*" (Simms, 2003; p. 31)

The trade and scientific literature have only made limited suggestions on improving running technique, because no one has developed a running method that explains how to effectively combine all the forces involved in running. Hay and Reid (1988) provide the only attempt at modelling running. However, there are deficiencies with their model, for example, viewing the constant force of gravity as only active during flight and not relating gravity to forces exerted (muscle and joint forces) and the time forces act despite gravity being a constant force.

In 1977, in the Soviet Union, a track and field coach and university lecturer in biomechanics was wrestling with the question of how to teach running. Dr. Romanov rejected popular wisdom that running is a simplistic movement skill, and that the best runners were genetically predisposed to success combined with hard training. He sought a comprehensive technique that would create a universal running method. He subsequently viewed teaching of other track and field events, throwing, jumping, and other movement skills such as ballet, dancing and the martial arts. Technique, he concluded, was of paramount importance for these sports, because, he realised that complex skills such as ballet and karate are broken down into simple movements that can be learned separately (i.e. Poses). Complex movements therefore derive from individual Poses. A complex skill is achieved, only after each Pose through numerous repetitions has thoroughly trained the neuromuscular pathways.

Using videotape of the world's best runners, Dr. Romanov identified the running Pose®. The Pose® method technique is based upon a running Pose®, which is a whole body Pose®, that vertically aligns the shoulder, hip and ankle of the support leg, while standing with the weight on the ball of the foot. This creates a 'S' like body shape. The runner then moves from this Pose® on one leg to the other by potentially falling forward via a gravitational torque. The support foot is pulled vertically upwards from the ground using the hamstring muscles as the body falls forward, while the ipsilateral leg is not driven forwards during flight but allowed to fall to the ground via gravity to land in the next running Pose®. Many technique and strengthening drills have been developed to teach the runner to fall forwards while pulling their support foot from the ground using their hamstring muscles, and at the same time not driving their swing leg forwards via the hip flexor muscles (Romanov, 2002). Romanov (2002) states the running Pose® is a theoretically optimal position for external forces to cause displacement, without requiring large reciprocal internal forces.

Dallam *et al.* (2005) identified a profile of economical endurance runners from the literature. This profile included a reduced vertical oscillation, stance time and peak vertical ground reaction force, alongside increased trunk lean and knee flexion during support. Eight heel-toe male endurance runners trained in the Pose® method by Dallam *et al.* (2005) found the above variables described Pose® running remarkably well, yet their economy measures showed poorer economy for their Pose® runners. These conflicting results may originate from running on a treadmill, which inhibits Pose® running owing to the foot being pulled backwards. Hence, clarification is needed on whether Pose® running is more economical using over-ground running.

Arendse *et al.* (2004) explored Pose® running (3-years after Dallam *et al.*, 2005) in reference to its similar lower-limb geometry with backward running in the hope it may aid in injury prevention. They identified a distinct biomechanical profile for Pose® running (supporting Dallam *et al.*, 2005) compared to heel-toe and forefoot running. However, they administered no performance test nor did they collect injury data for their runners. This thesis will rectify these omissions and will attempt to explain the distinct biomechanical profile of Pose® running.

Running technique is currently dependant on whether a runner lands on the forefoot or heel-toe (Kerr *et al.*, 1983). A universal running technique (which applies to all runners) that identifies the timing of all the forces with the displacement and timing of the body segments during the gait cycle would be useful. The literature has compared elite with recreational runners in the hope of distinguishing an elite runner's profile (Miura *et al.*, 1973; Williams and Cavanagh, 1987). This method though has failed to establish a clear universal biomechanical profile of an elite runner. This thesis will take a different approach. Owing to the scale of unanswered problems in endurance running within the literature, the author seeks to begin with the Pose® method (Romanov, 2002) as a universal running technique. Then, evaluate the Pose® method theoretically to determine whether it is a universal running technique using the new Gravitational hierarchical model. A biomechanical comparison with the predominant technique of endurance running (heel-toe) using experienced heel-toe and Pose® runners will follow. Next, evaluate the Pose® method's effectiveness with a group of male heel-toe endurance runners by training half of them in Pose® running and measuring performance via a 2400 m time trial and a 2400 m economy run. Biomechanical variables will distinguish between the two running techniques using inferential statistics. Finally, using a 3-month prospective injury study determine injury incidence in the Pose® and heel-toe running techniques.

1.2 STATEMENT OF PURPOSE

Several beliefs predominate in the running community that have hindered the development of a universal technique of running. For example:

1. Running technique is a simplistic movement pattern;
2. Individual differences between people make it impossible to have a universal technique for all runners (Nytro, 1987).
3. Various distances and speeds require a different running technique;
4. There are numerous points of view based on subjective and unsubstantiated non-biomechanical models (Wallack, 2004); and
5. Technique being solely associated with ground contact, i.e. eighty percent of all endurance runners land on their heels (heel-toe runners) and twenty percent of all endurance runners land on the front part of their foot (mid and forefoot strikers) (Kerr *et al.*, 1983; Whittle, 1991), whereas sprinters land on the forefoot (Mann, 1980).
6. Hay and Reid's (1988; pp. 287-288) hierarchical model highlights the current thinking that runners push off the ground via leg extension. The forces exerted box in their model represents shoulders, hips, knees, ankles and other joint forces (Hay and Reid, 1988; pp. 264 and 287-288). This focus on leg extension via muscle force has hindered development of other viewpoints on propulsive forces in running such as gravity being motive.

The primary aim of this thesis is to compare the Pose® method technique (Romanov, 2002; Arendse *et al.*, 2004; Dallam *et al.*, 2005) with the heel-toe running technique. Development of a new Gravitational hierarchical model based on the Pose® method using the laws of physics will enable the Pose® technique's systematic evaluation. The Gravitational hierarchical model and the current hierarchical model (Hay and Reid, 1988; p. 282) are reviewed highlighting the different biomechanical theories of running. There are deficiencies with Hay and Reid's model, for example, viewing the constant force of gravity as only active during flight and not relating gravity to forces exerted and the time forces act. Therefore, Hay and Reid's model does not systemise the forces involved in running but acts as general descriptor, whereas, the Gravitational hierarchical model will aim to structure these forces. A comparison of the Pose® and heel-toe running techniques will follow using two experienced male Pose® and heel-toe runners utilising the primary and secondary research variables (study 1; chapter 5) derived from the Gravitational hierarchical model. Upon establishment of the Pose® method technique, a group of male heel-toe recreational runners (study 2; chapter 6) will participate in a repeated measures design. An economy and time trial run will give the participants pre-test baseline physiological measures while the primary research variables will provide a biomechanical profile. The post-test will determine whether there is an improved performance on the economy and 2400 time trial run resulting from the potential biomechanical changes in the Pose® group from a 7-hour Pose® training intervention. A 2 x 2 mixed factorial ANOVA will assess the main effects of group (control vs. treatment) and trial (pre to post changes) on the primary research variables. Tukey's tests of honestly significant differences will be used to assess individual cell differences *post hoc*. A prospective 3-month injury study on all the participants post intervention will seek to determine injury incidence between the two running techniques.

Currently unanswered research questions on running biomechanics and their effects on performance, which this thesis aims to answer, include:

- Can the Gravitational hierarchical model based on the Pose® running technique clarify the relationship and timing of the forces involved in running?
- Can the Pose® running technique improve performance (economy and speed)?
- Can running injuries be reduced by the application of the Pose® running technique?

1.3 CHAPTER ORGANISATION

Chapter 2 reviews the literature on running economy, optimal running biomechanics, and injury mechanisms. These topics are reviewed using data collection tools, such as, a force plate, electromyography and two or three-dimensional analysis. The findings are then summarised to clarify whether a potential universal running technique is evident from the literature.

Chapter 3 conducts a detailed analysis of the forces involved in running while evaluating the Pose® method to determine if it is a universal running technique. A new

Gravitational hierarchical model is developed and compared with Hay and Reid's (1988; p. 282) hierarchical model of running.

Chapter 4 evaluates the experimental procedures. A statement of the problem is given. Hypotheses and the primary and secondary research variables derived from the Gravitational hierarchical model are stated. The research design and statistical model are specified.

Chapter 5 compares data for study 1 from two experienced male participants in the Pose® and heel-toe techniques of running. Kinetic and kinematic (primary and secondary) variables established from the Gravitational hierarchical model, distinguish the two running techniques. The Pose® method is discussed using the Gravitational hierarchical model.

Chapter 6 presents results from study 2 using sixteen male heel-toe endurance runners, where eight were trained for 7-hours in Pose® running (treatment/Pose® group). Sixteen 2 x 2 mixed factorial ANOVAs will assess the main effects of group (control vs. treatment) and trial (pre to post changes) on the primary research variables (physiological and biomechanical) derived from the Gravitational hierarchical model. Tukey's tests of honestly significant differences will be used to assess individual cell differences *post hoc*. A 2400 m time trial and economy run will record physiological performance, optimal running biomechanics will be documented via a laboratory assessment and a 3-month prospective injury study will record injury incidence.

Chapter 7 summarises the findings of the previous chapters and suggests possible areas for future research.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter follows biomechanical outlines from several comprehensive reviews of running (Williams, 1985; Novacheck, 1998): Economy, an optimal biomechanical profile and sustained injuries. Each one of these areas aims to improve running performance. Running economy research attempts to identify patterns of motion which improve economy and hence performance. Identification of an optimal biomechanical profile may reveal a universal running technique, which should improve performance in athletes of all abilities. High injury prevalence in runners can negatively influence performance.

2.2 RUNNING ECONOMY

2.2.1 Introduction

Economy and efficiency of running are often incorrectly applied.
"*Efficiency of movement refers to the mechanical energy produced relative to the metabolic energy used to cause the movement*" (Robergs and Roberts, 2000; p. 69).

Mechanical work is a key component of the work-energy relationship for efficiency of movement, which divides into two areas during constant speed running. Firstly, external work is the sum of work required to accelerate the centre of mass of the whole body, plus work completed against gravity. Secondly, are the work done by the limbs around the centre of mass, which is internal work. External work is higher than internal work up to speeds of 5.5 $m \cdot s^{-1}$, above this speed the work ratio is reversed (Cavagna and Kaneko, 1977). A major problem arises, however, estimating the storage and return of elastic energy associated with high muscular efficiencies (Cavagna *et al.*, 1964; Williams and Cavanagh, 1983; Kubo *et al.*, 2000). In eccentric exercise, mechanical energy can increase linearly, however, this appears to be individual owing to increases in stretching velocity of lower-limb muscles (Auro and Komi, 1986). Although initially this method seemed plausible, mechanical efficiency measures have varied enormously (22.7-75%) making subtle observations of mechanical changes in runners obsolete (Margaria, 1968; Asmussen and Bonde-Petersen, 1974; Kaneko *et al.*, 1983; Bosco *et al.*, 1987). Running economy presented itself as an appropriate and alternative measure of energy expenditure associated with running. Economy and efficiency however, are not synonymous (Robergs and Roberts, 2000).

Running economy refers to the energy cost of performing movement (Bransford and Howley, 1977; Daniels, 1985). Research into running economy tries to identify patterns of motion that improve economy and hence performance. Economy is defined as, the oxygen cost per kilogram of body mass per kilometre run (Cavanagh and Williams, 1982; Morgan *et al.*, 1989; Bergh *et al.*, 1991; Noakes, 2002) with substantial individual variation in running economy observed among those running at the same speed (Mayhew, 1977; Daniels, 1985). Meaning, economical runners consume less oxygen relative to body mass when running at a submaximal intensity. Changes in running economy link to the biomechanics of running technique (Bransford and Howley, 1977; Cavanagh and Williams, 1982; Daniels, 1985) with 54% of the variation in running economy attributed to biomechanical variables (Williams and Cavanagh, 1987). Further variance may have been unidentified owing to nonlinear relationships with the biomechanical variables. Increased running training (volume) can change running economy in individual runners (Bransford and Howley, 1977; Conley and Krahenbuhl, 1980). However, several studies have shown no improvement in running economy when training was increased (Costill *et al.*, 1973; Wilcox and Bulbulian, 1984). Furthermore, intra-individual oxygen uptake variation exists between different test dates and running speeds (Morgan *et al.*, 1987). Nevertheless, the term economy is the accepted physiological criterion for efficient running performance (Cavanagh and Kram, 1985). The next section discusses biomechanical variables associated with economical running.

2.2.2 Kinematics and running economy

Impact patterns

Research identifies two patterns of landing in runners: forefoot and rear foot or heel-toe (rear foot and heel-toe are used synonymously for this thesis) runners (Whittle, 1991). Nilsson and Thorstensson (1987) reported no significant difference in running economy between a group of six forefoot and six rear foot strikers; even when the runners voluntarily changed from fore to rear foot and vice versa. In contrast, Williams and Cavanagh's (1987) work indicated that heel-toe runners maybe more economical in their running style, although this was not consistent across their participants. For example, the fastest 10-km runner from their study was a heel-toe runner who had the third poorest economy. However, impact patterns by virtue of the kinetic chain are influenced by stride-length, stride frequency, joint angles, and the position of the centre of mass at impact and terminal stance (Mero *et al.*, 1992).

Stride length and stride frequency

Stride length is defined as successive contacts of the same foot, with step length (half a stride) as successive contacts of opposite feet (Cavanagh and Williams, 1982). Stride or step length is used depending upon the paper reviewed. However, step length can denote the distance the centre of mass travels during flight (Cavagna *et al.*, 1976). Stride length is one of the few variables established by direct experimental evidence to affect running economy (Anderson, 1996). Curvilinear increases in aerobic demand occur when stride length increases or decreases at any given speed from one self-selected by the runner (Hogberg, 1952; Knuttgen, 1961; Morgan *et al.*, 1989; Kyrolainen *et al.*, 2000a). Cavanagh and Williams (1982) report running economy as the primary reason for runners—10 well-trained participants—making self-selected stride lengths and stride frequencies. The optimal economical solution identified was a combination of self-selected stride lengths and stride frequencies. Cavanagh and Kram (1990) documented that stride length increased preferentially over stride frequency with increasing speed up to 7 $m \cdot s^{-1}$. Again, it appears that economy dominates the choice of stride length. Martin *et al.* (2000) state the typical explanation for this strategy (i.e., change in stride length rather than stride rate) is that it requires less energy to lengthen the stride within reasonable limits than to increase stride rate.

A four-year study by Nelson and Gregor (1976) in contrast observed varsity distance runners decrease their stride length at a given speed as their performance improved. This perhaps suggests that freely chosen stride length is possibly a variable quantity over a runner's life or they self-selected over-striding patterns to begin with. Morgan *et al.* (1994) monitored runners who self-selected an over striding gait pattern. They responded positively to step length optimisation training, because economy improved as step length decreased.

Rowland (1989) and Unnithan and Eston (1990) noted boys produced shorter stride lengths and higher stride frequencies than men, but the oxygen demand per stride was similar in both groups. It is possible that height and body mass in boys affect movement differences with their lower-limbs, which constitutes a substantial part of metabolic expenditure. Williams and Cavanagh (1987) however, found no differences in anthropometric measures for segmental lengths and masses in relation to an adult runner's economy.

In reference to step frequency, Kaneko *et al.* (1987) measured energy consumption during running at varying step frequencies while speed was kept constant at 2.5 $m \cdot s^{-1}$, 3.5 $m \cdot s^{-1}$ and 4.5 $m \cdot s^{-1}$. Energy was minimized for all three speeds at approximately the same step length, at about 2.9 $steps \cdot s^{-1}$, corresponding closely to the freely chosen step frequency of 2.8 $steps \cdot s^{-1}$. Kyrolainen *et al.* (2000b) used seven triathletes who ran a marathon to induce fatigue; step frequency increased and step length decreased. The authors suggested the triathletes compensated for impaired neuromuscular function with increased muscle activity, causing weakened economy. Cavanagh and Kram (1985) using twelve endurance runners recorded step frequency for running speeds of 3 $m \cdot s^{-1}$ to 4.2 $m \cdot s^{-1}$. Step frequency increased by 4%, in contrast to a 28% increase in stride length over the speed range. However, two runners had similar stride frequency across the whole speed range. They concluded that there might be an individual economical stride frequency at different speeds in distance running.

Lower and upper limb kinematics

Maximum thigh extension at terminal stance had a positive correlation (r = 0.53) with increased economy (increased oxygen consumption) from 13 elite males (Williams and Cavanagh, 1986). In contrast, thigh extension in 31 recreational runners showed no correlation with oxygen consumption (Williams and Cavanagh, 1987). Williams *et al.* (1987) did not provide an explanation for these opposing results. Miura *et al.* (1973) associated thigh extension with increased push-off at terminal stance, identifying this as 'good' and associated with their elite runners (14 min 48-56 s for 5 km), but recorded no economy data to support this. Further, elite runners' biomechanical profiles—thigh extension—may differ from recreational runners in this respect, owing to running speed differences.

Cavanagh *et al.* (1977) using elite runners demonstrated that more acute knee angles during the swing phase enhanced economy. Theoretically, greater knee flexion allows a faster recovery of the lower-limb by decreasing the moment of inertia (Bailey and Pate, 1991). In support, Enomoto *et al.* (1999) recommended a rapid recovery of the thigh required a flexed lower-limb, and this action was associated with efficient runners. Martin (1985) and Meyers and Steudel (1985) added leg weights to the distal end of runners' lower-limbs, producing oxygen consumption submaximal increases. It was evident an increased moment of inertia for the lower-limb reciprocally increased oxygen consumption.

Maximum knee flexion during support has also been associated with improved running economy (Williams and Cavanagh, 1987). Maximum knee flexion correlated significantly with less contact time, shank angle at impact and the second vertical ground reaction force peak. Improved economy was also associated with less extension of the knee (in contrast to Miura *et al.*, 1973) during terminal stance, and less rapid knee flexion velocity during stance. Williams and Cavanagh (1987) speculated lower-limb kinematics cause subtle changes in muscular activity patterns before and during support that are related to differences in metabolic energy costs. An alternative explanation is lower knee flexion, shank angle at impact, plus the second vertical ground reaction force peak and the reduction in contact time, were a result of the centre of mass moving anterior of the support foot more quickly allowing earlier forward progression.

Maximum ankle plantar flexion angles at terminal stance were a mean of 10° more for good runners (mean marathon time 2:34:40) than elite runners (mean marathon time 2:15:52) (Cavanagh *et al.*, 1977). Decreased plantar flexion would logically be associated with less push-off and lower muscle force. In support of this idea, Williams and Cavanagh (1987) found more economical runners had 6.4° less plantar flexion at terminal stance than their least economical runners.

Williams and Cavanagh (1987) and Anderson and Tseh (1994) demonstrated a trend for more economical runners to use less arm movement, measured by wrist excursion during one stride. These economical runners have lower arm amplitudes, which may indicate a skilled-balance mechanism rather than a method of forward drive. Arm action reduced side-ways rotations in runners giving further support to this theory (Hinrichs, 1987). Mann (1981) also concluded from extensive analysis of sprint running that the upper-limb's contribution is balance maintenance only. Therefore, arms appear not to contribute to the drive of the body in the anterior and posterior direction (Hinrichs *et al.*, 1987), and were not studied in this thesis.

Vertical oscillation of the body's centre of mass and trunk lean

Williams and Cavanagh (1987) found a consistent, but non-significant trend for oxygen cost, associated with lower vertical oscillation of the body's centre of mass in good and elite runners. Logically, excessive vertical oscillation would be ineffective for horizontal displacement, yet many individuals run economically despite high vertical oscillation. There is however, some general support for improved running economy with lower vertical oscillation (Slocum and James, 1968; Cavanagh, *et al.*, 1977). Several possibilities exist for the conflicting results. Firstly, measurement of vertical oscillation differed between using head-markers or displacement of the centre of mass. The use of head-markers assumes that trunk and neck angles remain neutral for each runner. Secondly, the variety of biomechanical variables associated with running economy, and their various combinations, make identification of one variable as an absolute economical variable in all runners unlikely. The source of vertical oscillation should be an important economy inquisition. Vertical oscillation can transpire from leg extension or the reciprocal flexion and extension of the stretch-shortening cycle. If certain runners predominantly utilise the stretch-shortening cycle, which requires lower muscle activity (Cavagna *et al.*, 1964), this provides a possible explanation for economy differences.

Williams and Cavanagh (1987) found runners with a mean forward trunk lean, relative to the vertical axis, more economical at 5.9° compared with 3.3° and 2.4°. However, excessive forward trunk lean may create increases in economy (James and Brubaker, 1973). There appears to be an optimal position for the trunk and by association the centre of mass position, to maintain postural alignment for improved running economy.

2.2.3 Ground reaction force and running economy

Increased stance time correlated positively ($r = 0.49$) with poorer economy (Williams and Cavanagh, 1986; Williams and Cavanagh, 1987), yet not all studies registered this relationship (Cavanagh *et al.*, 1977). An explanation for variations in stance time in the three studies is use of both fore and / or heel-toe runners. For example, Williams *et al.* (1987) used elite females (with no heel-toe or forefoot classification), whereas Williams and Cavanagh (1987) used recreational runners, who were both forefoot and heel-toe runners. Stance time differs between forefoot and heel-toe runners (Arendse *et al.*, 2004).

Williams and Cavanagh (1987) found significantly lower first peaks for vertical ground reaction force, plus less anterior and posterior ground reaction force in economical recreational runners. They suggested lower extremity kinematic demands just before ground contact, might have a significant affect on muscles both before and during support, which in turn can affect economy. Forefoot strikers rely more heavily on the musculature to assist with cushioning than heel-toe runners, who depend more heavily on footwear and skeletal structures to cushion and support impact force (Williams and Cavanagh, 1987). Kyrolainen *et al.* (2000a) speculated lower performances from poorer economy stem from limited action of the hamstrings. They linked poor economy with limited hamstring activity and higher braking forces at foot contact. Heise and Martin (2001) found total vertical impulse and net vertical impulse correlated with running economy ($r = 0.62$, $r = 0.60$, respectively) indicating a moderate correlation for stance time and the amount of force applied during stance. Inferred, was increased muscle support during stance produced reciprocal increases in economy.

2.2.4 Electromyography and running economy

Relationships between running economy and the temporal electromyography characteristics of biarticular leg muscles were quantified in a group of well-trained runners (Heise *et al.*, 1996). Nine runners completed three test sessions: a determination of maximal aerobic demand, an accommodation session at the experimental speed of

4.13 m·s^{-1} and a session during which electromyography and running economy data were collected at 4.13 m·s^{-1} (see figure 2.2.1). Measures of muscle onset, on-time durations and on-time co-activation durations were calculated from: rectus femoris, medial hamstrings, lateral hamstrings and gastrocnemius muscles. Earlier onset of rectus femoris during swing phase and a shorter duration of hamstring-gastrocnemius co-activation during swing were associated with economical runners. Individuals who exhibited more co-activation (improved coordination) between biarticular muscles during the stance phase of the running cycle tended to be more economical. Economical runners produced different activation patterns with their biarticular muscles, which cross two joints—ankle-knee and knee-hip— indicating economical runners had improved segmental coordination.

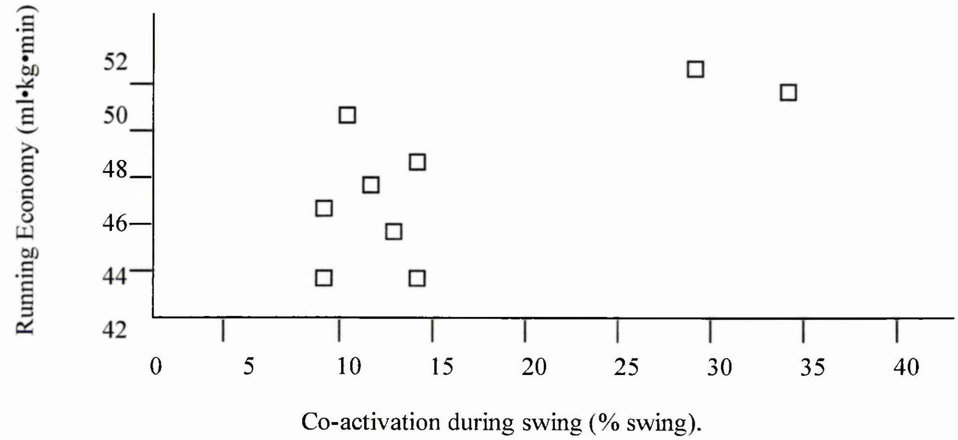


Figure 2.2.1 Scatter-plot of running economy versus hamstring-gastrocnemius co-activation during swing (Heise *et al.*, 1996). Note the position of the two most uneconomical runners.

Kyrolainen *et al.* (2000a) using seventeen well-trained endurance runners, found electromyography for the biceps femoris—a biarticular—muscle increased across thirteen different speeds. As running speed increased, power in the lower-limb joints increased in the ground push-off phase. This provided a weak correlation with muscle activity and energy expenditure ($r = 0.48$ at $p < 0.05$). However, no economy data were collected.

The stretch–shortening cycle of muscle contraction

The mechanical efficiency of running exceeds the efficiency of the conversion of chemical energy to kinetic energy by muscles (Cavagna and Kaneko, 1977; Winter, 1978; Cavanagh and Kram, 1985). Elastic strain energy stored during eccentric contractions of running is subsequently released during concentric contractions, which makes a substantial contribution to propulsion (Cavagna *et al.*, 1964; Cavagna and Kaneko, 1977; Hinrichs, 1990; Jung, 2003). A reduction in support time aids utilization of stored elastic energy in the muscle mechanisms, (Zatsiorsky, 1995; Paavolainen *et al.*, 1999a). Although there is no method of quantifying storage of elastic energy, there is a consensus that this phenomenon contributes to both efficiency and economy of movement (Cavagna and Citterio, 1974; Cavagna *et al.*, 1977; Winter, 1978; Luhtanen and Komi, 1978; Cavanagh and Kram, 1985; Komi, 2000). The runner's body possesses kinetic energy while the muscle-tendon unit contains potential strain energy. An optimal and complimentary combination of potential strain energy and conserved kinetic energy would theoretically improve a runners' economy.

2.3 AN OPTIMAL BIOMECHANICAL RUNNING PROFILE

2.3.1 Introduction

Cavanagh *et al.* (1985; p. 404) elaborated on whether elite runners exhibit a biomechanical profile that is substantially different from recreational runners:

"*Many observers might suggest that elite athletes have practiced their event so frequently as to have self-optimised their movement patterns. It is a mistake, to assume elite athletes have perfect body structures and ideal movement patterns. The elite athlete cannot succeed without excellent physiological attributes. However, he or she can succeed in spite of poor running mechanics and body structure.*"

They highlighted that identifying ideal running biomechanics from elite runners can be problematic. This section will use elite and recreational runners, to appraise kinematic analysis, ground reaction force and electromyography. Several points are worth noting when reviewing these areas of biomechanical research. Firstly, as stated earlier there are two types of foot contact with the ground in running. Kerr *et al.* (1983) and Whittle (1991) identified eighty percent of all runners land on the heel (heel-toe runners) and twenty percent of all runners land on the front part of the foot (forefoot runners). As speed increases, runners often change from a heel landing to a forefoot landing (Kerr *et al.*, 1983; van Mechelen, 1995). Secondly, attempts to quantify running biomechanics fall within two methods (Williams and Cavanagh, 1987): measures sensitive to the entire running cycle such as mechanical power, while other studies measure certain variables at or between discrete points within the gait cycle, such as knee flexion at impact.

No definitive relationships exist between mechanical power and economy (Norman *et al.*, 1976; Kaneko *et al.*, 1983). Calculated power varies widely between studies depending on which assumptions were made (Norman *et al.*, 1976; Williams and Cavanagh, 1983; Morgan *et al.*, 1989), for example, inaccuracies in modelling the runner as a multi-segment rigid body or choice of filter and cut-off stride frequencies applied to the kinematic data (Arampatzis *et al.*, 2000). Mechanical power is, therefore, not a sensitive enough measure for running performance evaluations. Williams (1990) stated, "*that a multitude of variables may be used to describe running action and it is therefore difficult 'a priori' to know which variables to select.*" Selecting too few may overlook vital variables while collecting too many variables may not enable identification of relationships between them. This problem confounds determination of an optimal running profile. Collecting many variables and using a factor analysis procedure to identify independent sets of variables is one method (Williams and Cavanagh, 1987). From this large number, a smaller set of variables may then be analysed in more detail. Williams (1990) recommended this method for each study even though this could be a time consuming approach.

There is another option for identifying an optimal biomechanical profile: construction of a hierarchical model via identifying relationships between various performance variables and the performance criterion (Bartlett, 1997; Glazier *et al.*, 2003). Models of this type eliminate any arbitrary selection of performance variables, and specify critical relationships between these variables and the performance criterion based upon the laws of physics. This thesis adopts this approach.

2.3.2 Running kinematics

Introduction

The kinematic review will only appraise biomechanical variables of running substantiated in the literature. Most studies are descriptive, with only a few finding causative relationships between certain biomechanical variables and running performance (Williams, 1985; McClay, 2000).

Kinematics of the Centre of mass

Vertical oscillation of the centre of mass decreased with increased running speed (Luhtanen and Komi, 1980; Ito *et al.*, 1983a). For example, Luhtanen and Komi reported vertical oscillations of 10.9 cm, 8.6 cm, and 6.7 cm for speeds of 3.9 $m \cdot s^{-1}$, 6.4 $m \cdot s^{-1}$, and 9.3 $m \cdot s^{-1}$ respectively, for six runners. Ito *et al.* (1983b) obtained similar results for speeds of 1.9 $m \cdot s^{-1}$ to 6.1 $m \cdot s^{-1}$, while also observing the vertical oscillation of the centre of mass decreased during contact but increased slightly during flight as speed increased. If vertical oscillation decreases and vertical ground reaction force increases (Cavanagh and Lafortune, 1980; Roy, 1982; Hamill *et al.*, 1983) at faster running speeds, logic dictates there is less vertical work. The increased ground reaction force reflects increased acceleration of the centre of mass, whereas decreased oscillation may reflect an increased angle swept by the lower-limb (Ferris *et al.*, 1999).

Cavanagh and LaFortune (1980) found a mean decrease in the horizontal velocity of the centre of mass of 0.18 $m \cdot s^{-1}$ during the braking phase for seventeen participants running at 4.47 $m \cdot s^{-1}$. The propulsive phase found a mean increase of 0.27 $m \cdot s^{-1}$. Wide variability exists between runners, for changes in horizontal velocity of the centre of mass during support (Fenn, 1930; Bates *et al.*, 1979). Perhaps the variability found in the horizontal velocity of the centre of mass during stance exists because impact patterns differed between the runners measured. For example, if the foot lands further ahead of the centre of mass at impact for one runner compared to others, a greater braking effect can occur (Fenn, 1930; Deshon and Nelson, 1964; Cavanagh *et al.*, 1977; Bates *et al.*, 1979; Kunz and Kaufman, 1981; Girardin and Roy, 1984; Hinrichs, 1990). Landing on the heel as opposed to the forefoot may decrease horizontal velocity at impact or vice versa. Impact patterns also affect stance-limb impact angles, at the hip, knee and ankle, via the kinetic chain (Bartlett, 2000), which subsequently alter the centre of mass's vertical displacement (Lee and Farley, 1998). Lower-limb angles, centre of mass and foot position at impact, therefore, have an important relationship to reductions in horizontal velocity of the runner.

In an extensive evaluation of running, Fenn (1930) combined vertical and horizontal movements of the centre of mass within the body in the sagittal plane. In general, the centre of mass moves diagonally upwards and backwards (stance), then, reversing to go forwards and downwards (swing) within the body during the gait cycle. Only the slowest runner (6.91 $m \cdot s^{-1}$ compared to 7.22 $m \cdot s^{-1}$ and 8.5 $m \cdot s^{-1}$) had their centre of mass pass through a negative position in relation to their centre of mass in the standing position. Fenn (1930) linked decreases in horizontal velocity of the body at impact with position of the centre of mass in relation to their anatomical standing position. His faster runners produced positive scores showing a forward position in relation to their standing centre of mass location. The data clearly indicated that the body is pushed forwards from the hip at foot contact (hip velocity exceeded that of the neck), because the body's centre of mass is in a positive position, with respect to their anatomical standing position at foot contact. Slocum and Bowerman (1961) state in reference to the cause of deceleration of the centre of mass:

"*A simple force diagram will reveal that the further ahead of the body the foot strikes the ground, the more acute the angle and the greater the deceleration from ground resistance.*"

Deshon and Nelson (1964) also found that runners that are more proficient kept their foot as close as possible beneath their centre of mass. Mann and Herman (1985) using all sprint finalists (100 m, 200 m and 400 m) from the 1984 Olympics, determined Gold medallist's centre of masses were 0.217 m behind the foot at impact compared to Silver medallists at 0.284 m and eighth position with 0.327 m.

Potential and kinetic energy of the centre of mass in running are minimum at mid-stance. The knee is maximally flexed at mid-stance—the centre of mass at its lowest point—which coincides with the braking phase during the first half of stance when horizontal velocity of the centre of mass is reduced (Enomoto *et al.*, 1999). During the second half of stance, kinetic energy of the centre of mass increases owing to the accelerating affect of ground reaction force and gravity. However, kinetic and potential energy in running are nearly in phase with each other (see figure 2.3.1). Exchange of kinetic and gravitational potential energy conserves less than 5% of the mechanical work required to lift and accelerate the centre of mass (Cavagna *et al.*, 1964). A biomechanical intervention that could reduce braking force would conversely preserve the centre of mass's kinetic energy. In fact, Enomoto *et al.* (1999) found an improvement in mechanical energy conservation owing to lower deceleration of the centre of mass in the first half of support.

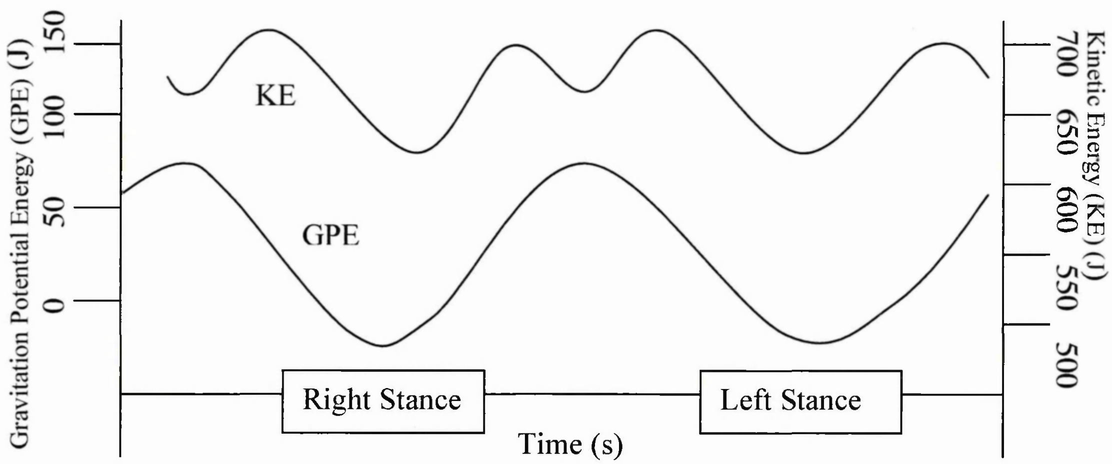


Figure 2.3.1 Running at 3.8 m·s^{-1}, the kinetic energy fluctuations of the centre of mass are approximately in phase with the gravitational potential energy fluctuations. Stance phases are identified at the bottom of the graph (Ferris *et al*., 1996; p. 260).

Estimated potential strain energy for a 70 kg man's total energy turnover in each stance phase was 100 J at 4.5 m·s^{-1} (Ker *et al*., 1987). They estimated 35 J are stored as strain energy in the Achilles tendon and 17 J in the arch of the foot, with more stored in the quadriceps and patella tendons. Strain energy can reduce half of the energy needed by muscles, for instance, when acting as brakes at impact or producing work at terminal stance (Ker *et al*., 1987). This essentially reduces the muscles shortening and lengthening action owing to the tendon being stretched while the muscles holds tension (Alexander, 1992; Novacheck, 1998).

Spring–mass model

Spring-like motion of a bouncing ball models oscillation of a runner's centre of mass (figure 2.3.2). The spring-mass model consists of a single linear spring (leg-spring) and a point-mass that is equivalent to the centre of mass (Alexander, 1988; Blickhan, 1989; McMahon and Cheng, 1990). Leg-spring stiffness represents the overall stiffness of the integrated musculoskeletal system. During early stance the leg-spring compresses (leg flexion), and then lengthens (leg extension) for the second half of stance. This model (figure 2.3.2) describes and predicts the dynamics of running remarkably well (Farley and Gonzalez, 1996; Fukunaga, *et al*., 1997).

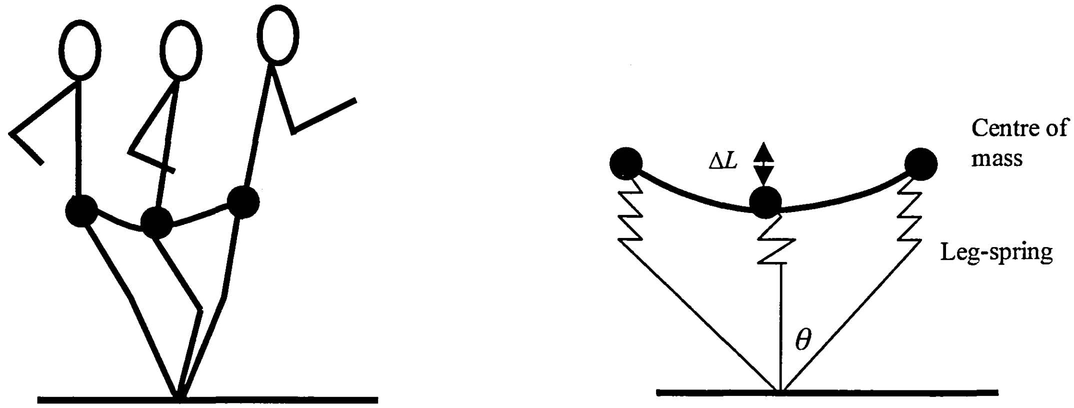


Figure 2.3.2 A spring-mass model and a stick figure representation of a single stance phase (Ferris and Farley, 1997). The model consists of a linear spring representing the leg and a point mass equivalent to body mass. This figure depicts the model at initial contact (left position), at mid-stance (middle position) and terminal stance (right position). ΔL = change in length.

Dynamic interaction between the stance leg and the ground are important: leg stiffness seeks to express this relationship. Components of leg stiffness include vertical excursion of the body's centre of mass, stance time and ground reaction force (McMahon and Cheng, 1990; Farley and Gonzalez, 1996). Leg stiffness is defined as the ratio of ground reaction force to the compression of the leg-spring (ΔL) at the instance of mid-stance when the leg is maximally compressed (figure 2.3.2). Increased ground reaction force produces an increased leg-stiffness ratio. Conversely, an increased knee flexion reduces leg stiffness. Running on five different surfaces of varying stiffness ranging from 75 to 945 kN·m^{-1}, a 12.5 fold change; knee angle increased by 2.5% as surface stiffness decreased while time of ground contact did not significantly change (Kerdok *et al.*, 2002). Kerdok *et al.* (2002) credited changes in leg-spring to local joint stiffness variations and overall limb posture adjustment. The more compliant running surface was attributed to leg-spring change, because it acts as an elastic substrate capable of storing and returning mechanical energy in this case, 1.8 W of energy metabolism.

Leg stiffness remains virtually the same for running speeds between 2-6 m·s^{-1} (He *et al.*, 1991), although as stride length increases stiffness decreases by up to 51% (Derrick *et al.*, 2000). To maintain leg stiffness across the endurance speed range the angle swept by the leg during stance increased enabling decreased stance times (figure 2.3.2; angle θ). Owing to the larger angle swept by the leg at faster speeds, the vertical displacement of the centre of mass is less at faster speeds, which reduces stance time (Ferris *et al.*, 1999). Alterations in leg stiffness while running are possible. Leg stiffness occurs with a change in stride frequency (Farley and Gonzalez, 1996), to reflect say, off-set changes in surface stiffness (Ferris *et al.*, 1996). By adjusting leg stiffness, runners were able to have the same peak ground reaction force, stance time and vertical displacement for the centre of mass regardless of the surface stiffness (Ferris *et al.*, 1996). Dixon *et al.* (2000) in contrast, found individual variation in these variables. Individual variations are possible revealing skill differences, but their model works on a premise that at impact the centre of mass increases its distance behind the point of contact as running speed increases. This is not evident however in faster runners (Fenn, 1930; Deshon and Nelson, 1964; Cavanagh *et al.*, 1977; Hinrichs, 1990).

Joint stiffness is defined as a change in joint moments divided by change in the joint angle (Kuitunen *et al.*, 2002). These two variables potentially affect vertical and horizontal excursion of the centre of mass by their roles in limb displacement and force production. Kuitunen *et al.* (2002) measured ten sprinters at different speeds, and identified that ankle joint stiffness remained constant. Knee joint stiffness increased across the speed range. However, only a minimal change in knee joint angle took place, which suggested knee moment was a prominent factor, unless elastic mechanisms can be utilised.

As endurance runners fatigue, stance time increases (Nicol *et al.*, 1991). This suggests that a time delay between the muscle stretch and the shortening action may have widened. In combination, peak braking and vertical ground reaction forces decrease with fatigue (Paavolainen *et al.*, 1999b). These data suggest that many repetitive stretch-loads—fatigue—decreased the capacity of the neuromuscular system to generate force rapidly (Mero *et al.*, 1992). One possible explanation may be a reduction of muscle stiffness in the braking phase (Nummela *et al.*, 1994). This scenario would lead to a reduction in stored elastic energy during the braking phase, reducing the ability to store and return elastic energy. Knee flexion and extension angular velocity increases with rising running speed allowing the spring-mass model to function. Greater impact spring stiffness arises from increased stride length of up to 20% (Dietz *et al.*, 1979; Derrick *et al.*, 2000). At sprint running speeds, high leg stiffness may produce a stiff rebound (Chelly and Denis, 2001). However, research does not support an equal flexion and extension relationship during stance for thigh or knee angles (Milliron and Cavanagh, 1990; De Wit and De Clercq, 2000; Li, 2000). Non-equal knee/hip flexion and extension may explain variations in position of the centre of mass to the support limb (see vertical oscillation of the body's general centre of mass p. 19). For example, Lee and Farley (1998) concluded that stance-limb compression and impact angle both play an important role in determining the trajectory of the centre of mass. However, they did not deduce from their model that the centre of mass is behind the point of contact at impact thus negatively affecting forward progression. In addition, vertical oscillations of the centre of mass may reveal changes in the reciprocal knee flexion and extension angular velocities, which may affect forward progression.

Spinal Engine Theory

Based upon the spines capability for torsion and compression: Gracovetsky (1988) formulated two hypotheses. Firstly, runners' legs cause the pelvis to rotate. Secondly, the spine can convert a lateral bending movement into an axial torque to drive pelvic rotation. Essential to the theory is the need to axially rotate the pelvis. In running, the hip extensors fire as the foot leaves the ground (see gait muscles and electromyography activity p. 35). Gracovetsky (1988) stated muscle power transfers directly to the spine and trunk through two distinct complementary pathways. The sacrotuberous ligament extends the action of the biceps femoris, through to the rib cage. This ligament crosses over the posterior superior iliac crest and continues as the lumbar intermuscular aponeurosis (Bogduk and Twomey, 1987), which has a direct link with the lumbar and longissimus lumbrum as well as the spinous processes via multifidus. Secondly, gluteus maximus connects to the lumbodorsal fascia, itself linked with latissimus dorsi and the upper extremities. Consequently, locomotion should be possible for a legless individual. Gracovetsky (1988) recorded legless participants walking on their ischiums by keeping normal spinal motion and electromyography patterns for the trunk musculature. These data corresponded to normal gait, except for amplitude of the movements. Justification for this phenomenon was the lordotic spine converts lateral bend into an axial torque driving the pelvis, thus demonstrating the need for compression and torsion in the spine during locomotion. Accordingly, spinal engine theory postulates that the legs follow pelvic motion in a desire to minimise energy expenditure. In addition, spinal engine theory promotes the central role of gravity as the motive force for legless locomotion.

Converted heel-toe runners

Williams *et al.* (2000) took six male and three female heel-toe runners and converted them to forefoot strikers in one laboratory session. Their research established a list of variables (table 2.3.1) that differentiated heel-toe and forefoot runners. Proceeding sections concentrate on the kinematic analysis of rear and forefoot strikers; the kinetics are discussed in section 2.3.3 p. 31.

Table 2.3.1 Variables found to be different between rear foot and forefoot strikers (Williams *et al.*, 2000)

Kinematics	Kinetics
Plantar flexion at impact	Vertical ground reaction force
Inversion at impact	Anterior ground reaction force
Dorsiflexion excursion	Peak plantar flexion moment
Eversion excursion	Ankle power absorption
Dorsiflexion velocity	Ankle negative work
Eversion velocity	Ankle inversion moment
Knee flexion at impact	Peak knee flexion moment
Knee flexion excursion	Knee power absorption
Knee internal rotation velocity	Knee negative work
	Vertical loading rate

Stride length and stride frequency

Over striding requires considerable power during propulsion, resulting in excessive vertical oscillation of the centre of mass. In turn, this produces an impact position that creates increased braking forces and requires reciprocal joint ranges of motion, which invoke increased internal friction and stiffness (Hinrichs, 1990). Conversely, short strides increase internal work through increased frequency of reciprocal movements. Nilsson and Thorstensson (1987), within a range of running speeds of 1.5-8 $m \cdot s^{-1}$, identified stride rates of 33 to 214 $strides \cdot min^{-1}$. These rates were the absolute lowest and highest the runners could perform. Runners can alter cadence and stride length, thus creating many different combinations (figure 2.3.3). Humans transition from walking to running at a critical speed of 2.2 $m \cdot s^{-1}$, rather than at a critical stride rate or length (Laurent and Pailhous, 1986; Hreljac, 1995), plausibly indicating that the speed of locomotion is not the result of leg-work but the trunk and possibly the spinal motion via gravity's work (see spinal engine p. 24). In addition, the flexibility to alter stride rate and stride length implies that the central nervous system must have mechanisms for actively controlling these variables. In support, the Froude number illustrates gravity's role in running as a combination of leg length and running speed.

$$\text{Froude number} = \frac{(\text{speed of locomotion})^2}{\text{gravitational acceleration x leg length}} \qquad (2.3.1)$$

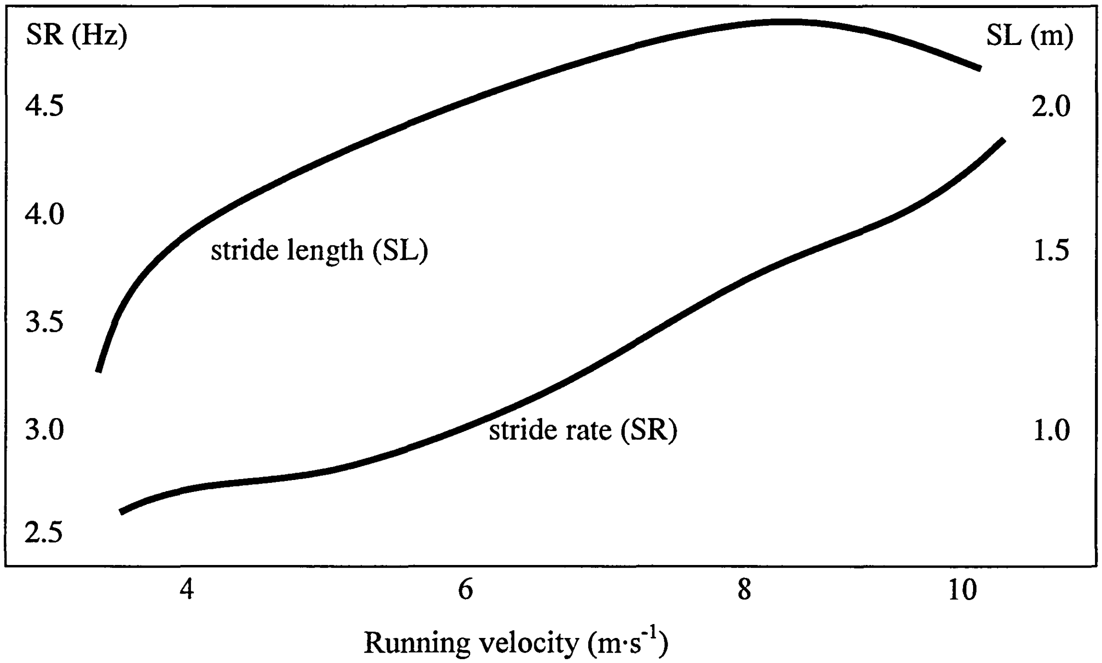


Figure 2.3.3 Variations in stride length and stride rate with increase running velocity (Luhtanen and Komi, 1978).

Dillman (1975) found better or more 'skilled'—experienced college cross-country—runners tend to have longer strides at any given velocity than 'poorer or less skilled' runners. In contrast, Cavanagh *et al.* (1977) found elite runners took shorter absolute and relative strides than good distance runners did. Trained sprinters on a treadmill took considerably longer strides than non-sprinters despite similar leg-lengths (Armstrong and Cooksey, 1983). A helpful requirement would be a clear definition of skilled runners, which perhaps explains the conflicting reports. Dillman's group had only four college runners. Cavanagh's study compared good and elite runners at 5 $m \cdot s^{-1}$, equivalent to five and half minute mile pace (3 min 26 s per km), which might have been faster than good runners were used to, hence leading to altered stride lengths on the treadmill. Further, stride length and stride frequency may differ because sprinters over endurance athletes often spend more time completing running drills and strength training (Dillman, 1975). These 'skill' factors may have contributed to the differences found. No mention was made of how stride length was produced for example, were hip flexors more or less active in athletes with longer stride lengths owing to their associated knee lift increases (Armstrong and Cooksey, 1983).

Longer strides may be associated with higher ground contact forces. Weyand *et al.* (2000) concluded maximal sprint speed occurs through an enhanced ability to generate and transmit muscular force to the ground, in contrast to a rapid repositioning of lower-limbs through stride length and stride frequency. Data collected on a treadmill rather than by over-ground running, possibly altered the findings (van Ingen Schenau, 1980; Nigg *et al.*, 1995). For example, stance time for over-ground running was 15% higher for world-class sprinters Weyand *et al.* analysed from live footage than for their own treadmill data. The effective force applied to the ground and the time of foot contact determined aerial times (Weyand *et al.*, 2000). Ariel times at maximal sprint speed between runners were similar, however, shorter stance times increased stride frequency in the fastest athletes. By applying higher ground contact forces, faster runners were able to increase both stride length and stride frequency. Although vertical force increased across the speed range (2-10 $m{\cdot}s^{-1}$), impulse decreased after 6 $m{\cdot}s^{-1}$. Ground reaction force reflects the acceleration of the centre of mass. This study showed a mean increase of 1 BW from 2 $m{\cdot}s^{-1}$ to 10 $m{\cdot}s^{-1}$. It seems unlikely that this increase in force alone reflects the considerable increase in speed. The top speed reached was 11.1 $m{\cdot}s^{-1}$ and the slowest was 6.2 $m{\cdot}s^{-1}$ from similar increases in force. There was more vertical force in the declined position (-6°) than the level, indicating body orientation to the ground (gravity) played a role in the vertical force found in running (Weyand *et al.*, 2000).

Speed increases at low running speeds occur primarily through amplified stride length, for at high speeds, stride frequency is the primary factor (Weyand *et al.*, 2000; Hay, 2002). Endurance runners' stride frequency reached a theoretical maximum at 5 Hz (Mann and Herman, 1985; Nilsson and Thorstensson, 1985). As noted earlier, Cavanagh and Kram (1985) found stride frequencies were individual, because runners appeared to maintain their chosen frequency for speeds of 3 $m{\cdot}s^{-1}$ to 4.2 $m{\cdot}s^{-1}$. With increased speeds (above 7 $m{\cdot}s^{-1}$), stride length did not increase significantly, whereas stride frequency continued to increase. Runners at high speeds, therefore, tend to enhance speed through increased stride frequency rather than stride length (Luhtanen and Komi, 1980). Increased frequency may cause shorter strides, casting reservation on the idea that this increase would amplify internal work (Hinrichs, 1990).

The running stride, further subdivides into support (stance) versus non-support (flight) (Bates *et al.*, 1979). Saito *et al.* (1974) found as running speed increased, the time for a complete running cycle decreased. Further, absolute and relative time spent in support decreased as running speed increased (Saito *et al.*, 1974; Bates *et al.*, 1978; Chapman, 1982). Stance time changed from 68% at 3.35 $m \cdot s^{-1}$ to 54% at 6.4 $m \cdot s^{-1}$, although there is substantial individual variation (Nelson *et al.*, 1972). Mann *et al.* (1986) found enlarged joint range of motion as speed of running increased, with subsequent reduction in support time (stance). They concluded that rises in angular velocity at the joints would create increased energy expenditure and force, thereby raising the possibility of injury. For example, in sprinting, hip flexion during swing was 80° compared to 40° for jogging (Mann *et al.*, 1986). Increased hip motion during swing raises the foot higher from the ground possibly elevating impact forces. Increased running speed, however, has not been associated with increased running injuries (see p. 42; Yzerman and Van Galen, 1987).

Lower and upper extremity limb kinematics

Hip joint kinematics can differ depending upon the method used. Two commonly practised methods are orientation of the thigh with respect to the vertical axis or, obtaining hip joint angles using some markers on the trunk to define the upper body segment. However, there is generally a forward lean of the trunk in running (Williams and Cavanagh, 1987). Therefore, inclusion of trunk orientation will tend to increase the measured flexion angles and decrease extension angles compared to the measurement of the thigh orientation angles alone (Milliron and Cavanagh, 1990).

The hip joint has been observed to extend during support from about 35°, and flex during the swing phase from 40° for jogging, 60° for running and 80° for sprinting (Mann *et al.*, 1986). Maximum hip extension occurs at or immediately after terminal stance, and maximum hip flexion occurs at about two-thirds of the way through the swing phase as contralateral terminal stance begins (Sinning and Forsythe 1970; Dillman 1975; Cavanagh *et al.*, 1977; Mann *et al.*, 1986). Mann *et al.* (1986) suggest hip flexion is the main instigator for increasing running speed with the rest of the lower extremity following the lead of the hip's increased angular velocity. Mann *et al.* (1986) also found that knee extension began at the end of maximum hip flexion during the last third of the movement, and occurred through the concentric contraction of the quadriceps. The degree of maximal hip extension while occurring at terminal stance is less at moderate than faster running speeds (Mann and Hagy, 1980). In contrast, Mann and Herman (1985) found elite sprinters had less hip extension at terminal stance, because extension occurred via momentum of the flexing hip, owing to silent quadriceps muscles during hip extension. It might be pertinent to decrease elevation of the knee via decreased hip flexion during swing because it would lower work done against gravity. Possible differences in hip flexion and extension may also reflect the relationship with knee and ankle kinematics owing to the kinetic chain (Bartlett, 2000).

At impact, the knee angle has been generally reported to be in the range of 10° to 30° (Bates *et al.*, 1978; Elliot and Blanksby, 1979; Clarke *et al.*, 1983). A variety of angles for knee flexion have been found for support, ranging from 38 to 50° for speeds of 3.4 $m \cdot s^{-1}$ to 7.5 $m \cdot s^{-1}$ (Cavanagh *et al.*, 1977; Bates *et al.*, 1978; Bates *et al.*, 1979). Although, only small changes of 1.5° to 4° in knee flexion have been identified during support across speeds ranges of 3.33 $m \cdot s^{-1}$ to 6.67 $m \cdot s^{-1}$, despite absolute differences in knee flexion among individuals (Sinning and Forsyth, 1970; Miller, 1978; Nilsson and Thorstensson, 1985). After impact, flexion occurs in the cushioning phase and continues through mid-stance, followed by a knee extension phase that lasts up to or slightly after terminal stance.

At terminal stance, the knee does not fully extend although there appears to be a trend towards greater extension with increased speed (Cavanagh *et al.*, 1977; Bates *et al.*, 1978; Elliot and Blanksby, 1979). This finding is not universal (Sinning and Forsythe, 1970). Cavanagh *et al.* (1977) indicated that the knee did not fully extend throughout the gait cycle and was almost the same angle at impact as terminal stance. At 2.5 $m \cdot s^{-1}$ to 5 $m \cdot s^{-1}$, knee extension was 23° (Elliot and Blanksby, 1979) and at 8 $m \cdot s^{-1}$, 18° (Mann *et al.*, 1986). Extension increases were found for sprinting at 8 $m \cdot s^{-1}$ but not for distance running speeds of 2.5 $m \cdot s^{-1}$ to 5 $m \cdot s^{-1}$, contradicting a commonly held assumption, that runners push off the ground via knee extension (Milliron and Cavanagh, 1990).

Bates *et al.* (1979) found no relationship between knee angle at impact and the amount of decrease in horizontal velocity of the centre of mass during stance. Barefoot runners had greater knee flexion angular velocity than shod, which began 0.02 s before impact (De Wit *et al.*, 2000). Running in shoes gave similar results, although comparison is not straightforward owing to other altered kinematic variables in barefoot runners as opposed to shod (Clarke *et al.*, 1983). De Wit *et al.* (2000) concluded barefoot runners make kinematic adaptations just before impact, including increased knee flexion velocity

0.02 s before, followed by a passive interaction between the ground and the contacting leg. Further, the initial ground contact phase indicated the overall stiffness of the support leg to be higher in barefoot running (see spring-mass model section p. 20).

At impact, the ankle is at approximately 90°, while at terminal stance, usually 20° of plantar flexion occurs (Milliron and Cavanagh, 1990). Mann *et al.* (1986) observed for jogging, running and sprinting dorsiflexion of the ankle joint occurred after foot contact. Dorsiflexion continued through mid-support, which occurred at about 50% of the support phase, followed by ankle plantar flexion until terminal stance and into swing. Magnitude of dorsiflexion was 10° for jogging and running with 15° for sprinting (Nilsson *et al.*, 1985). The magnitude of plantar flexion, which began at mid-stance was 45° for jogging and running with 35° for sprinting (Mann *et al.,* 1986). Plantar flexion is lower in sprinting than running and jogging, again contradicting the assumption of increased push-off at faster speeds. At all speeds, plantar flexion reached its maximum at terminal stance. For jogging and running progressive dorsiflexion occurred during the swing phase. For sprinting, plantar flexion reached a maximum just before impact (Mann *et al.*, 1986). Cavanagh *et al.* (1977) identified that elite runners had less plantar flexion at terminal stance than good runners (67° versus 59°). If the runner is a heel-toe or forefoot striker this will effect ankle dorsi and plantar flexion angles making comparisons difficult (Williams *et al.*, 2000). For example, forefoot compared to heel-toe runners plantar flexors, fatigue faster during exhaustive running (Pratt, 1989). Pratt suggested this finding supported why eighty percent of distance runners are heel strikers.

Several studies found that the arms increased the vertical oscillation of the body's centre of mass in running (Cavanagh, *et al.,* 1977; Cavanagh and Williams, 1987; Hinrichs *et al.*, 1987). Hinrichs *et al.* (1987) concluded the arms tended to reduce fluctuations in the forward velocity and in side-to-side movements of the runner. Hinrichs (1987) measured angular momentum during flight, finding total angular body momentum about the vertical axis is constant in the absence of external torques. Therefore, the lower body receives 100% of its angular impulse from the upper body. If the upper body where not present (arms and upper trunk), the legs could not change direction while airborne, and a recognisable swing would not be possible. The radius between the hip and ankle affects angular momentum during flight, owing to an increased radius reducing the angular velocity of the swing leg causing a potential increased energy cost.

Trunk lean has been observed to be in the range of 4° to 7° at impact at 7 m·s^{-1} with most of the literature supporting a forward trunk lean (Fenn, 1930; Girardin and Roy, 1984; Williams and Cananagh, 1987). Trunk lean in runners who ran against a head wind in a wind tunnel, 'leaned' into the wind, indicating it was mechanically efficient to do so (Davies, 1980). After impact, forward trunk lean has been reported to increase until mid-support, reaching 12 to 13° for speeds just over 5 m·s^{-1} (Elliot and Roberts, 1980; Elliot and Ackland, 1981). An increased trunk lean would permit a more forward position of the centre of mass during stance, subsequently allowing it to pass over the support foot earlier, potentially generating faster running.

2.3.3 Ground reaction force and optimal running biomechanics

Introduction

Ground reaction force reflects acceleration of the total body centre of mass. The position and direction of the runner's centre of mass determine the direction and magnitude of the ground reaction force. Hence, it is the sum of the acceleration of individual segments contributing in proportion to their masses. The support limb transmits the force to the ground, and theoretically need not create any contribution to the push (Miller, 1990). Collection of three-five trials is normally used to establish reliable data (Williams, 1980; Cavanagh and LaFortune, 1980; and Clarke *et al.*, 1983). Diss (2001) found a high reliability ($r = < 0.94$) for four ground reaction force variables from a single trial when compared to ten trials. Of the sixteen ground reaction force variables sampled, fifteen needed less than four trials at $r = < 0.90$. Only the commonly used ground reaction force variables that are relevant to thesis are reviewed.

The force plate and stride modification

Force plates positioned in a laboratory floor collect ground reaction forces. Data collection assumes that a typical runner's stride pattern is 'normal' (Hay, 1988; Miller, 1990). Related research has indicated that stride adjustments do occur when approaching a target (Hay, 1988). A study that intentionally manipulated stride lengths, noted differences in ground reaction forces, including support time, first maximum vertical force, mean vertical force, and anterior-posterior maximum braking and propelling forces (Martin and Marsh, 1992). Martin and Marsh (1992) recommend against constraining stride length and stride frequency for evaluating representative gait kinematics and kinetics, requiring gait laboratories to design adequate approach runways. The laboratory runway was 15.66 m for this thesis.

Differences between heel-toe and forefoot ground reaction force patterns

Oakely and Pratt (1988) identified essential differences for vertical, posterior and anterior ground reaction forces between heel-toe and forefoot runners. Forefoot runners typically have lower vertical ground reaction force peaks than heel-toe runners (Harrison *et al.*, 1988). The initial vertical peak in heel-toe runners is absent or attenuated in forefoot runners (see figure 2.3.4) (Cavangh *et al.*, 1977; Cavanagh and Lafortune, 1980; Harrison *et al.*, 1988). Posterior and anterior ground reaction force for forefoot runners produced a biphasic shape during the braking phase. Heel-toe runners typically showed a single retarding peak (Cavanagh and Lafortune, 1980; Clarke *et al.*, 1983). Many studies have repeated these findings over the last twenty-five years.

Payne (1983) using a sprinter running at 9.5 $m \cdot s^{-1}$ who landed on their heel found increased ground reaction forces compared to forefoot sprinters. Normally sprinters land on the ball of the foot (Mero and Komi, 1986). Mero *et al.* (1992) recommended that the braking force and contact time be very short to avoid loss of velocity during impact with the ground, and associated this with forefoot landing.

Williams *et al.* (2000) using six male and three female trained heel-toe runners, asked them to land on their forefoot instead of their heels while running across a force platform (table 2.3.1; p. 24). All runners successfully changed from heel-toe to forefoot contact, eliciting loading rates lower than their heel-toe scores. Comparison of the converted forefoot runners with experienced forefoot runners showed similar movement patterns, with one significant exception, decreased peak vertical ground reaction force. The authors suggested it was owing to decreased plantar flexion force at push-off.

Vertical ground reaction force

Figure 2.3.4 illustrates a spike (known as an impact peak) on the vertical ground reaction force for the heel-toe runner, which is absent on the forefoot runner. The impact peak for running velocities of 3 $m \cdot s^{-1}$ to 6 $m \cdot s^{-1}$ usually falls within 2-3 body weights (Denoth *et al.*, 1983; Nigg, 1983). The onset-time of the vertical impact peak has been associated with overuse injuries (Nigg, 1986).

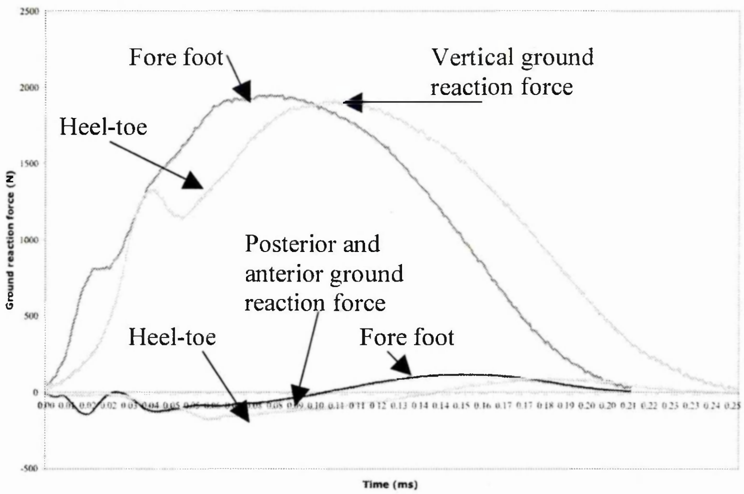


Figure 2.3.4 Heel-toe (rear-foot) and forefoot ground reaction forces for two 740 N males at 3.35 m·s^{-1}.

Twenty heel-toe runners in one laboratory session were asked to run normally—heel-toe—then on their forefoot (Arendse *et al.*, 2004). A Pose® running intervention followed for an accumulative period of 7.5 h (1.5 h for 5-days). The heel-toe and forefoot styles were accompanied by greater magnitudes (F = 28.2, p = <0.001) and loading rates (F = 35.1, p = <.001) of the vertical impact force at 25 ms of stance and at peak magnitude compared with Pose® method running. Increased vertical impact force has been associated with injury mechanisms (see p. 44; Radin and Paul, 1971; Verbitsky *et al.*, 1998).

The posterior and anterior (horizontal) ground reaction force

Posterior and anterior ground reaction force is biphasic in running (Miller, 1990). The initial horizontal ground reaction force is termed braking (posterior), and the latter phase propulsion (anterior) (Cavanagh and Lafortune, 1980). Mason (1980) reported mean braking and propulsive maxima of 38% and 50% body weight at 4.7 m·s^{-1}, 70% and 75% body weight at 7.6 m·s^{-1} respectively. Forefoot strikers running at 4.5 m·s^{-1} had mean braking maxima of 45% body weight and 50% for propulsive maxima at 4.9 m·s^{-1} (Cavanagh and Lafortune, 1980). Kunz (1978) recorded high-jumpers approach runs across speed ranges of 2.5 m·s^{-1} up to 6.5 m·s^{-1}. The posterior component of the ground reaction force did not increase across the whole speed range yet the speed of running increased by 4 m·s^{-1}. This research used high jumpers (forefoot strikers) and not distance runners, nonetheless the speed of running increased with no reciprocal increase in posterior ground reaction force. Hoshikawa *et al.* (1973) found as stance time decreased with running speed, the posterior component decreased in time in relation to the anterior component, despite an increase in running speed. It appears in certain runners braking force reduces as speed increases. Horizontal braking (F = 18.0, p = <.001) and propulsive forces ($F = 3.6, p = .035$) were less in the Pose® than the heel-toe and forefoot running styles (Arendse *et al.*, 2004).

Stance time

Stance time is the period when the foot is in contact with the ground. Stance time and velocity are negatively related (Munro *et al.*, 1987). Time spent on the ground can be logically linked to the position and timing of lower-limb in connection with the centre of mass's flight path. The more extended the knee at ground contact, and the further the foot is in front of the centre of mass, the longer the foot remains on the ground (Kunz and Kaufman, 1981; Mann and Herman, 1985). Barefoot runners compared with shod, elicited shorter stance time when both landed on the heel at 3.5 $m \cdot s^{-1}$, 4.5 $m \cdot s^{-1}$ and 5.5 $m \cdot s^{-1}$ (De Wit *et al.,* 2000). Stance time may denote global biomechanical changes, because stride length, stride frequency, vertical loading rate and knee angular velocity were significantly different between the two conditions (De Wit *et al.,* 2000).

Inverse dynamics method

During the braking and push-off phases of running, the ankle, knee and hip joints have negative and positive angular velocities (Ito *et al.*, 1983a). Calculating external mechanical work during running is the combination of kinematics with ground reaction force (Fenn, 1930; Cavagna, 1975; Zatsiorsky and Fortney, 1993; Yeadon and Challis, 1994). The inverse dynamic method therefore, aims to account for all the forces necessary to accelerate the body mass, such as, positive and negative work absorbed and produced at each joint. Instantaneous values for joint kinetics and muscle function during stance are included (van Ingen Schenau *et al.*, 1983; Wells, 1988). However potentially effective inverse dynamics is (and will be), certain difficulties exist with this method. The inverse dynamics model does not account for the computation of multi-joint movements or measurement of biarticular muscles (Yeadon and Challis, 1994). Precise estimation of the mechanical work completed by extensor and flexor muscles of the lower-limb is also problematic (Yeadon and Challis, 1994). Employment of joint angular velocity to characterize eccentric and concentric actions of leg extensor muscles is questionable (Zatsiorsky and Fortney, 1993). Co-contractions of lower-limb muscles are difficult to account for and identify between runners (Belli *et al.*, 2002). Assumptions of the method usually are as follows: body segments are rigid; the line of action for ground reaction force is at the head of the fifth metatarsal bone and elastic energy is also not accounted for. The number of assumptions and limitations preclude this method of analysis for this thesis.

2.3.4 Electromyographical research and optimal running biomechanics

Introduction

A simple joint system (rigid link, synovial joint, muscle, neuron and sensory receptor) has five elements that interact to produce movement (Marieb, 1992). In this system, the muscle is able to exert a force that can vary in magnitude, a variation that is profoundly influenced by the nervous system. The most effective measurement of the neuromuscular response to movement is electromyography (Basmajian and Deluca, 1985).

Physiologically muscles and motor units can be compared to one another based upon discharge characteristics owing to biomechanical responses of the motor units to different inputs: speed of contraction, magnitude of the force exerted and resistance to fatigue (Burke *et al.*, 1973). It is difficult to interpret the relationship between estimations of muscle moments and measurements for electromyography activity, because torque about a joint is affected by other anatomical and environmental factors. At present, electromyography cannot therefore determine net muscle moments (Pierrynowski, 1995). This section covers, muscle force prediction, electromyography of gait muscles and the stretch-shortening cycle in relation to optimal running biomechanics.

Electromyography and muscle force prediction

Using electromyographical signals to directly estimate individual muscles activity during motion is based upon the assumption that quantitative relationships between the electromyographical signal and muscle forces are known, or can be determined. The assumption of a linear relationship between the rectified integrated electromyographical signal and force is questionable (Hof and van den Berg, 1981). Muscles produce an electrical signal when activated. Magnitude and intensity of the electromyographical signal related to the force produced by a muscle under given conditions has been reported at least qualitatively (Liu *et al.*, 1999). Difficulties of relating electromyography to corresponding force signals were associated with highly non-linear and a time-variable relationship between these signals. Measuring electromyography consistently and repeatedly compounds this relationship. Currently, the electromyographical-force relationship in human skeletal muscle is still at a developmental stage and actual force predictions plus validations across muscles are not yet available. Liu *et al.* (1999) carried out promising work in this field with an artificial neural network approach. They predicted cat gastrocnemius muscle force from electromyographical data. Force predictions for walking cat's gastrocnemius muscle correlation coefficients were $r = 0.96$ at 0.4 $m \cdot s^{-1}$ and $r = 0.93$ for 1.2 $m \cdot s^{-1}$. This is promising work but is not a feasible option for this thesis.

Another perspective involves force production, electromyography and fatigue. Studies on fatigue using repetitive stretch-shortening cycles for performance, demonstrated an acute decrease in force generating capacity in both prolonged (Nicol *et al.*, 1991), and short-term intensive exercises (Moritani *et al.*, 1990; Nummela *et al.*, 1994) plus a long bout of running (Hausswirth *et al.*, 2000). Significant reductions in the integrated electromyographical signals were identified from the fatigued states.

Gait muscles and electromyography activity

Altered muscle activity patterns should correlate to changes in running style. Patla *et al.* (1989) have shown that transient increases in stride length produced increases in activity of some muscles, and decreases in the activity of others. Unfortunately, there is no research to the author's knowledge on muscle activity differences between forefoot and heel-toe runners. Unless stated, the electromyographical studies may either represent heel-toe or forefoot runners, who are usually endurance athletes, or sprinters, respectively.

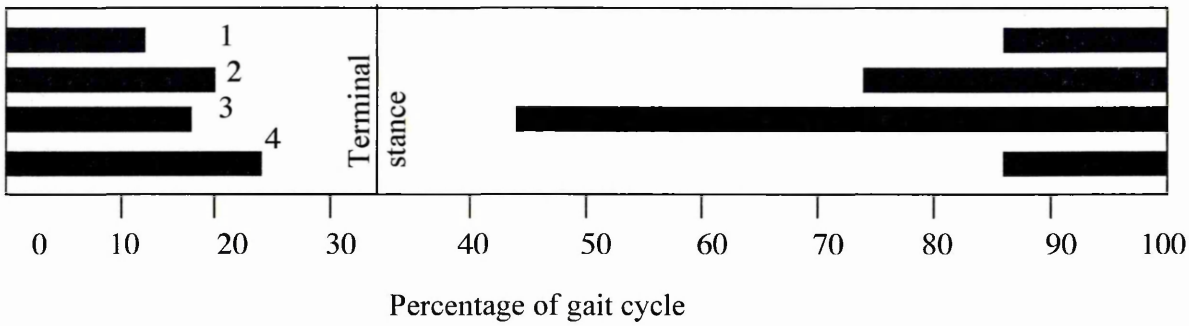


Figure 2.3.5 Electromyography activity expressed as a percent of gait cycle at 3.35 $m{\cdot}s^{-1}$ (adapted from Mann *et al.*, 1986). Note the lack of muscle activity after mid-stance. 1 = m. Quadriceps; 2 = m. Hamstrings; 3 = m. Tibialis anterior; 4 = m. Gastrocnemius

Semimembranosis is active just before maximum hip flexion and shortly after the onset of knee extension. This activity continues throughout most of the support phase, where it may act as a hip extensor during support (Mann *et al.*, 1986). Kyrolainen *et al.* (2000a) found as running speed increased hamstring activity for hip extension amplified in magnitude and time duration during stance. Smidt (1973) using 26 runners reported moment arm lengths for their hamstrings increased as the knee flexed, reaching a peak at 45°, then, decreasing again as flexion reached 90°. Relative positions of the knee and hip affect the hamstrings role, which may explain this biarticular muscles varied, but important activity.

The quadriceps femoris group includes: rectus femoris, vastus medialis, vastus lateralis and vastus intermedius. Rectus femoris is active during early swing, associated with hip flexion (MacIntyre and Robertson, 1987). Both rectus femoris and vastus lateralis recorded peaks during mid-stance (Elliot and Blanksby, 1979). Vastus lateralis's main activity was eccentric muscle action during early stance while the knee was undergoing flexion. An interesting observation is that quadriceps muscles were quiet during the extension phase of stance, suggesting knee extension may occur without their assistance (see figure 2.3.5 and Figure 2.3.6) (Brandell, 1973; Schwab *et al.*, 1983; Nilsson *et al.*, 1985; MacIntyre and Robertson, 1987). During submaximal constant-speed running, the electromyographic activity of the quadriceps muscles increased owing to marathon type fatigue (Komi *et al.*, 1986). Increased quadriceps muscles activity could raise internal work, which may cause a detriment in running technique.

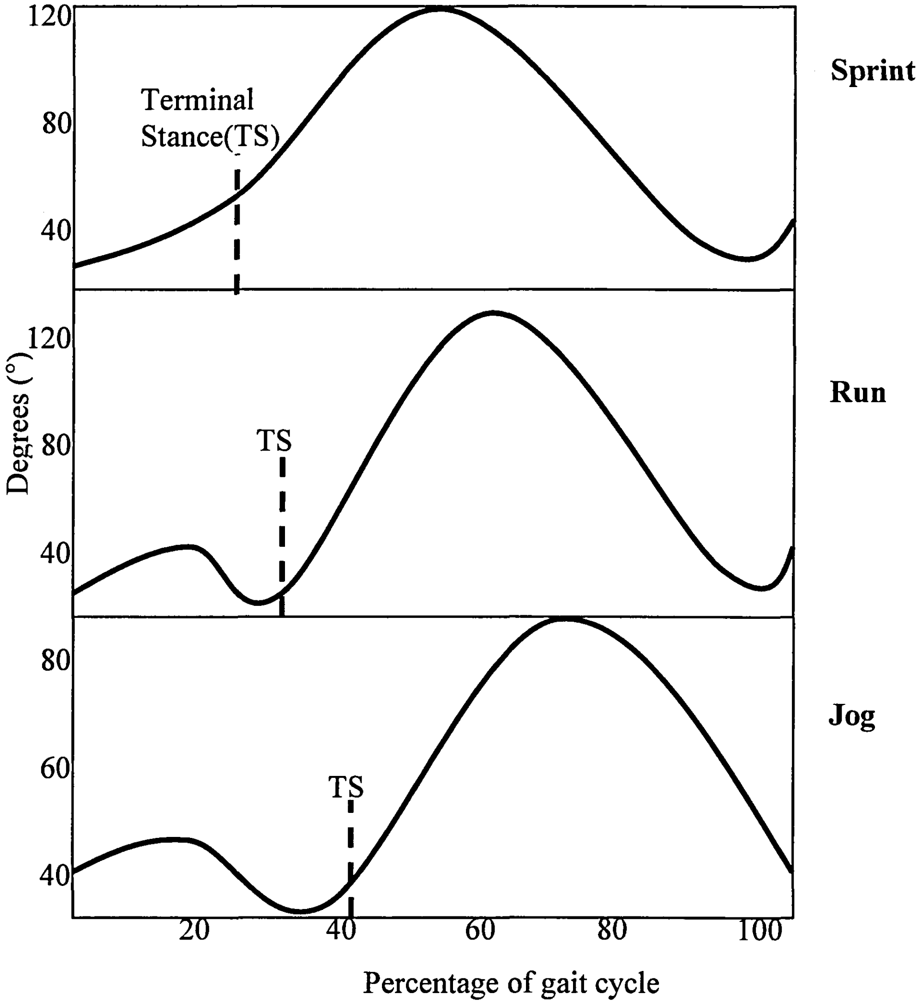


Figure 2.3.6 Range of motion of knee during sprinting, running and jogging (Mann *et al.*, 1986). Notice the absence of knee extension during stance in the sprint condition.

The tibialis anterior represents muscle function for the anterior compartment of the lower leg. It is active just after terminal stance, and remains active throughout most of the swing through mid-support, when maximum dorsiflexion occurs (Mann *et al.*, 1986). Elliot and Blanksby (1979) recorded tibialis anterior acting concentrically to bring the shank forward, and eccentrically to control the lowering of the foot during the first part of ground contact (for heel-toe runners). This muscle identifies foot contact for heel-toe runners.

Gastrocnemius represents the posterior compartment's muscular activity, during foot descent for the swing phase, foot contact and mid-support. Gastrocnemius is mainly active at the middle of stance with a heel-toe runner (Winter, 1987). There is some controversy over the gastrocnemius's role during support for different running speeds.

Faster speeds showed more activity (Elliot and Blanksby, 1979; Mann *et al*, 1986) but with slower speeds, the gastrocnemius muscle persisted for only 30-50% of plantar flexion (see figure 2.3.5) (Mann and Hagy, 1980). Komi *et al.* (1987) found a higher pre-activation before impact for the gastrocnemius muscle with barefoot compared to shod runners, possibly identifying different body-foot landing positions. The activity of the vastus lateralis, rectus femoris, anterior tibialis, gastrocnemius and the hamstring muscle group are, therefore, important in gaining understanding of lower-limb motion in running.

The stretch-shortening cycle and electromyography

Running involves lower-limb eccentric and concentric muscle actions. For example, at the ankle, the gastrocnemius muscle group is active during initial lengthening through early stance before shortening during plantar flexion. This movement is called 'length-shortening', and is usually referred to as the stretch-shortening cycle (Kreighbaum and Barthels, 1996). The cycle allows for preloading of the muscle, which enhances force output (Pugh 1971; Cavagna and Kaneko, 1977; Komi and Bosco, 1978) for a given neural innovation. Concentric muscle action occurs for 5-10% of the gait cycle and is both preceded and followed by eccentric action. It appears that eccentric loading may be owing to alternative central nervous system recruitment of motor units (Enoka, 1996; Christou and Carlton, 1999; Jung, 2003). For instance, time to peak force was less for eccentric contractions than concentric contractions. Auro and Komi (1986) using integrated electromyography for vastus lateralis and gastrocnemius muscles found a positive correlation in men and women ($r = 0.45$ at $p < 0.001$) in the eccentric-concentric ratio. The ratio rose linearly with increasing pre-stretch loading. They hypothesised maximum elastic capability of the muscle was 40% to 50% of its normal contractile capacity. Improved pre-stretch loading potentially enhances force output in runners. It would seem pertinent, therefore, to train this component. Kubo *et al.* (2000) found endurance runner's vastus lateralis muscle were less compliant than their untrained counterparts. Lack of compliance was associated with a lower potential for elastic energy storage measured by less lengthening of the muscle-tendon complex. Fatigue can also decrease the stretch-shortening cycle. Nicol *et al.* (1991) studying a 10-km run observed increases in contact time as the event progressed owing to fatigue. Fatigued runners increased their quadriceps electromyographical output (Komi *et al.*, 1986), suggesting possible reductions from the stretch-shortening cycle, owing to changes in stride length and frequency (see p. 10 Kyrolainen *et al.*, 2000a). Long-term running training may therefore decrease the stretch-shortening cycle possibly increasing muscle work and injury.

Electromyographical activity of the lower extremity muscles increased with faster running (Elliott and Blanksby, 1979). In contrast, Ito *et al.* (1983b) using four runners, found muscle activity remained constant for the support phase during speed increases of 3.7 $m \cdot s^{-1}$ to 9.3 $m \cdot s^{-1}$, but increased for the non-support phase. Mann *et al.* (1986) tested fifteen runners at 3.35 $m \cdot s^{-1}$, 4.4 $m \cdot s^{-1}$ and 9-10 $m \cdot s^{-1}$ and found very little differences in electromyographical activity. Ito *et al.* (1983b) suggested that during support, lower recorded muscle activity was owing to increased elastic energy contributions. Elastic energy is less when jogging owing to the shortening phase of muscle gaining little from reduced muscle lengthening (Jacobs *et al.*, 1993). Both studies only tested elite forefoot runners. These findings warrant further investigation into whether heel-toe runners are less able to utilise their elastic mechanisms owing to different foot contact placement, and lower-limb-centre of mass positioning.

Electromyographical studies have shown that the knee extensor (vastus lateralis) and knee flexor (gastrocnemius) muscles are simultaneously active. There is a higher force in the extensors if the flexors are in use (Ferris *et al.*, 1996). Further, length-shortening of the gastrocnemius muscle allows strain energy to be utilised. The vastus lateralis muscle is not active as leg extension begins (MacIntyre and Robertson, 1987), possibly owing to the potential use of elastic energy (figure 2.3.5). This may explain the decreased eccentric loading at the knee recorded for Pose® compared to heel-toe and forefoot runners (figure 2.3.7).

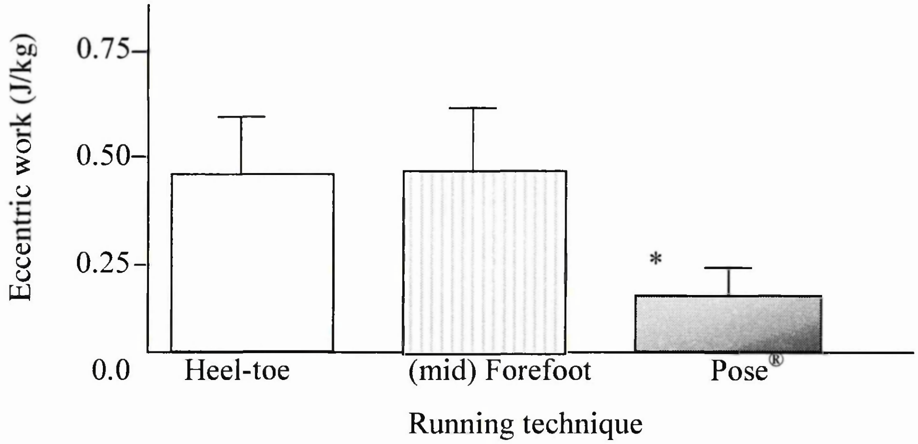


Figure 2.3.7 A comparison of the knee eccentric work between heel-toe, (mid) forefoot and Pose® running (N=20) (Arendse, *et al.*, 2004). * denotes significant difference from heel-toe and forefoot running.

Another method, known as muscle-tendon length change, estimates the instantaneous muscle-tendon length from approximate origin and insertion sites for a given muscle-tendon unit, and from joint kinematic data (Morrison, 1970; Grieve *et al.*, 1978). Unfortunately, this approach does not account for muscle-tendon length changes owing to muscle fibre displacement, muscle fibre pennation angle change, or tendon strain. Each of these factors can affect the total muscle-tendon length (Narici, *et al.*, 1996; Fukanaga *et al.*, 1997).

However, a new approach using sonomicricrometry measures muscle fibre displacement and velocities *in vivo* (Caputi *et al.*, 1992), by suturing piezoelectric crystals into a muscle bundle. Recorded was the time required for ultrasound pulses to travel from one crystal to another. Transit time is used to calculate instantaneous fibre length. Interestingly, the medial gastrocnemius muscle fibres in walking cats shorten at the beginning of stance, even though the muscle tendon unit lengthens during this phase (Griffiths, 1991). This means tendons stretch further than has been currently predicted, with a subsequent elastic energy increase. Applying this theory to muscle work in running, a theoretically lower muscle force may be found in those runners able to utilise the increased elastic components.

2.4 RUNNING INJURIES

Introduction

Injury incidence and biomechanical research associated with injury are appraised. Reference to injury and running technique are included.

Injury incidence

Running is one of the most popular leisure activities in the United Kingdom. Next to its beneficial health effects, there are negative side effects in terms of sports injuries. A runner has been defined as a person running a minimum of three days a week covering a distance of at least 3 km during each session (Taunton *et al.*, 1987). An injury—specifically an overuse injury—is an overload or repetitive impact to the musculoskeletal system (Renstrom, 1994). Since overuse symptoms usually occur over time, it may be difficult to determine the onset and specific cause. Rate of exposure and intensity are also difficult to define. For instance, is a two-hour run on concrete similar to a forest trail run? Are hill repetitions the same intensity as track repeats? These areas require more detailed scientific-work (Rolf, 1995). Reported injury incident rates differ between studies. Person-incidence rates are the number of injured runners per 100 runners, injury-incidence rates record the number of injuries per 100 runners and injury incidence per exposure, are the number of injuries per 1000 hours of running (van Mechelen, 1992).

It appears that for the average recreational runner, who is steadily training for long distance running, there is a large range in yearly incidence for running injuries. For example, 37% and 56% injure using sample sizes > 500 runners (Yzerman and Van Galen, 1987), 25% to 75% (van Mechelen, 1995), and 33-85% (Macera, 1992) for 583 runners with 24% for 482 runners (Blair *et al.*, 1987). These rates are dependent on the specificity of the group of runners concerned, such as, competitive athletes rather than recreational joggers, or children as opposed to adults. If incidence is calculated in relation to time, it varies from 2.5 to 12.1 injuries per 1000 hours of running (Lysholm and Wiklander, 1987; van Mechelen, 1992). In comparison, skiers are six times more likely to injure per 1000 hours of activity (Marti *et al.*, 1988). Most running injuries are lower extremity injuries, with the knee joint being the main site of injury (van Mechelen, 1992; Stanish and Wood, 1994). About 50% to 75% of all running injuries appear to be overuse-injuries owing to constant repetition of the same movement (Lehman, 1984). A recurrence of running injuries, results in 20% to 70% of recorded cases (van Mechelen, 1992; Brill and Macera, 1995). From epidemiological studies, it can be concluded, that running injuries lead to a reduction or cessation of training for 30% to 90% of all documented injuries (Walter *et al.*, 1989). Medical consultation or medical treatment is required for 20% to 70% of all injuries, with up to 5% resulting in absence from work (Gudas, 1980; Macera *et al.*, 1989).

Aetiological factors associated with running injuries include previous injury (Powell, 1986), lack of running experience (Powell, 1986; Blair *et al.*, 1987), competitive running and excessive weekly running distance (James *et al.*, 1978; Andrews, 1983; Harvey, 1983; Stanish, 1984; McKenzie *et al.*, 1985). The association between running injuries and factors such as warm-up, stretching exercises (Koplan *et al.*, 1982; Jacobs and Berson, 1986), stature (Walter *et al.*, 1989), misalignment (Clement *et al.*, 1981; Lysholm and Wiklander, 1987), muscular imbalance (van Mechelen *et al.*, 1987), restricted range of motion (Subotnick, 1985), running frequency (Jacobs and Berson, 1986), ability (Clement *et al.*, 1981) stability of running pattern (Stanish, 1984), and shoes and in-shoe orthoses (Kaelin *et al.*, 1985; Frederick, 1986; Winter and Bishop, 1992) remain unclear. Age (Koplan *et al.*, 1982; Blair *et al.*, 1987; Holmich *et al.*, 1989; Walter *et al.*, 1989), gender (Johansson, 1986), body mass index (Koplan *et al.*, 1982), running hills (Yzerman and Van Galen, 1987; Macera *et al.*, 1989), running on hard surfaces (Clement *et al.*, 1981), participation in other sports (Jacobs and Berson, 1986; Yzerman and Van Galen, 1987), time of the year and time of the day (Yzerman and Van Galen, 1987) are not significantly associated with running injuries. Yet, Lysholm and Wiklander (1987) registered a significantly higher injury incident rate during spring and summer, a time typically associated with increased volume and intensity of running.

Running volume was an important risk factor for increased injury incidence, whereas, running velocity was not associated with injury risk (Yzerman and Van Galen, 1987). Powell (1986) concludes that sudden increases in volume and intensity are the cause of running injuries, because the body has not had time to adapt to the new regimen. Holmich *et al.* (1989) recommended as an injury prevention method that runners reduce their volume. One solution was to run less than 30 km per week, which substantially reduced injuries (Holmich *et al.*, 1989), although it is not a realistic option for elite athletes.

Eccentric and concentric muscle contractions in a stretch-shortening cycle are potential components for overuse injury (Johansson, 1992). Repetitive impact loads may decrease the ability of leg extensor muscles to sustain impact loads and, subsequently, the muscles would lose part of their recoil abilities (Komi *et al.*, 1987). In support, muscle strains usually occur during eccentric contractions (Glick, 1980). For instance, hamstrings muscles act in the running stride to decelerate knee extension, and the quadriceps act to decelerate knee flexion, therefore, acting eccentrically (Cavagna *et al.*, 1977). No mention of different running styles or technique was made in reference to eccentric contractions and injury incidence.

Running injury epidemiology should include denominator-based incidence rates, in which the number of new injuries observed during one year is related to the population of runners at risk (Hoeberigs, 1992). In ten studies with denominator-based incidences selected from the literature, the annual incidence rates of injured runners vary from 24 to 65% (Hoeberigs, 1992), which is in fact similar to the incidence rates. Comparison of denominator-based incidence rates from different studies requires clarity of what the denominator and the numerator are, for example, the study population and the definition of a running injury (Blair *et al.*, 1987). Injury definitions differ from one study to the next (Koplan *et al.*, 1982). Subgroups may differ in origin: volunteers, runners from a mailing list or entrants to a road race. Incidence rates are higher among supervised volunteers than among listed runners, and higher in both these groups, compared with race-entrants (Hoeberigs, 1992).

Biomechanical research into injuries

Current biomechanical injury research has primarily focused on impact forces and different running surfaces. Lower-limb biomechanics are discussed in reference to potential impact forces. Anatomical mechanisms related to impact will be reviewed.

Vertical impact force has been strongly associated with the transmission of shock waves upward through the musculoskeletal system (Radin and Paul, 1971; Verbitsky *et al.*, 1998). It has been suggested that a positive relationship exists between the magnitude of impact force and the numbers of overuse injuries (Voloshin and Wosk, 1982; Wosk and Voloshin, 1982; Cavanagh, 1990). Impact force with insufficient attenuation by natural shock absorbers of the locomotion system, may cause over-loading, resulting in subchondral bone micro-fractures, and subsequent articular cartilage degeneration and osteoarthritis (Wosk and Volishin, 1982). There is speculation that impact-force peaks play a role in the development of pain and injuries in runners (James *et al.*, 1978; Clement *et al.*, 1981), indicating potential differences in injury rates for forefoot and heel-toe runners. Furthermore, increased ground reaction forces might result in the need for more intense muscular contributions to control segmental movements and stabilise body position during the support phase of running (Williams, 1990). This would result in an increased metabolic demand from the muscles involved. Williams tested this hypothesis using twenty-two runners by inducing fatigue (determined when end tidal Co_2 pressure decreased). A lightweight accelerometer was placed on the tibial tuberosity and whenever fatigue ensued, peak acceleration during stance increased. He concluded, that fatigue and heel-strike induced shock waves are correlated. Fatigue-induced changes in shock wave attenuation can therefore have important implications for the etiology of injuries (Verbitsky *et al.*, 1998).

Laughton *et al.* (2003) found a direct linear relationship between vertical ground reaction force and peak tibial acceleration. However, Hennig and Lafortune (1991) were only able to find a moderate correlation. Clarke *et al.* (1985) clarified the issue through use of an accelerometer attached to the lower leg. He identified tibial accelerations increased by taking longer strides, giving circumstantial evidence that increased stride length results in increased impact force. The estimated muscle moments during sprinting correlated significantly ($r = 0.7$ at $p = 0.05$) with the magnitude of the knee flexor moment at impact for athletes with a history of hip extensor and knee flexor injuries (Mann and Sprague, 1980). Findings from Stergiou *et al.* (1999) support this study, in that they identified coordination patterns between the ankle and knee joint change with vertical impact forces. Overall, these studies suggest lower-limb activity at impact affects the vertical loading of the body (increase risk of injury), but again no mention is made of how technique modifications can affect these changes.

Crossley *et al.* (1999) using forty-six males, half with a history of tibial stress fractures and half with no record were measured for ground reaction forces and tibial bone geometry. They discovered the tibial stress fracture group had significantly less tibial cross sectional area ($p = 0.02$) than the non-injured runners. No ground reaction force differences were found, underlying the difficulty in early identification of chronic injuries. Kawamoto *et al.* (2002a) measured torsional moments at the tibia for running on curved paths. Six male participants running unshod at 3.5 $m \cdot s^{-1}$ navigated a track curvature of radii 15 m and 5 m. For comparison, a straight section of track was used. Torsion moments increased from the straight to the most sharply curved track (11 Nm, 12.2 Nm and 28.5 Nm respectively). For comparison, a typical 400 m running track has a radius of 35 m and the static fracture load of human tibia is 100 Nm. However, track-running speeds are usually several times faster than the study speed. Forwood and Parker (1989) reported less than 16.3% of the ultimate loading force could cause observable micro-damage in rat tibia, therefore, lending some risk of tibial torsion in running on tightly curved paths. Kawamoto *et al.* (2002b) took eight male runners and ran them on a straight running track at 5 $m \cdot s^{-1}$. The moment for tibial torsion showed considerable inter-individual variations during stance, and was correlated with vertical ground reaction force ($r = 0.7$ at $p = 0.05$) and outward tilt angle of the shank in the frontal plane ($r = 0.78$ at $p = 0.05$). A suggestion from the authors was reductions in ground reaction force, which reflects the acceleration of the centre of mass, might lead to a reduction in running injuries, in athletes' tibiae. Perhaps, a more specific strategy should seek an understanding of how to modify the centre of mass's movement patterns that subsequently produced the different tibial torsion.

Loading characteristics of the foot that are associated with fatigue were investigated in nineteen non-injured heel-toe runners (Willson and Kernozek, 1999). A Borg rate of perceived exertion scale quantified fatigue. Increased cadence and decreased loading of the heel at landing through increased medial forefoot loading occurred when fatigued. Christina *et al.* (2001) measured eleven female recreational runners who produced significant changes for loading rates, impact and push-off peak magnitudes for vertical ground reaction force and ankle joint motion. Further, a less inverted foot at heel-strike at 2.9 $m \cdot s^{-1}$ resulted from induced fatigue of the ankle invertors and dorsiflexors. These changes may play a role in lower extremity running injuries (Christina *et al.*, 2001). During a 10-km race, eight elite runners were filmed at different stages of the race (Elliot and Ackland, 1981). Fatigue produced a more extended lower-limb throughout the gait cycle during the later stages of the race. Clearly, different foot contacts and possibly limb-body geometry affect loading and muscle activity at impact. Therefore, technique should play an important role in injury reduction interventions.

Surface stiffness has been associated with overuse injuries, although mainly from circumstantial evidence. Dixon *et al.* (2000) used six heel-toe runners who performed shod running trials over three running surfaces: conventional asphalt, a rubber-modified asphalt surface and an acrylic sports surface. Surfaces were categorised according to impact absorbing ability (BS 7044). Mechanical impact absorption was greatest for rubber-modified asphalt, whereas conventional asphalt was the least. The rubber-modified asphalt compared with the conventional asphalt exhibited lower participant loading rates for peak impact force ($p = 0.1$). Individual and not group differences were found for kinematic variables. For example, peak joint angles, peak joint angular velocities and initial joint angles. Explanation of the different peak impact forces on conventional asphalt for some runners was via increased initial knee flexion, while others did not show compliance. This suggests that the lower extremity exhibited compliance on an individual basis to the harder surface stiffness, perhaps alluding to certain runners' skill in reducing load through attenuated movement patterns.

Stride smoothness is a quantitative measurement based on jerk-cost (JC) function (Hogan *et al.*, 1987).

$$JC = \int_0^T (d^3r)^2 \, dt \, / \, dt^3 \qquad (2.4.1)$$

Where T is total movement time, and r is the position vector of a limb segment. When applying this function to evaluate smoothness of complex multi-joint movements, it has been demonstrated that the position vector, r, is best represented in terms of end-point Cartesian coordinates (Hogan *et al.*, 1987). The theory of maximum smoothness (minimum jerk) suggests that the trajectory of a movement endpoint is planned in a manner that would minimise the jerk-cost function. In running, the endpoint is the foot. Winter (1987) suggested the major motor function during the gait cycle is control of the foot. Control of the foot trajectory achieves safe ground clearance and a gentle heel or forefoot landing. In support, Dixon and Kerwin (1999) found significant correlation with heel-lift height and reduced ankle dorsiflexion at heel contact, signifying an increased surface area for the foot at impact, suggesting heel contact is undesirable.

Using a 1-metre depth jumping exercise as an exaggerated motion for landing while running, ten healthy males landed on their heels or forefeet (Kovacs *et al.*, 1999). The first vertical ground reaction force impact peak was 3.4 times greater for heel-toe landing compared to forefoot landing. The second peak was 1.4 times lower. During flexion, the hip and knee joints contributed 40-45% of the total torque (heel-toe group), whereas forefoot landing found the knee and ankle joints contributed 37% each. Total torque contributions were highest in the heel-toe landing (during the extension phase) with 41% and 45% for knee and ankle joints and 34% and 55% with the forefoot. Electromyography for vastus lateralis muscle activity differed during re-contact for the heel-toe landing, whereas gastrocnemius muscle activity in the forefoot group increased. Exaggerated motion (depth jumps) highlights greater loading characteristics between heel and forefoot contact, which in light of previous comments, suggests limb and body positions relationships play important roles in force attenuation and injury incidence.

Hreljac (2000) procured twenty-four well-trained athletes of whom twelve were experienced runners and twelve were team players (non-runners). All were heel strikers. The heel ascended and descended (lower jerk-cost) more gradually for the experienced runners than non-runners despite slight differences in vertical displacement. Bergmann *et al.* (1995) hypothesised that smooth gait patterns reduce joint loading and thus decreased the risk of injury. Hreljac *et al.* (2000) in a second study, took two groups of runners, those who had at least one overuse running injury and others who had been injury free for their entire running career. Using a sit-reach test, the injury-free group demonstrated increased hamstring flexibility. The injury-free group had a lower vertical force impact peak, maximal vertical loading rate and the maximal rate of rear foot pronation. This suggests that the injury free runners had developed stride patterns that incorporate relatively low impact forces, and a lower maximum rate of rear foot pronation. Muscle induced fatigue for the hamstring group of twelve sprinters, running 40 m maximal run repeats, identified differences between the fatigued and non-fatigued state (Pinniger *et al.*, 2000). These variables were significantly different from the fatigued maximal runs: decreased knee and hip flexion at maximum knee extension in the swing phase, decreased leg angular velocity immediately before impact and a decreased angular swing phase. Electromyography indicated a significant increase in the duration of hamstring activity and earlier cessation of rectus femoris activity during the swing phase. They concluded the changes were a protective mechanism to reduce stress on the hamstring muscles at critical stages of the gait cycle. Effective hamstring muscle function (including increased flexibility), therefore, plays an important role in running biomechanics, although its injury prevention remains unclear.

Overpronation at the subtalar joint, which is external rotation, dorsiflexion and calcaneal eversion has been associated during the stance phase with injuries to the hip, knee, Achilles tendon and the foot (James *et al*, 1978; Taunton *et al.* 1982). As body weight moves forwards over the support foot after impact with the ground, the subtalar joint everts, the ankle dorsiflexes, while the knee and hip joints also flex. Stress fractures have been associated with poor alignment and overpronation (Slocum and James, 1968; Lysholm and Wilander, 1987). However, Stanish (1984) contested that overpronation was a causative factor in stress fractures. He cited lack of scientific support. A more recent review concludes that lower extremities injuries are still not well understood in reference to pronation in runners (Hintermann and Nigg, 1998). Risk of injury owing to increased and excessive pronation is unclear at this time in heel-toe runners.

Iliotibial band friction syndrome (lateral knee pain) and patellofemoral pain syndrome (anterior knee pain) are two of the most common complaints in runners (Clement *et al.*, 1981; Johansson, 1986). Downhill and fast running aggravated anterior knee pain. These activities increase the negative impact from retarding knee flexion and extension motions (Bennet and Stauber, 1986). To decrease load, increased initial knee flexion is used (Dixon *et al.*, 2000). Bennet and Stauber (1986) administered eccentric training to an injured group of runners with good results, concluding motor control imbalance was a contributing factor to anterior knee pain. Lateral knee pain results from an increased compression of the iliotibial band against the lateral femoral epicondyle. Sutker *et al.* (1981) reported iliotibial band friction syndrome was an overuse injury most commonly affecting males running about 30 km a week for at least three years. Several etiological factors given were excessive pronation of the subtalar joint, a tight iliotibial band and excessive genu varum. Nutig (1981) observed this injury occurred from uphill running owing to increased loading. Not mentioned was the runner's uphill technique may have altered their loading compared to level running.

A recent two-year study provides the latest published database for specific running related injuries (Taunton *et al.*, 2002). Risk factors were associated with being under thirty-four years old for patellofemoral pain syndrome, iliotibial band friction syndrome, patella tendinopathy and tibial stress syndrome. Interestingly, McKenzie *et al.* (1985) recorded similar results nearly 20 years ago. Being active for less than eight and half years was positively associated with tibial stress syndrome. Patellofemoral pain syndrome was the most common injury, followed by iliotibial band friction syndrome, plantar fasciitis, meniscal injuries of the knee and tibial stress syndrome (Taunton *et al.*, 2002). These data suggest a chronic injury accumulation, possibly owing to poor running biomechanics. Supporting this line of enquiry, Lewis *et al.* (2000) in their review on back injuries identified runners lifetime prevalence is as high as 47%. Specific predisposing factors to injury included: poor stability, muscle imbalances, weakness and fatigue, including an increase in load imposed on the spine while running. Again, these studies are descriptive without reference to prevention. However, a theoretical model that follows the laws of physics could establish a standard (ideal technique). Deviation from the standard technique would then quantifiably address injuries mechanisms. Those runners that deviate from the standard in a certain dimension would possibly develop certain types of injuries. Potentially, reduction in injuries may then occur through changes in technique.

Injury and technique

The correlation between running technique and injury has little direct research. Nytro (1987; p. 3196) states the current view,

"*there is no scientifically founded technique, that suits everyone ... therefore there are no possibilities of evaluating individual dispositions for a certain event. Absolute postulations that 'this is wrong' and 'this is right' are only revealing the coach's lack of insight into the technical evaluation...*"

Only one injury and technique study was found: McClay *et al.* (1999), possibly owing to the viewpoint above. In a single participant design, they used a 40-year old female with right plantar fasciitis and a left tibial stress fracture (recently healed) who underwent a gait analysis (VICON 6 cameras at 120 Hz; BERTEC Corp, OH.). An 8-week, 3-times per week training intervention was administered. The training intervention took place on a treadmill running at 3.35 $m \cdot s^{-1}$. A mirror provided feedback for the first three weeks. The participant began running for 10 min and progressed to 32 min by the end of the eight weeks. Hip internal rotation and adduction plus knee abduction for the right leg were altered (improved). Peak braking force and loading rates on the left foot decreased.

These results suggest it is possible to modify gait biomechanics and potentially reduce the risk of injury, because previous symptoms of pain abated for their participant.

2.5 SUMMARY

Many of the reported findings present conflicting observations for economy, optimal biomechanics and potential injury mechanisms found in runners. The aim of the review, therefore, has been threefold: To highlight confusion that exists within the research literature, to review various assumptions, while presenting relevant findings. The summary's purpose is to draw together the various findings, in an attempt to clarify whether a universal running technique currently exists.

Although there is an intuitive link between running biomechanics and energy cost, the belief persists that individuals are unique both anatomically and biomechanically, and so arrive at their own most economical running motion. However, biomechanical variables account for at least 54% of the variation in running economy (Williams and Cavanagh, 1987). An alternative viewpoint suggests runners become economical through continuous repetition of their gait pattern at a familiar speed, regardless of its biomechanical effectiveness. For example, intra-individual oxygen consumption variation exists between different running speeds—2.83 $m \cdot s^{-1}$ to 4.88 $m \cdot s^{-1}$—highlighting experienced runners become economical at their own well-trained pace (Morgan *et al.*, 1989), which might not always be associated with 'good' biomechanics. The optimal economical solution identified was a combination of self-selected stride lengths and stride frequencies.

Immediately a contention arises because, certain 'skilled' runners tend to have longer strides at any given velocity than 'poorer or less skilled' runners, while in contrast it was found elite runners took shorter absolute and relative strides than good distance runners. There appears to be an optimum stride length, however, its cause is complex. Driving the leg forwards increases stride length, which is ineffective owing to increased braking forces from longer strides. Foot placement in front of the body at impact decelerates the body, which may affect the next stride. Further, driving the knee forwards increases work against gravity. Increasing running speed through increased ground reaction force appears to be ineffective, because amplified push-off from the ground was absent in elite endurance runners, who recorded lower vertical ground reaction force for the second vertical peak than good runners. Over-striding and short strides increase internal work. Over-striding requires an increased thigh extension and leg drive shown to be uneconomical. Further, tibial acceleration increases (from longer strides), raise impact forces and potentially increase injuries. Shorter strides can increase internal work. An alternative external force to ground reaction force that enabled forward progression in a legless man was gravity. This novel idea of gravity being the prime motive force in running requires exploration. If the length of stride were as long as the horizontal displacement of the body during flight, and the foot landed under the body, theoretically lower braking force would occur. Increased trunk lean from the vertical axis improved economy and increased running speed, which suggests stride length from increased trunk lean maybe effective. Hip horizontal velocity was greater than neck velocity at terminal stance, indicating the drive forwards emanates from the hip. Increased forward progression correlated with hip flexion. Less plantar flexion, and higher hamstring activity after terminal stance were associated with runners that are more economical. Further knee extension did not increase with rising speed while electromyography of all gait muscles ceased well before terminal stance. It is therefore possible that running speed originates from the body (gravity's work on the runner's mass) and not from the leg-drive usually associated with stride length. Hence, differences in stride length maybe attributed to the combination of gravity and ground reaction force, together with body-foot position while reducing muscle activity at terminal stance.

Continuing to evaluate external forces and running, an interesting observation is that vertical oscillation of the centre of mass decreases with increases in running speed. In addition, increases in ground reaction force (associated with increased running speed) should raise the centre of mass. However, increased trunk lean and knee flexion during stance (and flight), plus shorter contact time also occur with increases in running speed. Running faster increases momentum of the centre of mass. Shorter time on the ground and less braking force conserves momentum allowing the centre of mass to move more quickly past the point of support (support foot). Increased momentum may explain the lack of push-off (less knee extension) and muscle activity at terminal stance seen in elite runners. Lower leg extension would also potentially reduce vertical oscillation at terminal stance.

The stretch-shortening cycle is maximised with a forefoot landing with increased knee flexion (greater eccentric stretch) and shorter contact time. Forefoot landing, increased knee flexion and shorter contact time may allow the lower-limb to facilitate improved elastic energy, theoretically enhancing economy owing to reduced internal muscle force. In support, economical runners have effective co-activation of their biarticular muscles, which they potentially maximise via a certain lower-limb geometry.

Stride frequency increases by only 4% at speeds of 3 $m \cdot s^{-1}$ to 4.2 $m \cdot s^{-1}$. With increased speeds (sprinting above 7 $m \cdot s^{-1}$), stride length did not increase significantly, whereas stride frequency continued to rise. At sprint speeds keeping the foot under the body differentiated Gold from Silver medallists at the 1984 Olympics. Applying this concept, stride frequency should correspond with the speed of the body to enable the foot to land under the body to allow the next stride to begin. Lack of higher frequency at endurance speeds may be associated with mainly heel-toe runners landing ahead of their bodies thus creating a slower turn over. Possible support for this idea is more economical runners had an increased hamstring activity during swing, which allowed for a faster leg recovery.

The review highlights the current lack of a clear universal running technique. However, certain variables were associated with improved performance. Therefore, the summary points out elite runners do not extend the knee, which requires less push-off and lower vertical oscillation. They plantar flex the ankle less, have an increased trunk lean, land with the foot more vertically aligned to their centre of mass and potentially utilise elastic mechanisms more effectively. Further, leg and hip extensor muscles were not active during leg extension. Finally, gravity, a constant force, may provide momentum conservation through increased trunk lean. As the body leans past its point of support (support foot), a gravitational torque overbalances the runner driving them forwards, seen in the legless walkers. Gravity may provide an alternative external force for locomotion. This thesis, therefore, aims to research a universal running technique that explores gravity as the motive force. This universal running technique should potentially reflect the variables associated with improved performance.

CHAPTER 3

THEORETICAL MODELS

3.1 INTRODUCTION

A brief background of the historical development of running technique is given. Key discoveries are highlighted. Possible reasons for heel-toe running becoming the most popular style of running in recent years conclude the background. Then, two hierarchical models of running are discussed: the current hierarchical model of running (Hay and Reid, 1988) and a new Gravitational hierarchical model based on the Pose® method technique.

3.2 BACKGROUND

Running has interested people throughout history from a theoretical and practical standpoint. Many earlier observations and measurements were attempts to develop or understand a clear biomechanical model of efficient running.

Several Greek vase paintings depict sprinters (circa 470 B.C.) and endurance runners (circa 525 B.C.), which clearly illustrate differences in limb range of motion (Gardner, 1967; p. 134 and p. 138 respectively). Both runners land on the ball of the foot and no one straightens their legs at terminal stance. Whether this is artistic license or astute observation may never be known. During this time, Aristotle (384-322 B.C.) wrote the earliest known accounts of locomotion:

Concerning vertical oscillation of the body:
"If a man were to walk parallel to a wall in sunshine, the line described (by the shadow of his head) would not be straight but zig zag, becoming lower as he bends and higher when he stands and lifts himself up" (Encyclopaedia Britannica, 1952; p. 247).

Concerning joint motion:

"*For if one of the parts of an animal be moved, another must be at rest, and this is the purpose of their joints; animals use joints like a centre, and the whole member, in which the joint is, becomes both one and two, both straight and bent, changing potentially and actually by reason of the joint*" (Nussbaum, 1978; p. 32).

Early resemblance to Newton's third law:

"But the point of rest in the animal is still quite ineffectual unless there be something without which is absolutely at rest and immovable. And further the force of that which initiates movement must be made equal to the force of that which remains at rest. For as the pusher pushes so is the pushed pushed, and with equal force" (Nussbaum, 1978; p. 44).

Another eighteen hundred years passed before records of running research are available. Leonardo Da Vinci (1452-1519) wrote the following concerning motion, balance and foot contact.

"Motion is created by the destruction of balance, that is, of equality of weight, for nothing can move by itself which does not leave its state of balance, and that thing moves most rapidly which is furthest from its balance" (McMahon 1956; pp. 133-134).

Again, this is re-stated. *"That figure will appear swiftest in its course, which is about to fall forwards"* (McMahon 1956; p. 135); "*A man running on level ground has it first on his heels and then on the toes of his feet*" (Keele, 1983; p. 175).

Giovanni Borelli (1608-1679) was the first to systematically study locomotion in his classic "De Motu Animalum" published in 1682. He measured the centre of mass of the body during walking and described how balance is maintained through constant forward movement of the supporting area provided by the feet. Wilhelm and Eduard Weber one hundred and fifty years later published in 1836 a detailed work on human gait. Basic definitions established distinguishing differences between step length in sprinters and walkers; running involved smaller vertical oscillation than walking and the lower-limb appeared to act as a pendulum.

Etianne Jules Marey (1830-1904) was the first to record displacement and force simultaneously.

He noted: "*All muscular actions which alter the centre of gravity of the body in such a manner as to raise it augment the foot pressure on the ground*" (Marey 1972; p. 150).

Vierordt, (1881) was the first to record quantifiable evidence for the variability in step parameters, and Eadweard Muybridge (1830-1894) produced excellent photographs of running gait showing foot contact to be forefoot in barefoot running.

In the early twentieth century, Graham-Brown (1912; p. 875) wrote.

"The cycle of progression may be supposed to commence at a point at which one of the limbs is perpendicular to the ground. The 'initial velocity' then carries the body past this point, and it then falls forwards along the circumference of a circle the radius of which is the limb in contact with the ground."

A.V. Hill's (1927) Nobel Prize winning work, which included the development of a velocity curve for sprinting and the efficiency of running, showed that a combined physiological and biomechanical approach could provide considerably more insight than either approach in isolation. Fenn (1930) building on Hill's work used film records, and a force platform, where he estimated the work completed against gravity through total body segment analysis. The migration of the centre of mass with respect to a fixed point on the body was studied showing it moves upwards and backwards, then downwards and forwards twice in each running cycle.

The modern growth and interest in running research has been spurred by the vast increase in participation in the late 1960's and early 1970's. This period of research was essentially descriptive. Early work focused on the rear foot using high-speed cinematography in two-dimensions digitized by hand (for example, Inman, 1976; Bates *et al.*, 1978). Alongside this were technical advances in shoe design. Interest in differences between barefoot and shod running were identified during this period. Shoes tend to cause greater pronation producing an increased impact angle (Bates *et al.*, 1978; Nigg and Luethi, 1980). They identified barefoot impact angles ranged from 0.8°-1.9°, whereas shod runners ranged from 3.7°-11.8°.

Although rear foot motion was the focus of most running studies, other studies focused on sagittal plane motion of the ankle, knee and hip joints (Nigg, 1986). Nilsson and Thorstensson (1985) found as running speed increased, joints moved through increased ranges of motion in less time, resulting in higher angular velocities. Cavanagh and LaFortune (1980) were the first to identify differences between rear foot and forefoot strikers: the impact peak of the vertical ground reaction force curve was attenuated or missing in forefoot strikers.

A new generation of research emerged in the 1990's with the advent of automated motion-analysis systems capable of obtaining three-dimensional data. The ability to assess secondary planes of motion must still be viewed with caution owing to errors caused by marker placement and soft-tissue movement (Allard *et al.*, 1995). However, coordination and timing of lower extremity joints were topics that could now be examined. Further, more hypothesis driven research was being reported in the literature (Bartlett, 1997; McClay, 2000). Prior research focused on heel-toe runners, and it was not until recently kinematic differences between rear foot and forefoot runners were investigated. McClay and Manal (1997) compared lower extremity biomechanics of ten rear and forefoot strikers. Forefoot strikers landed with greater flexion and external rotation at the knee.

Recent research has focused on the interaction of lower-limb joints (Zajac, 1993), rather than previously, on individual joint activity. For example, coordination of movement between the rear foot and knee may result in injury (Bates *et al.*, 1983). The rear foot and knee are linked mechanically through the subtalar joint, thus motions at the foot will influence movements of the knee known as a coupling effect (McClay, 2000). Joint coupling can also be explored by assessing the relative timing of motion between two joints (De Wit and De Clercq, 2000).

It is not possible, therefore, to conclude that before modern running shoes most runners landed on the forefoot as opposed to eighty percent of runners today, landing on the heel (Kerr *et al.*, 1983). Leonardo da Vinci concluded many years before running shoes that a man running lands first on their heel and then on their toes. Therefore, it is not certain whether modern running shoes really changed the biomechanics of runners to create predominantly heel-toe running. Individual technique differences seem a more plausible explanation for choosing heel-toe or forefoot running.

Gravity's role as a constant force in running has been the subject of little research in modern times (1931-present). Observations and measurements from the past (Leonardo Da Vinci, 1452-1519; Graham-Brown, 1912; Fenn, 1930) have still not been harmonised into a universal running technique. Instead, the current prevailing scientific belief is that each runner optimises their own ideal running biomechanics (Nytro, 1987). This is in contrast to swimming which has attempted to teach universal techniques of freestyle to children as the 'only way to swim' (for example, Counsilman, 1977; Laughlin and Delves, 1996).

3.3 TWO HIERARCHICAL MODELS OF RUNNING

3.3.1 Introduction

From a biomechanical perspective, running is simply the horizontal displacement of a runner's centre of mass. However, scientists, coaches and athletes have a disparity of views on this activity. Some scientists insist, "*there is no commonly accepted running model which will suit everyone*" (Nytro, 1987). Similarly, the common views of coaches and athletes are: "*No, there is no correct running form, and you couldn't learn it. Form is God-given. If you systematise it, you destroy it*" (Wallack, 2004). This thesis takes an opposing view that a clear and comprehensively applied universal technique of running will be helpful to the running community.

Movement is the changing position of a material body in space, and the reason for this change is the action of a force. Classical mechanics uses the term 'force' as a quantitative measure of the interaction between material bodies. The action of force on a free material body (not interacting with a third party) is the acceleration of that body. Therefore, a force alters, or has a propensity to alter, the state of motion of a runner's body. Whether at rest, or moving with constant velocity in a straight line, the runner will continue in that state unless compelled to change by an external force exerted upon them. An applied external force enables accelerated forward motion (horizontal displacement of the centre of mass) for the runner. Their acceleration is directly proportional to the net force acting on their body and inversely proportional to their mass. Hence, the body will accelerate in the direction of the net unbalanced force. Increased horizontal acceleration only occurs during stance, while during flight gravity accelerates the runner towards the earth, with air resistance minimally reducing horizontal acceleration.

A certain number of known forces exist in running: external forces include gravity (Graham-Brown, 1912; Fenn, 1930) and ground reaction force (Cavanagh, and Lafortune, 1980) plus an internal force, such as, muscle force (Heise *et al.*, 1996); and muscle elasticity (Cavagna *et al.*, 1964). Air resistance is neglected in-line with most other gait research (Anderson, 1996). These forces only increase horizontal acceleration during stance but not flight. The centre of mass's horizontal displacement during flight is therefore, a consequence of the action of these forces throughout stance. The hierarchical order of these forces involved in running and their relationship to each other is not currently lucid. This thesis seeks theoretical (hypothetical) and numerical answers on the role of gravity as the main force defining the interrelations between the applied external and the internal forces involved in running. Numerical work on gravity's role in running will follow in later chapters. Section 3.3.2 briefly reviews the heel-toe technique of running using Hay and Reid's (1988) hierarchical model, while section 3.3.3 presents a new Gravitational hierarchical model of running based upon the Pose® technique (Romanov, 2002).

3.3.2 The current hierarchical model of running

The literature review provides background regarding current running research. This section aims to review the only current attempt to hierarchically model running. Therefore, examination of Hay and Reid's (1988) model in figure 3.3.2 summarises the current lack of a clear integration of the forces involved in running. For example, in the current model, gravity is not in affect during stance nor does it relate to forces exerted (muscle and joint forces; Hay and Reid, 1988; p. 264) and time forces act despite gravity being a constant force. The basis of this section is to briefly show the current hierarchical model of running fails to identify gravity's key role.

Description of the current running model (adapted from Hay and Reid, 1988)

In running (figure 3.3.2), the result is the *time* taken by the runner to cover a specified *distance*. Two factors determine time: The *distance* involved and the *mean speed* of the runner over that distance. The *distance* that the runner travels is generally subject to race conditions with minor variations, and is therefore not developed any further in this model. The mean speed of the runner is equal to the product of the runner's *mean step length* and *mean step frequency*.

Step length may be considered the sum of three separate distances:

1) The horizontal distance between the runner's centre of mass and the toe of the take-off foot at the instant of take-off (*take-off distance*);
2) The horizontal distance that the centre of mass travels while the runner is in the air (*flight distance*); and
3) The horizontal distance between the centre of mass and the toe of the leading foot at the instant the runner lands (*landing distance*).

Take-off distance (figure 3.3.1) for a given runner is determined by their *physique* and *body position* at the instant of take-off. *Landing distance* is similarly governed by *physique* and *body distance* at the instant of landing. *Flight distance* of a runner is determined by the speed and angle of projection into the air, *relative height at take-off*, *air resistance* and *acceleration of gravity*. These are expressed as *velocity at take-off*, the *relative height at take-off* and *air resistance*.

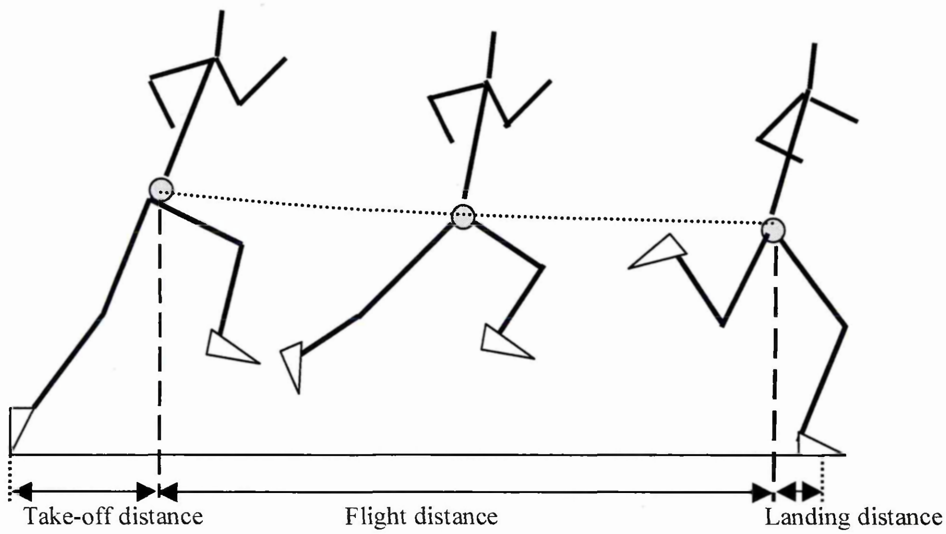


Figure 3.3.1 Flight, take-off and landing distance totalling the runner's step for the centre of mass. Note the runner is falling during most of flight.

Change in velocity is equal to *velocity at take-off* and velocity at impact. The *change in velocity* during the support phase is determined by the forces exerted (muscle and joint forces) on the runner, the times for which these forces act (*time forces act*), and the mass of the runner.

Mean step frequency of a runner is determined by the mean length of time taken to complete one step (*mean step time*). Step time is the sum of:

1) Time of ground contact (*time of support*).

2) Time in the air (*time of non-support*).

Time of *non-support* is determined by *velocity at take-off*, *relative height at take-off*, *air resistance* and *acceleration of gravity*.

Hay and Reid (1988) suggest that the sub-division of the performance criterion be broken into a series of distinct, consecutive parts such as take-off distance and flight distance etc. Following this procedure, the identification of performance parameters that affect the performance criterion are selected. These performance parameters should be mechanical quantities that are measurable (Bartlett, 1999). For practical application in their running model, the *forces exerted* need clear specification similar to their high jump model (Hay *et al*., 1981). For example, ground reaction force only acts during stance, whereas gravity is a constant force. These differences should be distinct in the model and their affects on performance measurable. In fact, *forces exerted* in their model, represents shoulders, hips, knees ankles and other joint forces (Hay and Reid, 1988; p. 264). Despite Hay and Reid (1988) focusing on muscle force, each force in running (gravity, ground reaction force and muscle elasticity) will be reviewed. Potential inconsistencies will be highlighted.

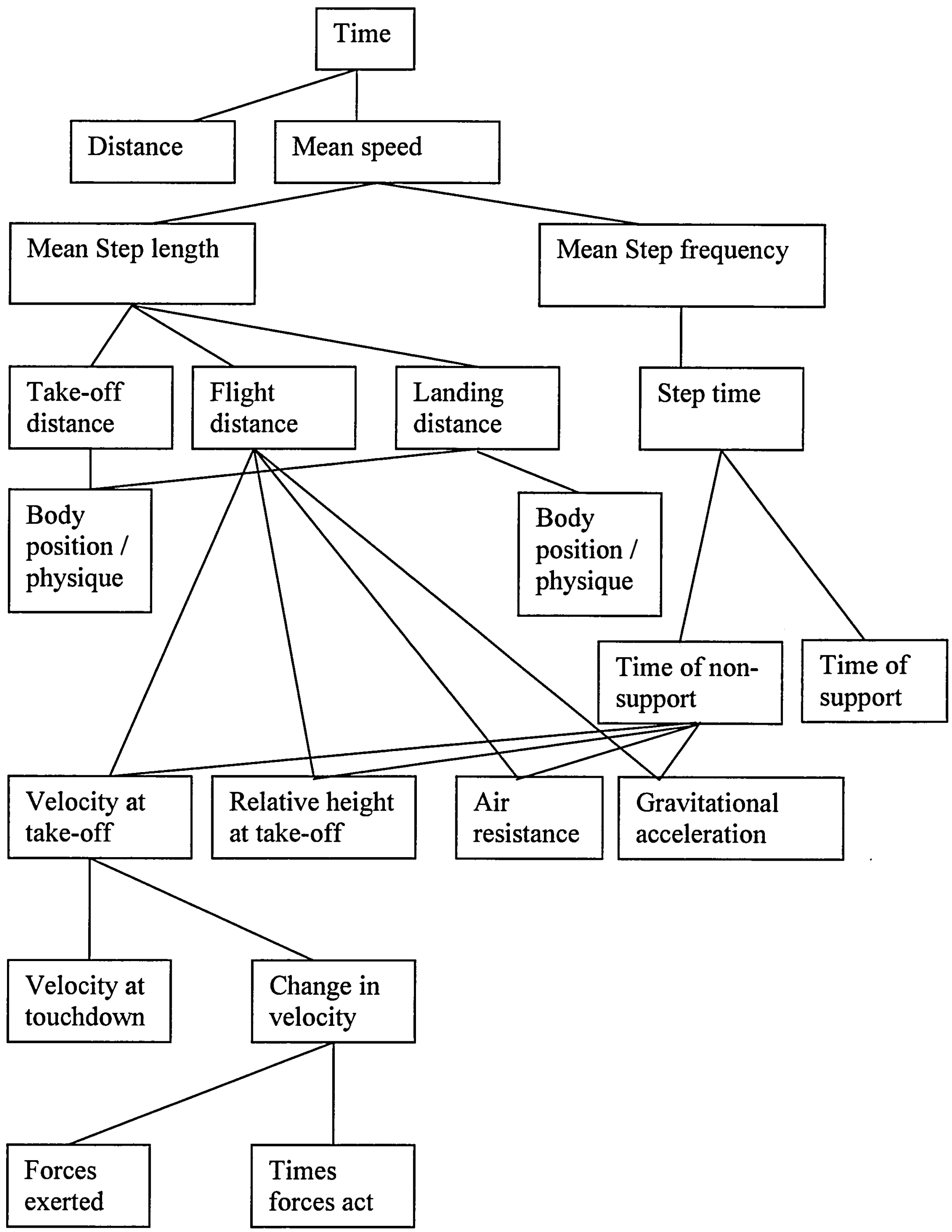


Figure 3.3.2 Current hierarchical model of running (Hay and Reid, 1988; p. 282).

Internal force: Muscle activity

Co-ordinated muscle activity plays a significant role in running (Elliot and Blanksby, 1979). Muscles can change the motion of body segments so that their relative accelerations contribute to the total ground reaction force (Cole *et al.*, 1996). Hay *et al.* (1981) include joint torques broken down into several time intervals in their updated high jump hierarchical model, whereas their running model remains unspecified.

Beginning with muscle activation before impact, there are accelerations of body segments from muscle contractions via the swing leg (Montgomery *et al.*, 1994). From impact until maximum vertical ground reaction force body weight lowers, which requires the muscle system to support the runner at the knee and hip as the quadriceps and hamstring muscle groups co-contract during early support during knee flexion (Elliot and Blanksby, 1979; Mann *et al.*, 1986; Montgomery *et al.*, 1994; Heise *et al.*, 1996). These muscles are therefore, resisting the work of gravity, as the body lowers from impact to mid-stance (maximum vertical ground reaction force and maximum knee flexion). Maximum quadriceps muscle activity occurs at the transition between knee flexion and extension coinciding with maximum vertical ground reaction force (Brandell, 1973; Nilsson and Thorstensson, 1985). After this, hip and knee extensor muscle activity begins to decrease and ends just as leg extension begins (Brandell, 1973; Mann and Hagy, 1980; Schwab *et al.*, 1983; Nilsson and Thorstensson, 1985; Montgomery *et al.*, 1994; Wank *et al.*, 1998). Therefore, as the leg is rapidly extending, the leg extensor muscles are silent; this has become known as the 'extensor paradox' (McClay *et al.*, 1990). MacIntrye and Robertson (1987) noted the hamstring group recorded the greatest variability in phasic activity of all the knee muscles they examined. Elliot and Blanksby (1979) who reported maximal activity for one female for biceps femoris just before terminal stance, in contrast to others who found no activity during terminal stance and early swing (Brandell, 1973; Mann and Hagy, 1980; Schwab *et al.*, 1983; Nilsson and Thorstensson, 1985). Kyrolainen *et al.* (2000a) identified poorer running performances from limited action of their hamstrings.

Only two exceptions of muscle activity at terminal stance where identified. At terminal stance the hip flexors are active, but show peak activity at the end of early swing (Montgomery *et al.*, 1994). Findings for the gastrocnemius muscle activity are conflicting. Some studies have shown maximal activity at terminal stance suggesting a push-off motion (Elliot and Blanksby, 1979, Mann, 1982; Jonhagen *et al.*, 1996), while others found activity persisted for only 30-50% of plantar flexion (Brandell, 1973; Mann and Hagy, 1980), or produced no push-off at all (Reber *et al.*, 1993).

However, it is commonly accepted that the foot pushes off the ground in running. Figure 3.3.3 shows muscle activity of the leg extensors for a single runner at 4 $m \cdot s^{-1}$ taken from a group of six participants. Muscle activity is synchronised with his knee flexion and extension. Interestingly, all three leg-extensor muscles cease activity simultaneously approximately 20 ms (mean for six participants 29.2 ±10.4 ms) after peak knee flexion, while knee extension continues in this participant for another 150 ms (mean for six participants 133.7 ± 16.5 ms). Extension time is longer than electromechanical delay (range 30-100 ms) between electromyography activity and force production, meaning the leg is extending without muscle force (Cavanagh and Komi, 1979). The mean knee flexion and extension time for the six participants was 162.8 ± 19.5 ms.

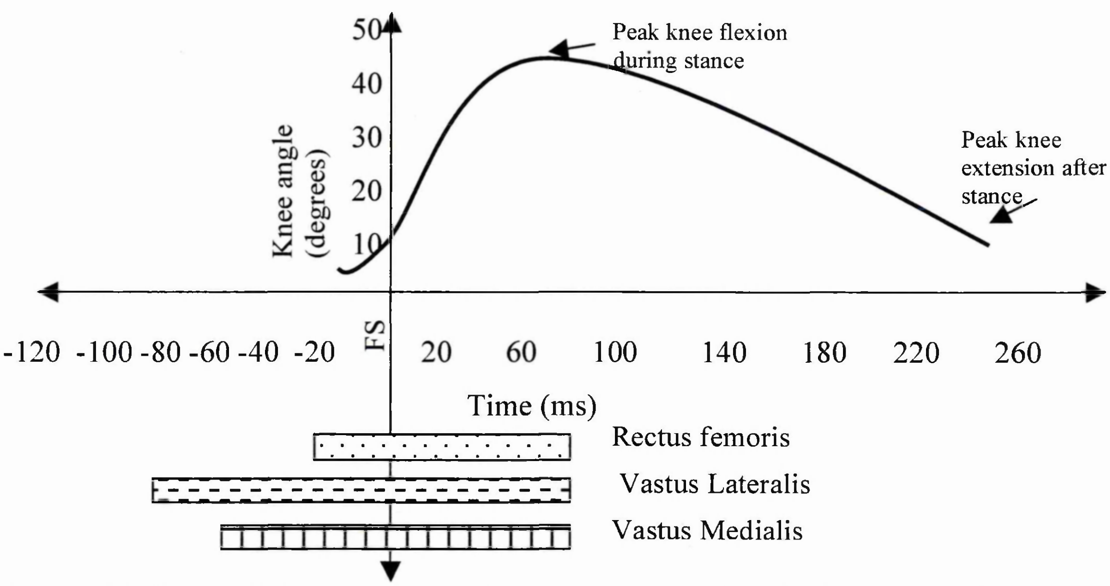


Figure 3.3.3 Results of phasic quadriceps electromyography and knee flexion-extension for a typical endurance runner averaged over six foot strikes (adapted from McClay *et al.*, 1990).

These data (figure 3.3.3) were obtained from a treadmill, which may have influenced the results. However, Mann *et al.* (1986) showed extensor muscle activity ceased as leg extension begins using over-ground running. This lack of muscle activity is supported by many studies using both treadmill and over-ground running (Brandell, 1973; Mann and Hagy, 1980; Paré *et al.*, 1981; Schwab *et al.*, 1983; Nilsson and Thorstensson, 1985;

MacIntyre and Robertson, 1987; Kyrolainen *et al.*, 2003). Gluteus maximus also extend the hip, however their activity is in late swing and the first third of stance (Mann and Hagy, 1980; Nilsson *et al.*, 1985; Montgomery *et al.*, 1994), showing this muscle is also inactive during the propulsive phase of stance. No comprehensive explanation for this 'extensor paradox' presently exists.

Potential strain energy

Cavagna *et al.* (1964) estimated oxygen consumption during running would be 30% higher without contributions from elastic storage and return of strain energy. Mechanical efficiency of running exceeds the efficiency of the conversion of chemical energy to kinetic energy by muscles suggesting there is another source of energy (Cavagna and Kaneko, 1977; Cavanagh and Kram, 1985). Elastic strain energy stored during eccentric contractions during early stance subsequently releases during concentric contractions (Cavagna *et al.*, 1964; Cavagna and Kaneko, 1977; Hinrichs, 1987; Alexander, 1992; Taylor, 1994; Jung, 2003) and is the other source of energy.

To effectively use stored elastic energy in the muscle mechanisms, support time must be short (Zatsiorsky, 1995; Paavolainen *et al.*, 1999a). Although there is no exact method of quantifying storage of elastic energy—although real-time B-mode ultrasound apparatus looks promising (Fukunaga *et al.*, 1997)—there is a consensus that this phenomenon contributes to both efficiency and economy of movement (Cavagna and Citterio, 1974; Winter, 1978; Luhtanen and Komi, 1980; Taylor, 1994; Cavanagh and Kram, 1985; Komi, 2000). The runner's body possesses minimum kinetic energy at maximum vertical ground reaction force, while the stretch-shortening cycle of the muscular-tendon unit contains maximal potential strain energy at this point. This potential strain energy results from gravity's work during impact. However, 'an ideal' body geometry and the ability to reduce stance time have not yet been clearly documented.

External forces related to running: Ground reaction force

Ground reaction force is not a propulsive force as of itself in running, but operates according to Newton's third law (Zatsiorsky, 2002). The ground reaction force experienced by the runner is equal and opposite to the force exerted by the runner on the ground. Muscle force is an active internal force and can displace one body part with respect to another, but it cannot displace the centre of mass without an external force (i.e.

ground reaction force). However, without the ground it is not possible to move using the muscle system alone. During the propulsive phase of running, as noted earlier, the muscle system is inactive ('extensor paradox'), casting doubt that the ground in combination with the muscle system can propel the runner into the air.

Ground reaction force increases as it resists body weight from impact to maximum vertical ground reaction force and reduces after this point reflecting a rising body. The body is rising, but the ground is not pushing the runner upwards (Zatsiorsky, 2002). Presently, conventional running theory postulates applying increased ground reaction force to increase acceleration of the centre of mass (Munro *et al.*, 1987; Hay and Reid, 1988; Weyand *et al.*, 2000). Further, increased running speed is directly associated with a greater force application to the ground enabling the runner/sprinter to drive themselves forward (Hay and Reid, 1988; Weyand *et al.*, 2000). Hunter *et al.* (2005) however, found it was not advantageous to have a large vertical impulse during the acceleration phase of a sprint. In fact, their fastest runners only produced relatively moderate vertical impulses. Further, as running speed increases the decay rate during the propulsive phase from maximal vertical ground reaction force until terminal stance increases (Miller, 1990). Hunter *et al.* (2005) also found vertical impulse non advantageous, because maximal vertical ground reaction force occurs at mid-stance while the body is at its lowest position with the centre of mass poised to move almost vertically upwards. A large vertically directed impulse cannot produce a horizontal displacement for example, a step length of 1 m, but rather step length requires a horizontal force. The increased ground reaction force in sprinters may simply reflect their increased acceleration from their bodies at impact. However, sprinters also exhibit the 'extensor paradox' suggesting they are also not using the ground to accelerate themselves (Mann and Hagy, 1980; Novacheck, 1998).

Viewing ground reaction force in heel-toe runners, two peaks are usually identified, while forefoot runners elicit an attenuated first peak (Cavanagh and LaFortune, 1980). The first vertical ground reaction force impact peak (figure 3.3.4) is associated with the shock of contact with the ground. The first impact peak is related to body mass, stature and step length, vertical hip excursion, running speed, running technique, area of the foot-ground contact, as well as the properties of the shoe and surface involved (Hamill *et al.*, 1983; Frederick and Hagy, 1986; Nigg *et al.*, 1987; Bobbert *et al.*, 1991; Nigg and

Wakeling, 2001). Frederick and Hagy (1986) found body mass correlated highly with the second peak of the vertical ground reaction force ($r = 0.95$ at $P = 0.05$) coinciding with the lowest position of the centre of mass. The leg and hip extensors are inactive after this point coupled with decreasing ground reaction force, which strongly suggests another force is causing propulsion.

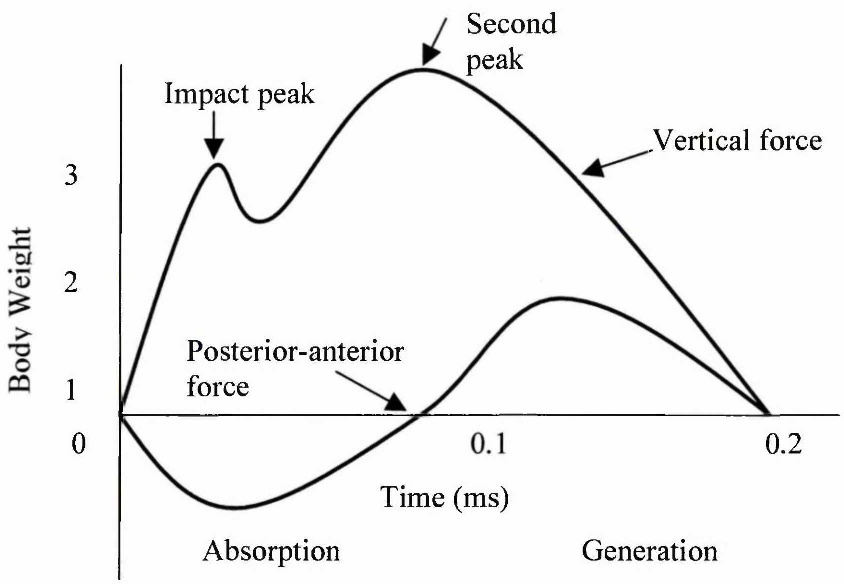


Figure 3.3.4 A typical vertical and posterior-anterior ground reaction force curve for a heel-toe runner. The first peak is associated with the shock of contact with the ground (absorption). The second peak (vertical dashed line) beginning at or about mid-stance is associated with both body mass and muscle force generation.

External forces related to running: Gravity

On Earth, gravity is by far the strongest mechanical force among all the forces of nature, where nothing can cancel its attractive pull owing to its constant manifestation. As a result, gravity should be considered as the dominant force on Earth. Anokhin (1978; p. 29) stated, *"all biological systems, the most essential characteristics of it, are defined by the Universal Law of Gravity."* Despite this knowledge, the role of gravity is not regarded as a dominant or leading force in the current hierarchical running model. The current hierarchical model considers gravity only acts during flight, not stance. However, this contradicts the dynamic similarity hypothesis that predicts that animals and humans travelling with equal Froude numbers will use the same gait, because in equation 3.3.1 gravity is significant in determining the biomechanics of locomotion.

$$\text{Froude number} = \frac{(\text{speed of locomotion})^2}{\text{Gravitational acceleration x leg length}} \qquad (3.3.1)$$

The Froude number is the square root of the ratio of inertial (mass x acceleration) to gravity forces (mass x gravity), while Dynamic similarity is an application of the pendulum principle, being the interaction between gravity and inertia. Motions are dynamically similar if they could be made identical by uniform changes of the scales of length and time. Thus, two pendulums of different lengths but identical angular amplitude are dynamically similar. Likewise, two running animals with different leg lengths but the same ratio of step-length-to-leg-length are also dynamically similar. Mathematically, pendulums (and running animals) are dynamically similar if they have equal Froude numbers. When Froude numbers are applied to animal locomotion, speed of locomotion refers to forward velocity.

Animals exhibit a preferred walking speed above which they normally switch to a running gait. The change from a walking to a running gait in humans occurs abruptly rather than as a gradual transition (Thorstensson and Roberthson, 1987). Individual humans switch from walking to running at different absolute speeds, but at biomechanically equivalent speeds (Kram *et al.,* 1997). That is the transition occurs at a similar Froude number. Alexander and Jayes (1983) further state, that animals and humans running have step lengths proportional to their leg lengths so:

$$\lambda / l = F \frac{(\text{speed of locomotion})^2}{\text{Gravitational acceleration x leg length}} \qquad (3.3.2)$$

Where l is leg length, λ is step length and F is the same function for animals of different sizes and species. This clearly illustrates again that the current model of running, which postulates step length is from leg extensor muscle activity is questionable. Animals and humans have consistently shown step length is based on running speed, gravity and leg length without reference to strength or muscle activity. Maxwell-Donelan *et al.* (1998) though, state the Froude-based hypothesis ignores the role of muscle-tendon spring forces in determining running mechanics. However, their calculations must include the vertical Froude number (instead of the horizontal Froude number) indicating the muscle-tendon spring is predominantly vertical in direction not horizontal. Alexander (1989) using the Strouhal number support the muscle-tendon spring motion is in the vertical direction.

In summarising this critique of the current running model, there are several important questions. Firstly, if the runner pushes off the ground why is ground reaction force decreasing from mid-stance and why are the extensor muscles silent at this time? Secondly, gravity is a constant force, yet its work has not been discussed during the propulsive phase of stance nor hierarchcially linked to forces exerted. The Froude number clearly shows the importance of gravity in running, which is illustrated in the Gravitational hierarchical model.

3.3.3 A Gravitational hierarchical model of running

The model in figure 3.3.5 attempts to hierarchically model all the forces involved in running. A description with supporting evidence is given for the Gravitational hierarchical model. It should be pointed out the evidence used here from the literature was not discussed or identified by the authors in their papers. Therefore, the Gravitational hierarchical model presented is the first to fully integrate and explain all the forces in running and how to potentially maximise them.

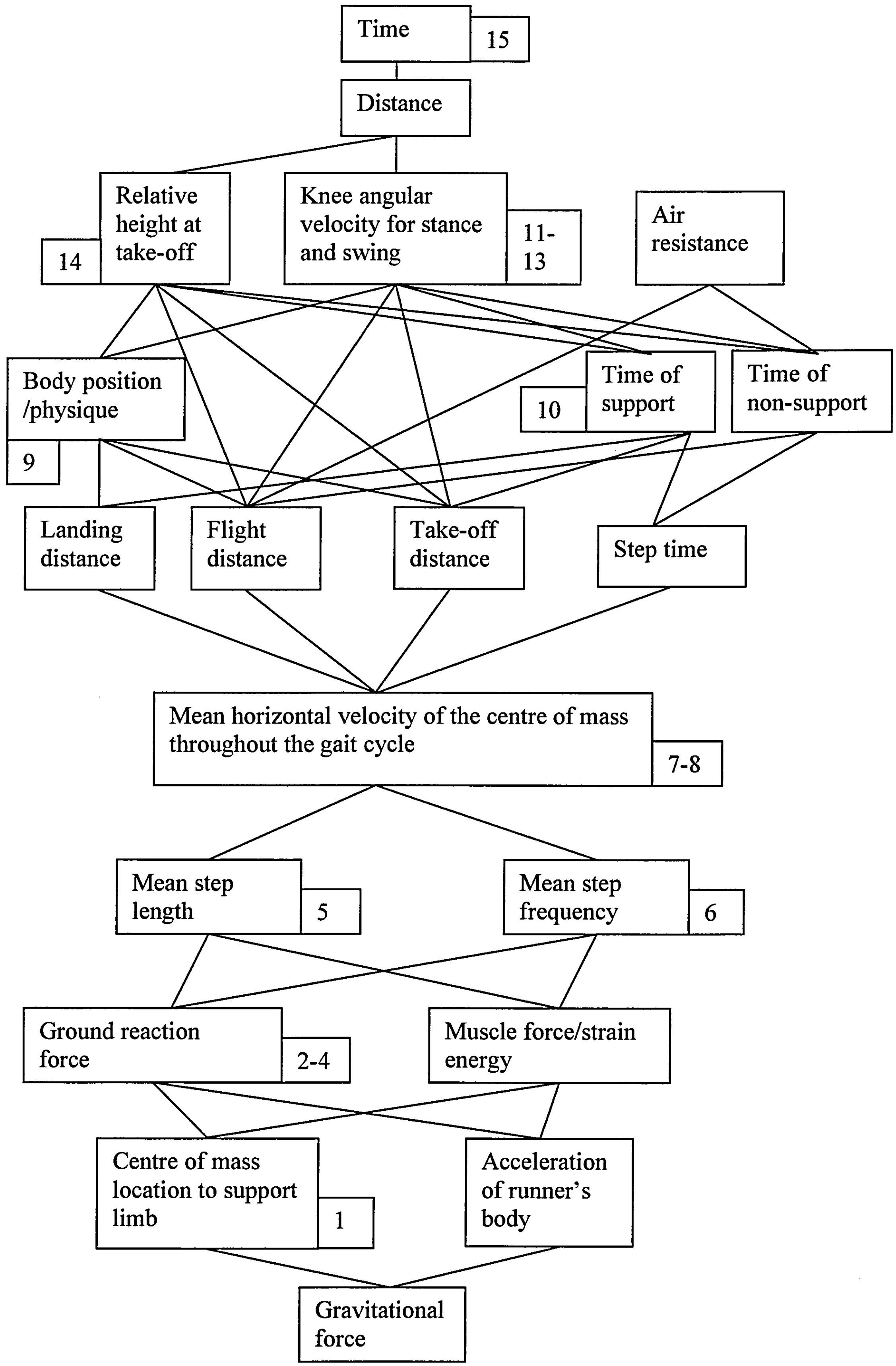


Figure 3.3.5 The Gravitational hierarchical model of running. A gait cycle is right foot contact to right foot toe contact of the same foot.

Description of the Gravitational hierarchical running model

In running, the result is the *time* taken by the runner to cover a specified *distance*. The distance is covered in less *time* by running faster. *Angular velocity for knee flexion and extension during stance* reduce *time of support* thus directly affecting running speed via their relationship with reduced *landing* and *take-off distance* from a more aligned *body position/physique*. Increased *horizontal velocity of the centre of mass* results from a shorter *step time* (reduced *time of support/non support*) because of a reduced *landing distance* where the centre of mass is vertically above the support limb. *Non-support time* decreases via increases in *angular knee flexion velocity* during swing leading to the swing foot returning earlier to the ground. The relative vertical position of the *centre of mass* to the toe of the support foot determines the *relative height at take-off*. Lower *angular knee flexion and extension velocity* during stance affects the *relative height at take-off* by increasing *time of support*. Increased *time of support* increases the *relative height at take-off* through increased leg extension that raises the centre of mass, which subsequently reduces the gravitational torque via work against gravity (*gravitational force*).

The *time of support* and *non-support* affect the *horizontal velocity of the centre of mass* (less time for a given distance). *Air resistance* can reduce the *horizontal velocity of the centre of mass,* which consequently affects the *time of non-support*. The *horizontal velocity of the centre of mass* at terminal stance (with *body position* and *height at take off*) determines *time of non-support* and *step length*. Driving the swing leg forwards via hip flexors causes the foot to land in front of the *body* increasing l*anding distance*, thus decreasing *horizontal velocity of the centre of mass* and *flight distance* (Cavanagh and LaFortune, 1980). The body (*acceleration of the runner's body*) causes the runner's *horizontal velocity of the centre of mass* via a gravitational torque (*gravitational force*) rather than using the leg extensors to push off the ground during leg extension. *Muscle force* is the result of *gravity* (via impact) and the action of the swing leg is to keep up with the body (*acceleration of the runner's body*) from *gravity* during flight.

Mean step frequency is determined by the mean length of time taken to complete one step (*mean step time*). Step time is the sum of:

1) The time of ground contact (*time of support*).

2) The time in the air (*time of non-support*).

Step length may be considered as the sum of three separate distances:

1) The horizontal distance is from the runner's centre of mass and the toe of the support foot at the instant of take-off (*take-off distance*). *Take-off distance* creates the moment arm for the gravitational torque. The relative position of the centre of mass to the toe of the support foot determines the *relative height at take-off*. The faster the foot leaves the ground via reduced leg extension less vertical oscillation ensues, which increases the gravitational torque.

2) The horizontal distance is the distance the centre of mass travels while the runner is in the air (*flight distance*). This is affected by *horizontal velocity of the centre of mass*, *relative height at take-off*, and the take-off angle (*body position*).

3) *Landing distance* is the horizontal distance between the centre of mass and the toe of the leading foot at the instant the runner lands. The more vertically aligned the centre of mass is above the support limb upon landing, the shorter time required before the centre of mass moves past the support point (ball of the foot). A more vertically aligned *body* causes less reduction in the *horizontal velocity of the centre of mass* (Fenn, 1930; Deshon and Nelson, 1964; Cavanagh *et al.*, 1977; Bates *et al.*, 1979; Kunz and Kaufman, 1981; Girardin and Roy, 1984; Hinrichs, 1987) and shorter stance time. A shorter stance time improves elastic recoil (Zatsiorsky, 2002).

Step frequency and *step length* are a consequence of the forces of *gravity, ground reaction*, *muscle action* and *elastic strain energy*. The timing and combination of these forces produce the *mean velocity of the centre of mass* throughout the gait cycle. These forces cause the angular (limbs) and linear (displacement of centre of mass) motion of the runner resulting in *step length* and *step frequency*, which is measured as *mean horizontal velocity of the centre of mass.*

Ground reaction force reflects the *acceleration of the centre of mass*. During the first half of stance, the gastrocnemius and quadriceps muscle groups (*muscle force*) are being eccentrically stretched by *gravitational force* (absorption, figure 3.3.4). After maximum vertical ground reaction force following muscle-tendon lengthening, the support leg extends while the muscles shorten, known as the stretch-shortening cycle (Cavagna *et al.*, 1964). After mid-stance as the muscles shorten in *elastic recoil*, the hamstrings (*muscle force*) begin to pull the support foot from the ground and continue their activity into swing. *Elastic recoil* reduces work against gravity.

The *mass* is the body of the runner. *Acceleration* (horizontal and vertical) of the runner's *mass* is downwards by *gravitational force* during impact to mid-stance and during flight (vertically downwards) but from mid-stance until terminal stance it is via a gravitational torque (causing a horizontal acceleration). *Centre of mass position* as it passes anterior to the support limb via momentum from impact to maximum vertical ground reaction force allows *gravitational force* to then create an external gravitational torque around the axis of the support foot (ball of the foot) until terminal stance (figure 3.3.6).

Gravity (gravitational torque) is the motive external force from mid-stance until terminal stance (see figure 3.3.6) because *muscle activity* is absent, but during flight, *gravity* causes no horizontal acceleration.

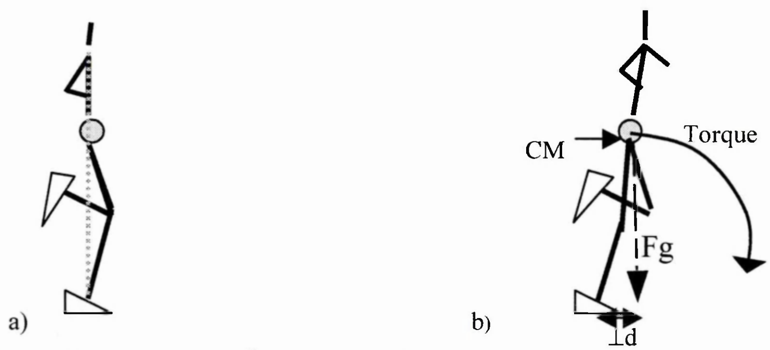


Figure 3.3.6 The running Pose® (Romanov, 2002) a) impact to maximal vertical ground reaction force: shoulder-hip-ankle vertical alignment, which potentially allows gravity to maximise the stretch-shortening reflex and enables the whole body to work as a unit. b) A gravitational torque accelerates the body while the hamstring muscle group pulls the support foot from the ground.

The research variables that were readily quantifiable, identified as important from the literature and that adequately describe the Gravitational hierarchical model are presented:

1. Centre of mass distance behind toe marker (horizontal difference at 25 ms) (cm)
2. Posterior ground reaction force (braking) (BW)
3. Maximum vertical ground reaction force (BW)
4. Anterior ground reaction force (propulsion) (BW)
5. Step length for the right foot (cm)
6. Step frequency (Hz)
7. Centre of mass horizontal velocity largest decrease after impact to maximum vertical ground reaction force ($cm.s^{-1}$)
8. Centre of mass horizontal velocity largest increase from maximum vertical ground reaction force to terminal stance ($cm.s^{-1}$)
9. Centre of mass horizontal displacement during stance
10. Stance time (ms)
11. Mean knee flexion angular velocity for stance ($rad.s^{-1}$)
12. Mean knee extension angular velocity for stance ($rad.s^{-1}$)
13. Mean knee flexion angular velocity from terminal stance to maximum swing angle ($rad.s^{-1}$)
14. Vertical oscillation of the centre mass (cm).
15. Time (s) (time trial)

Support for the Gravitational hierarchical model of running

Clearly, if gravity, ground reaction force, muscle activity and muscle elasticity acted as a precisely coordinated system, efficient running would ensue. The main requirement for the interaction of forces in running is an efficient translation of body weight, regardless of the speed or distance of the event. Bernstein (1947) defined efficiency of movement as a ratio between external forces, such as gravity, which does not require or extensively utilise adenosine triphosphate (muscle contraction), as opposed to those that do, such as, ground reaction force. Efficient movement, he concluded, emphasised external forces that do not heavily engage muscles. Applying Bernstein's concept to running, hierarchical relationships of these forces when structured reveal their specific functions during the running step. Gravity is constant throughout the gait cycle, whereas the other forces are restricted to a certain point in time and space. This section seeks to establish gravity as the motive and hierarchically leading force, over the other forces. Following this order, all forces will act efficiently in time and space.

Gravity was historically regarded as a key motive force: Leonardo Da Vinci was the first to recognise gravity as a propulsive force, when he stated that "*motion is created by the destruction of balance, that is, of equality of weight for nothing can move by itself which does not leave its state of balance and that thing moves most rapidly which is furthest from its balance*" (Keele, 1983: p. 173).

Graham-Brown (1912, p. 786) 400 years later wrote in support of gravity as a motive force: *"It seems to me that the act of progression itself- whether it be by flight through the air or by such movements as running over the surface of the ground-consists essentially in a movement in which the centre of gravity of the body is allowed to fall forwards and downwards under the action of gravity, and in which the momentum thus gained is used in driving the centre of gravity again upwards and forwards; so that, from one point in the cycle to the corresponding point in the next, no work is done (theoretically), but the mass of the individual is, in effect, moved horizontally through the environment."*

Fenn (1930) following extensive work on running found his fastest runner in comparison to a slower runner had his centre of mass further forward during stance (an increased body lean). He went on further to say: "*that a runner does not leap into the air through* *rises in their centre of mass because they are maximal after take-off*' (Fenn, 1930). Instead, the centre of mass rises while the foot is still on the floor and can continue briefly after terminal stance. The runner then falls while they are in the air for about 3 cm (Fenn, 1930). However, this research was not pursued and it is still unclear today how gravity relates hierarchically to the other forces in running. For example, no one has combined gravity's work on the runner with the action of the lower-limb until Romanov (2002) identified as the body falls via a gravitational torque, the support foot needs to be pulled from the ground rather than pushed, in order to catch up with the body.

Gravitational torque from mid-terminal stance

In an attempt to model gravity's role in running, it is necessary to find the point in the gait cycle where gravity could be propulsive, or rather, produces a gravitational torque. In fact, there is only one phase in the gait cycle: from maximal vertical ground reaction force (mid-stance) until terminal stance (Romanov, 2002). At this point (at peak vertical ground reaction force) in constant speed running, the centre of mass begins to move over the support foot (ball of the foot). The body (centre of mass) rotates forward and upward, while the foot acts as a pivot. Rotational movement of the body created by gravity appears as a gravitational torque, so the body could fall forwards (figure 3.3.7). The gravitational torque may therefore explain the 'extensor paradox.' If gravity is the motive force, the leg extensors do not need to thrust the body forwards and upwards, hence their silence as knee extension begins.

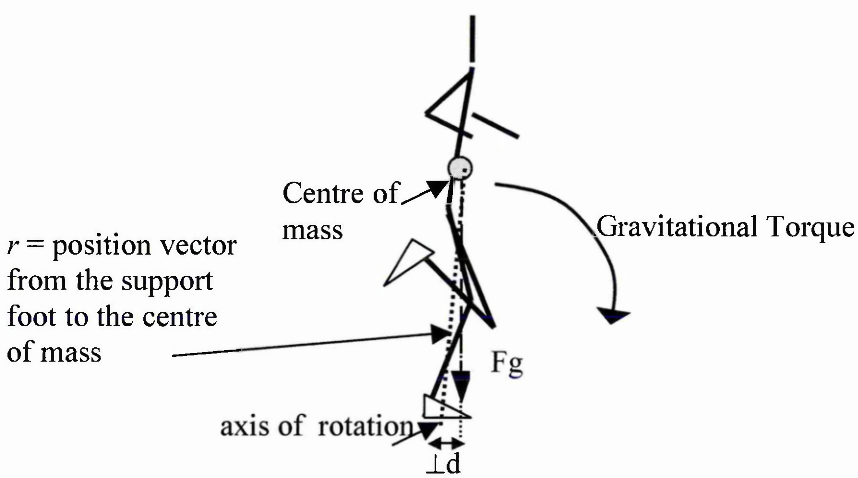


Figure 3.3.7 A torque created around an axis (support limb; ball of foot) from gravitational force. CM = centre of mass; Fg = gravitational force, ⊥d = moment arm and the axis of rotation is the ball of the foot.

By taking the position vector and gravity vector from figure 3.3.7, it is possible to represent the gravitational torque from its vector components (figure 3.3.8). The vector product of any two vectors **A** x **B** is defined as a third vector **C**, the magnitude of which is $AB \sin \theta$, where the angle θ is the angle between **A** and **B**. That is, if **C** is given by

$$\mathbf{C} = |\mathbf{A}| \times |\mathbf{B}| \qquad (3.3.3)$$

Then its magnitude is

$$|C| = |A|\,|B| \sin\theta \qquad (3.3.4)$$

Following the right hand rule the gravitational torque vector is in the clockwise direction about the axis perpendicularly out of the paper. Therefore the gravitational torque is:

$$\tau = Fgr \sin\theta \qquad 0 \leq \theta \leq 180° \qquad (3.3.5)$$

However, the gravitational force is comprised of two components. The Fr component creates no torque on the centre of mass because it acts through the axis of rotation, however the propulsive component (Fp) creates the torque about the support foot.

$$Fr + Fp = \sum F \qquad (3.3.6)$$

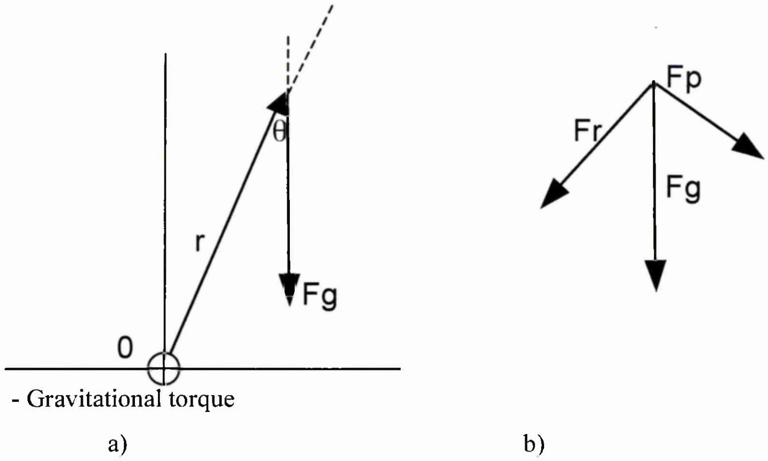


Figure 3.3.8 a) The vector cross product of the centre of mass's position vector and the force of gravity (Fg) create a gravitational torque around the support limb in the clockwise direction. r = position vector of the centre of mass from the support limb. b) Fg = gravity, and its components during stance are Fr, which is the force applied to the ground and causes no torque while Fp is the propulsive force that causes the gravitational torque.

Ground reaction force is absent until two bodies contact one another and gravity has no components (Fr and Fp) until the runner touches the ground. As the runner falls forwards after mid-stance, ground reaction force is decreasing reflecting the runner's rising centre of mass. There is also another torque that occurs via the ground reaction force vector and its moment arm about the centre of mass (figure 3.3.9), which reflects the acceleration of the centre of mass, as it moves in a non inertial frame during stance because of its acceleration and deceleration. A better option for an inertial frame is the gravitational torque around the support foot making it more suitable for analysis. More importantly, the point of application for the ground reaction force vector is the support foot and therefore the ground reaction force is in fact reflecting Fr. Fr is equal to the ground reaction force but in the opposite direction. Further, the ground reaction force is not propulsive because it is a reactive force (reacting to Fr). There is also no ground reaction from the leg and hip muscle extensors because they are not active during the propulsive portion of stance. The gravitational torque is therefore the motive torque and not ground reaction force, which is reflecting gravity's work. The resultant (net) force (figure 3.3.9 b) is the resultant of the ground reaction force and gravity vectors. However, the resultant vector of gravity and ground reaction force is the same as Fp (figure 3.3.10) the propulsive component of gravity.

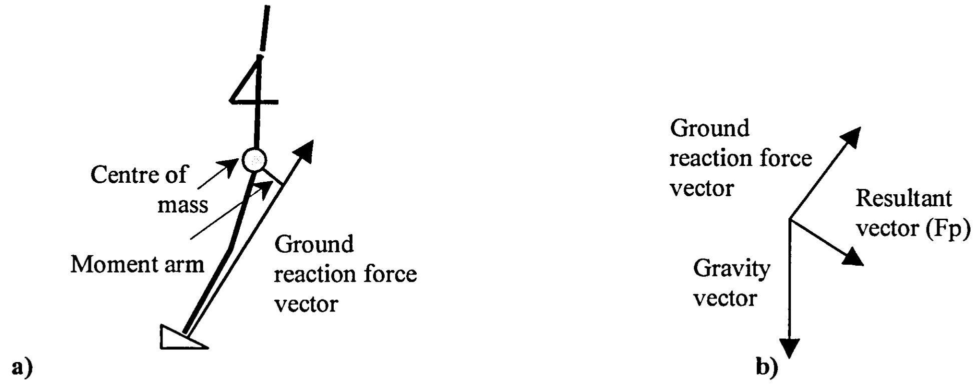


Figure 3.3.9 a) Ground reaction force torque about the centre of mass b) The ground reaction force and the gravity vector taken at the same point of stance as the vector product in figure 3.3.8.

Figure 3.3.10 uses figure 3.3.9 b but includes the components of gravity. Fp creates the gravitational torque representing the resultant of the two external forces (gravity and ground reaction force) acting on the runner and is the net force causing the gravitational torque that accelerates the runner in the direction of the net force. The net force (Fp) is perpendicular to the position vector representing the radius for the centre of mass around the support foot. Fp causes a tangential acceleration, which changes the speed of the centre of mass. Fr causes a radial acceleration, which changes the direction of the centre of mass. This motion is similar to an inverted pendulum where the centre of mass swings around the support foot. The torque (tangential component of gravity) for a pendulum is the same (if $l = r$) equation as the gravitational torque for running giving further support the gravitational torque (inverted pendulum) is the motive torque in running:

$$\tau = -mgl \sin\theta \qquad (3.3.7)$$

Where –mg is the weight of the pendulum, l is the length of the cable and sine theta is the angle between the cable and gravity.

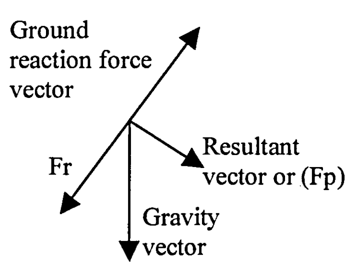


Figure 3.3.10 Gravity and ground reaction force vectors with gravity's components included, showing the net force is Fp. Notice Fr is equal and opposite to the ground reaction force vector, leaving Fp as the net force or the resultant of gravity and ground reaction force.

The body is also moving upwards from mid-stance until terminal stance so the runner is working against gravity, but this does not negate the gravitational torque seen from figure 3.3.11.

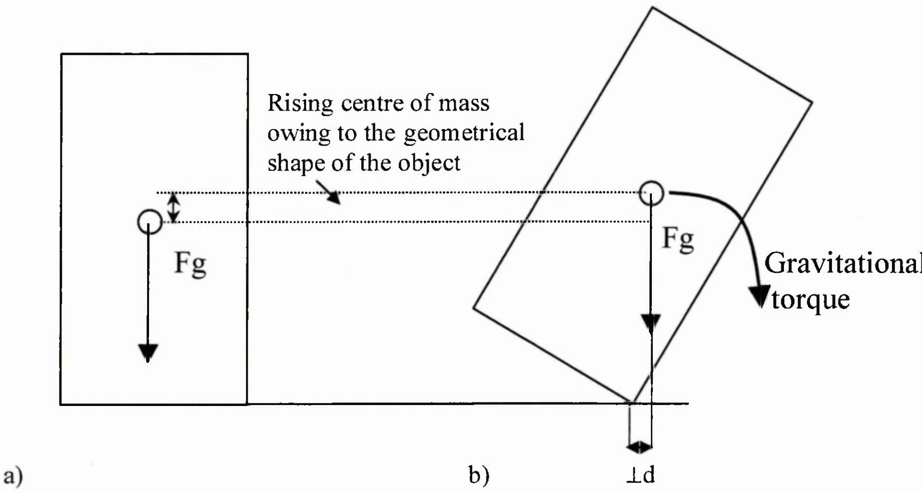


Figure 3.3.11 Two identical rectangles are given with their centre of masses marked as ○ Fg = gravity. a) The upright rectangle represents the runner at mid-stance with their centre of mass above the supporting limb (ball of the foot). b) The rectangle (runner) tips forwards via momentum. A gravitational torque around the runner's centre of mass subsequently moves them horizontally forwards. Note however, the centre of mass rises owing to the rectangles geometry and the runner rises via elastic recoil and leg extension from the rising body.

The centre of mass rises (does work against gravity), because of the lower-limb geometry (support/stance leg extends), whilst the gravitational torque horizontally displaces the runner. The stance leg is extending (passively) at this time owing to geometry of the body and elastic recoil, which raises the centre of mass. Obviously, less leg extension will result in lower work against gravity. Cavanagh, *et al.* (1977) found general support for improved running economy with lower vertical oscillation (less work against gravity). The momentum of the runner in the vertical direction would slow at this time owing to the work against gravity, except for the rebound effect of the muscle-elastic system. The leg extensors are maximally active (eccentrically) at mid-stance as the body absorbs landing and the centre of mass is at its lowest vertical position (Mann, 1980; Wank *et al.*, 1998). The angle of the centre of mass at or just after this time is just past the vertical (in the clockwise direction) where the leg extensor muscles become inactive. Any muscle force at this time would be directed more vertically than horizontally (Farley and Ferris, 1998). The elastic recoil of the musculotendinous junctions therefore, contribute to the vertical oscillation of the centre of mass thus reducing the work against gravity (Alexander, 1989). However, elastic recoil cannot create a typical one-metre step length. Rather, the constant force of gravity after maximum vertical ground reaction until terminal stance creates a gravitational torque, which produces step length from horizontally accelerating the runner's body.

Returning to the Froude number, comprised of leg length, running speed and gravity. Gravity reflects the centre of mass's height because it is the point about which gravity acts. The height (centre of mass position) of falling is also dependent upon the length of the leg. Alexander and Jayes (1983) proved that the longer the leg the longer the step. A longer leg increases the height of release, which will increase step length. However, running speed comprises of both step length and step frequency. When step length is maximal the only way to increase speed is to increase step frequency. The increase in step frequency at faster speeds is simply reflecting the ability to fall has been maximised (angle of inclination is maximal), therefore, to increase running speed, higher step frequency is required (more opportunities to fall), which is self-evident in sprinting. Step length reaches a maximum value at a running speed of around 7.0 $m \cdot s^{-1}$ (Luhtanen and Komi, 1978). To compensate, step frequency increases at faster running speeds—than 7.0 $m \cdot s^{-1}$—and up to maximum speeds (Luhtanen and Komi, 1978). If step length reflects these three components, it is possible to state, running speed increases via a gravitational torque up to a point where the maximal angle of inclination (from the centre of mass to the support foot) is reached, thus producing a maximal step length.

In support that gravity is creating forward progression, Chang *et al.* (2000) using three conditions: increased gravity and inertia, increased inertia and reduced gravity, took eight participants and ran them at 3 $m \cdot s^{-1}$ for all conditions. By increasing gravity and inertia, the magnitude of the horizontal ground reaction force impulse increased. By increasing inertia only, the horizontal impulse did not increase. As gravity was reduced, the magnitude of the horizontal impulse reduced proportionally. This suggests gravity is affecting the horizontal impulse. Perhaps this explains why the horizontal propulsive ground reaction force does not coincide with maximal muscle activity, but in fact, may reflect the gravitational torque. The vertical impulse had similar results to the horizontal impulse, indicating gravity strongly influences the vertical ground reaction force. Step length increased in reduced gravity and decreased in increased gravity and inertia but remained stable with increased inertia. This clearly suggests gravity is affecting step length and by implication, step length is created via a gravitational torque. The resultant ground reaction force peak angles of braking, propulsive and peak force were constant for all conditions. As running speed was constant for all conditions this would suggest the angle of inclination of the body would be constant, which is exactly what their results showed. A constant body angle would not change the gravitational torque (owing to the same moment arm) and hence changes in the vertical and horizontal impulses would be proportional to changes in gravity for the same leg-length.

Figure 3.3.12 illustrates the length of the force vectors are proportional to the vertical and horizontal components of the ground reaction force. Regardless of which technique of running—heel-toe and forefoot—both show maximum ground reaction force occurs on the ball of the foot when the body is in its lowest position reflecting maximum weight illustrating gravity's work (figure 3.3.13). It is important to also note that the body cannot move forward until the centre of mass passes the ball of the foot (pivotal point of support) which only begins after maximal vertical ground reaction force in constant speed running.

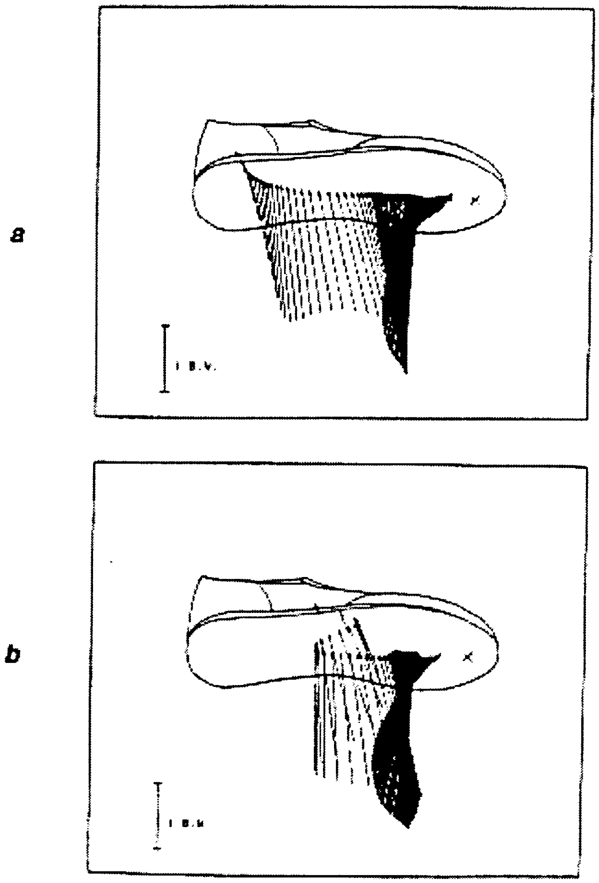


Figure 3.3.12 Vector representation of the ground reaction force in running for two participants (a) A heel-toe runner, (b) A forefoot runner. The view is of the right shoe from the lateral aspect with the shoe tilted 30° upward (adapted from Cavanagh and Lafortune, 1980).

Leg extension during the propulsive of stance

Figure 3.3.13 illustrates the centre of mass reaches its lowest position and velocity at maximum vertical ground reaction force in running and hence its lowest gravitational potential and kinetic energy (McMahon *et al.*, 1987; Farley and Ferris, 1998). Combining figure 3.3.12 with figure 3.3.13, it is possible to see that the centre of mass is lowest at maximal vertical ground reaction, and this point, is on the ball of the foot. Further, maximal vertical velocity occurs 0.1 ms (40% of stance time later) after maximal vertical ground reaction force. In fact, vertical ground reaction force is decaying too below body weight at maximal vertical velocity, thus it must be reflecting the vertical elastic re-bound affect, which subsequently causes the change in vertical velocity and not ground reaction force.

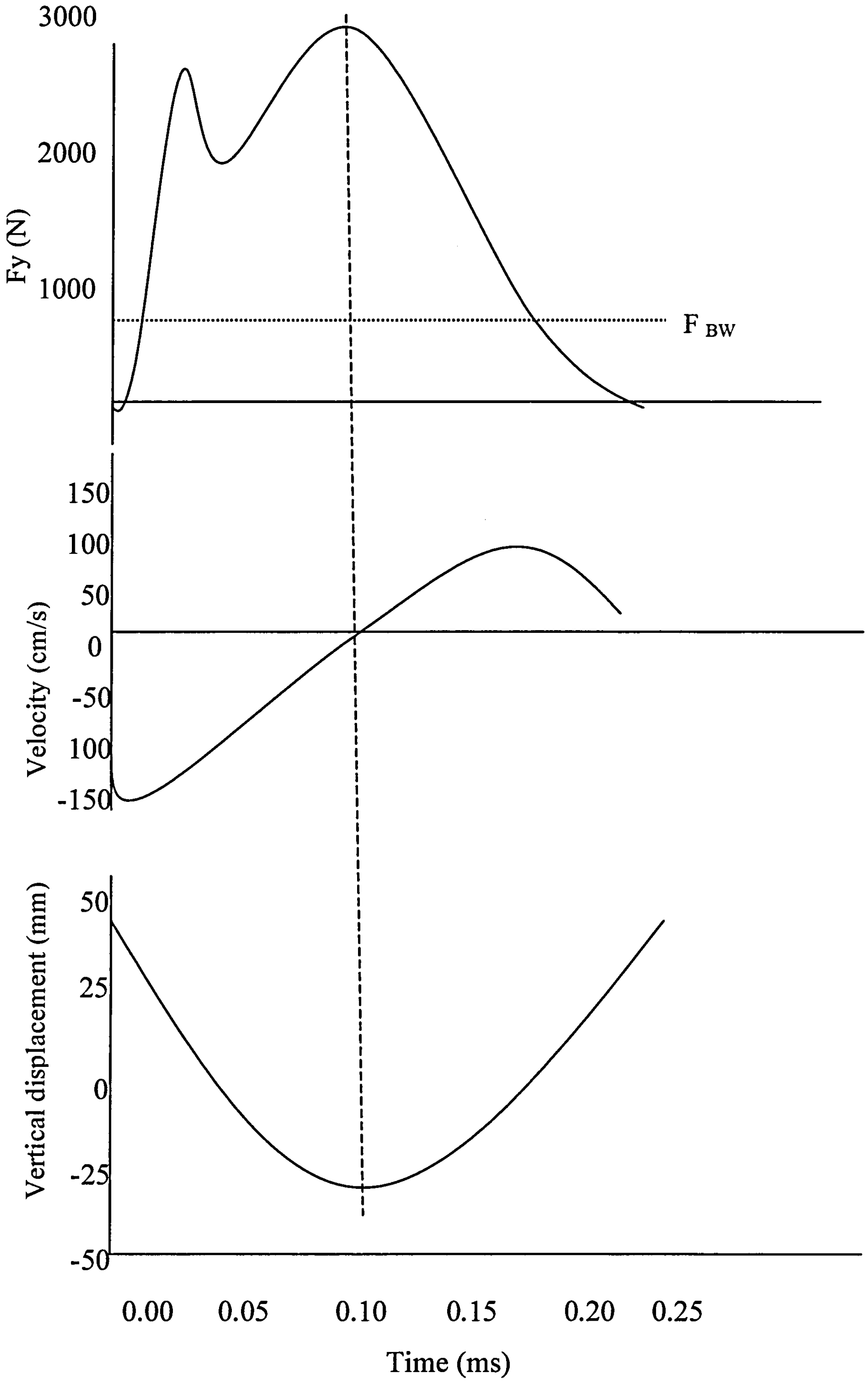


Figure 3.3.13 Vertical ground reaction force, during the stance phase of running (a) vertical velocity of the centre of mass (b) and the vertical position of the centre of mass (c). The vertical dotted line illustrates the timing of maximal vertical ground reaction force with zero velocity and the lowest point of the centre of mass (adapted from Enoka, 2002; p. 192).

In support of the muscle system not pushing the runner forwards, the flic-flac (figure 3.3.14) illustrates there is a distinct thrust (active leg extensors) just before leaving the ground reflected by sudden increased vertical and horizontal ground reaction force traces. This trace is not evident in running, because the leg extensors are not active. In fact, in running, there is a rapid decay in the vertical ground reaction force reflecting the body leaving the ground coupled with silent extensor muscle activity ('extensor paradox'; McClay *et al.*, 1990).

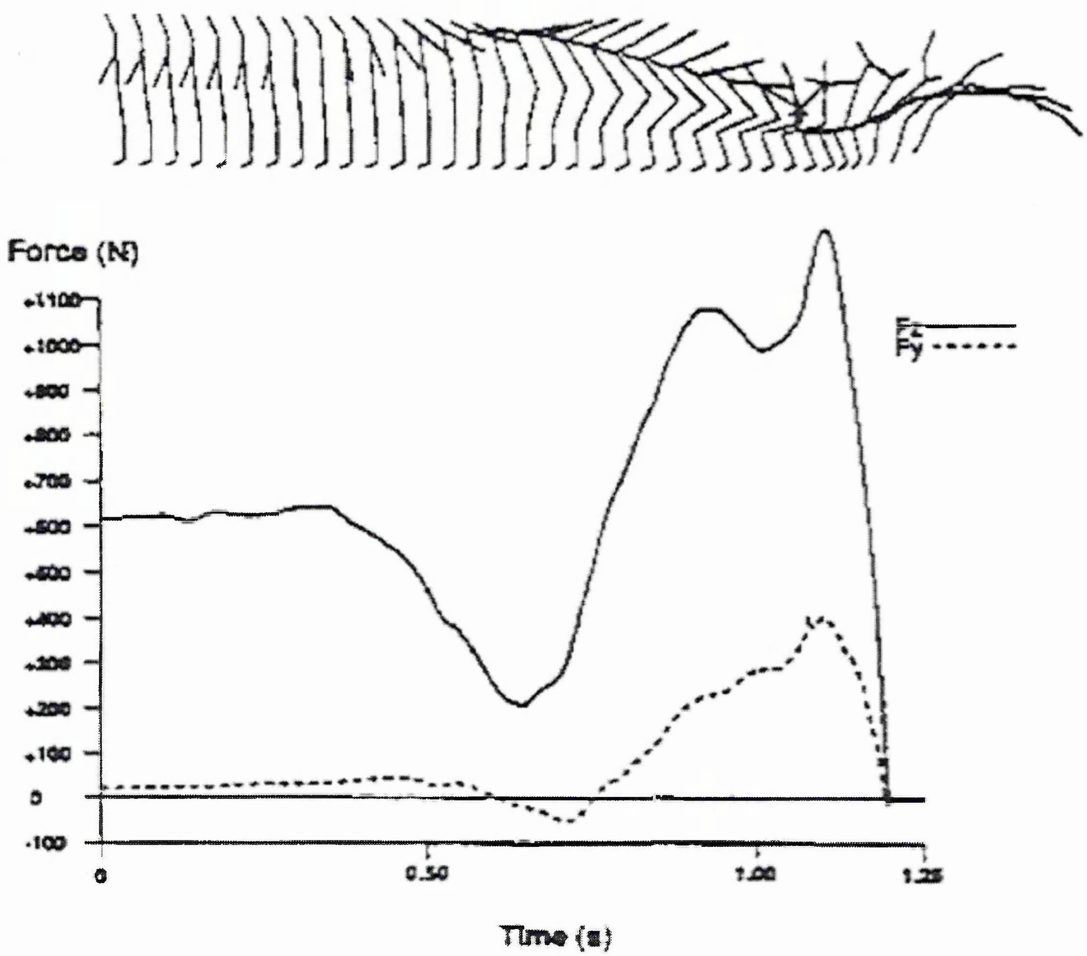


Figure 3.3.14 A gymnast performed a flic-flac (stick figure) showing vertical (Fz) and posterior-anterior (Fy) ground reaction force. Note the spike in ground reaction force at push-off with the feet (Yeadon and Challis, 1994).

Fenn (1930) identified that the body pushes forwards from the hip at foot contact because hip velocity exceeded that of the neck. In fact, the hips begin extension before the knee and ankle during stance (Mann *et al.*, 1986; Montgomery *et al.*, 1994), which supports Fenn's observation. However, hip extension that produces forward movement, which leads the knee and ankle joints, is not universally accepted (Winter 1983). Montgomery *et al.* (1994) suggest the ankle musculature stabilizes the ankle while the trunk moves forward rather than these muscles producing an active push-off (Reber *et al.*, 1993). Whereas, Winter (1983) suggested the calf musculature pushed off at terminal stance. However, Cavanagh *et al.* (1977) found elite runners did not plantar flex the ankle at terminal stance compared to less able runners, suggesting it is not effective. In figures 3.3.15 and 3.3.16, at the third position for each runner, which is just past maximum ground reaction force the hip is just about to begin extension. While positions, 4 and 5 show both runners extending their hips as vertical ground reaction force is decreasing, noting leg extensor muscle activity ceases just after leg extension begins (Montgomery *et al.*, 1994; Wank *et al.*, 1998). Hunter *et al.* (2005) also dismissed leg extension at terminal stance as a cause of increased propulsion in sprinters, but found the mean of hip extension velocity was associated with greater propulsion. Therefore, owing to the body's horizontal velocity, the body moves forward of the foot (having almost zero horizontal velocity) and leg extension will occur primarily because of the body's inertia (reflected by hip motion). The body continues past the support point (ball of the foot), where the ankle musculature stabilises the ankle, and then the body accelerates via a gravitational torque. Leg extension is also aided via the stretch-shortening cycle. Changes in the length of the muscles belly are minimal, because most of the change in length comes from the stretch and recoil of the respective tendons (McMahon, 1990). Consequently, muscle tendons lengthen during the eccentric phase (impact to maximum vertical ground reaction force) and recoil elastic energy during the propulsive phase of stance. The muscles still exert tension but elastic energy allows the muscles to shorten less, thus reducing muscle work (Ker *et al.*, 1987). Short stance time and correct body geometry (landing with the centre of mass over the ball of the foot to increase the pre-stretch via a more vertical weight vector) all potentially increases the stretch-shortening cycle. The release of elastic energy aids leg action through tension in the Achilles tendon at terminal stance (Kyrolainen *et al.*, 2003) rather than an active push-off. Shorter stance time will result from a more vertically aligned body at impact, because the body travels a shorter horizontal distance during stance. A shorter stance time also enhances the elastic mechanisms (Zatsiorsky, 1995; Paavolainen *et al.*, 1999a).

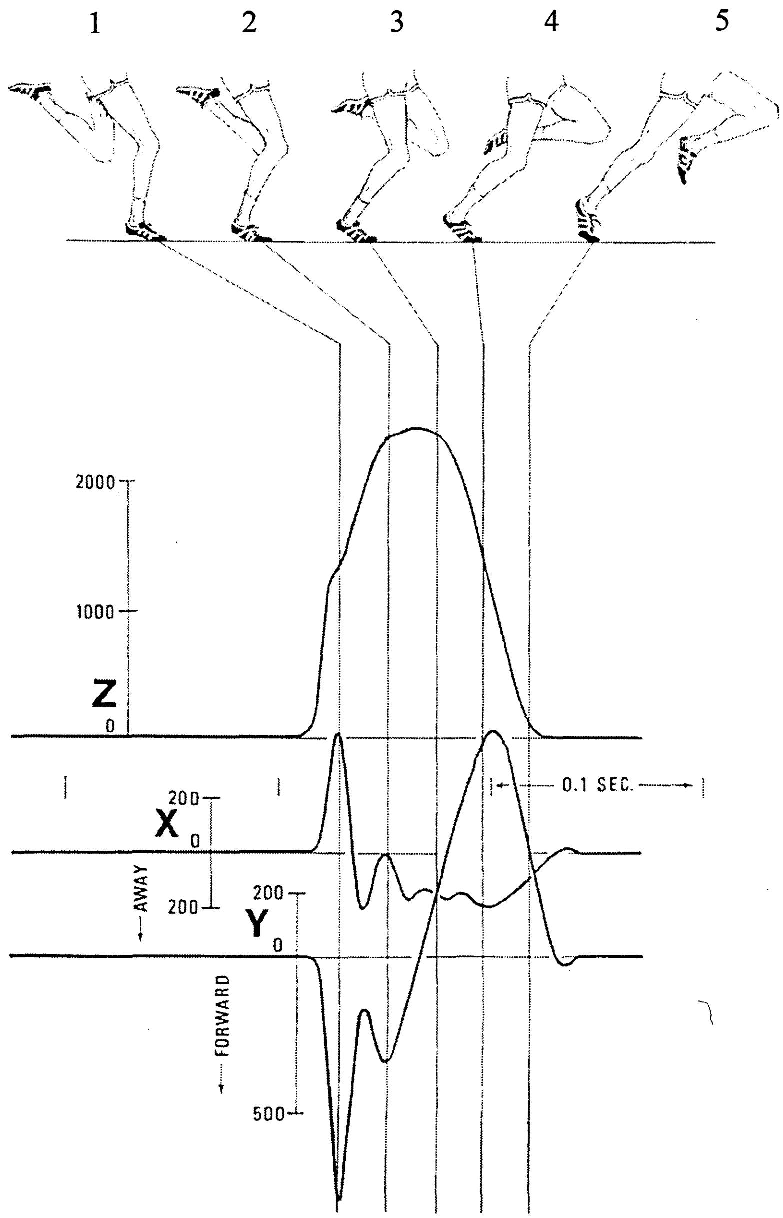


Figure 3.3.15 Force-time recording of a forefoot runner (mass 80 kg, velocity 9.2 m·s^{-1}) (Payne, 1983; p. 749).

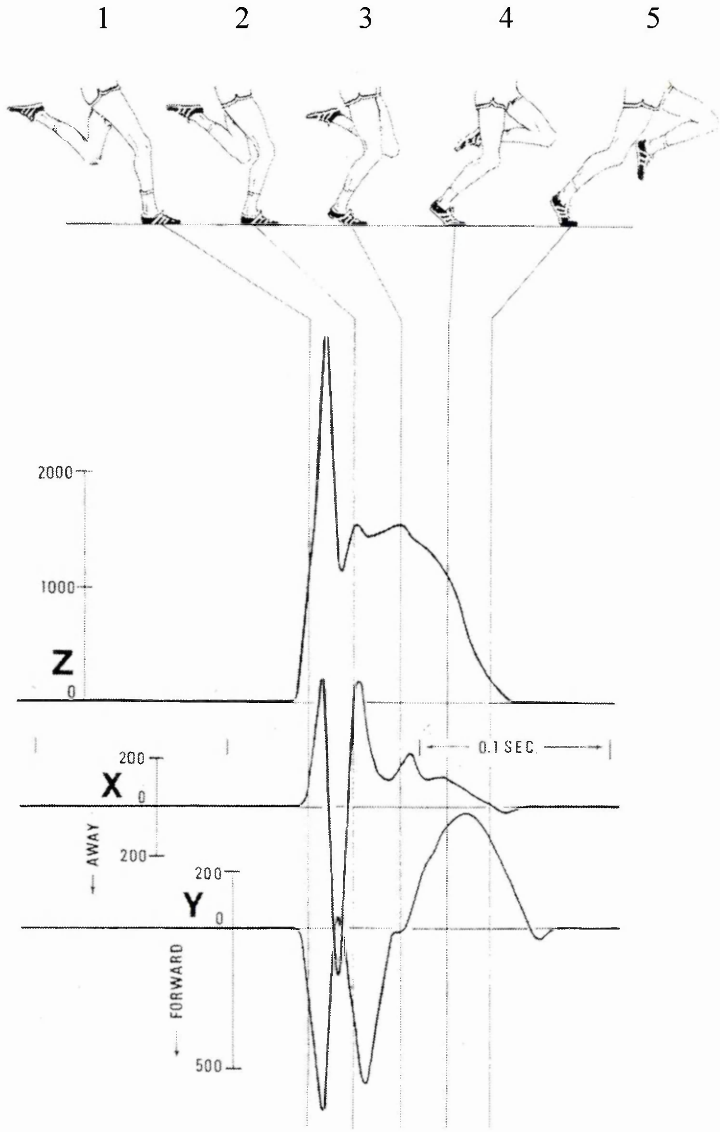


Figure 3.3.16 Force-time recording of a heel-toe runner (mass 63 kg, velocity 9.5 $m \cdot s^{-1}$) (Payne, 1983; p.748).

Further evidence for the support leg being passively extended is seen in figure 3.3.17. Both runners have similar vertical oscillations until position 3, possibly illustrating comparable knee flexion angles. The vertical displacement of the centre of mass rises from mid-stance (position 3) until terminal stance (or just after) in both runners. However, the good runner does not extend his leg as much as the poor runner—position 6—possibly leading to lower vertical oscillation from position 4 to 7. Note the term ‘poor’ is relative in relation to his 5-km time making him still a very competitive athlete. Miura *et al.* (1973) found that the good runner’s centre of mass deviation from the vertical axis was greater on average at 34.7° compared to 31.8° for the poorer runner. A larger angle from the vertical axis increases the moment arm for the gravitational torque, which potentially increases forward progression (increases running speed) while passively extending the leg. The lower leg extension in the faster runner may be related to his increased angle of deviation.

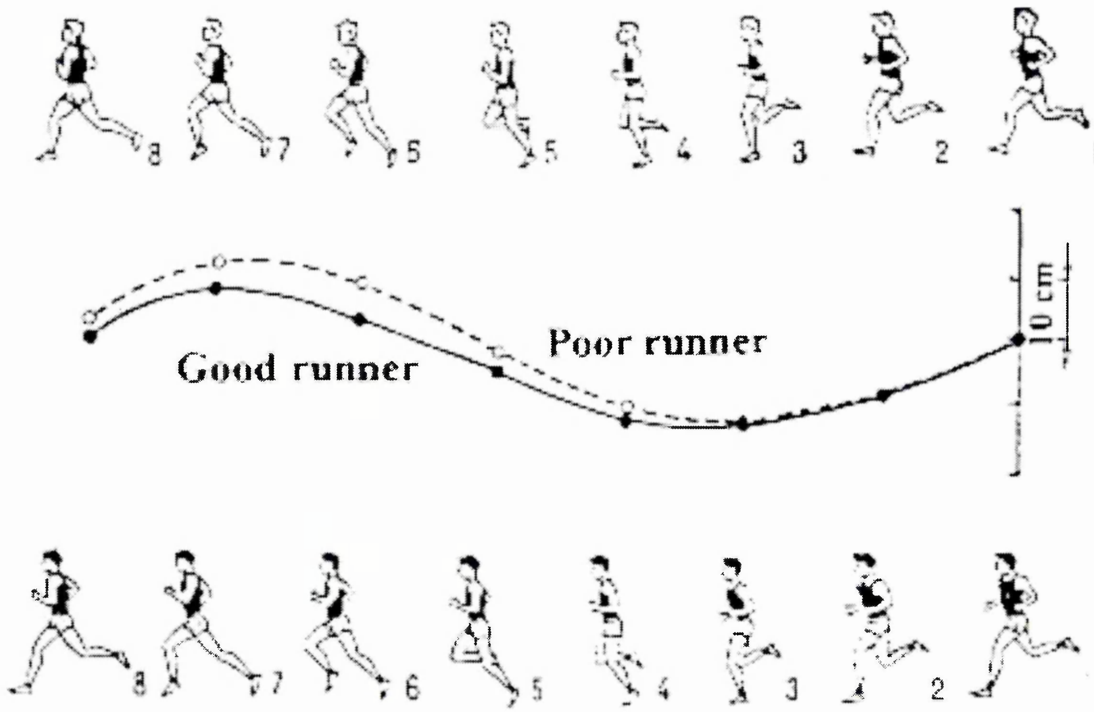


Figure 3.3.17 Vertical displacement of the centre of mass for a good runner (14 min 52 s, 5 km) and a poor runner (16 min 29 s, 5 km) (Miura *et al.*, 1973).

Milliron and Cavanagh (1990) also support a passive leg extension. Using four participants on a treadmill at a negative grade of –20%, level and a positive grade of 20%, they found that leg extension decreased from level to uphill (20%) and increased for downhill running (-20%). These data suggest that downhill running causes greater extension (32.1°) owing to a faster body speed passively extending the leg further than uphill (13.0°) or level running (15.1°). Paradisis and Cooke (2001) also found similar results. In addition, the most variability in phasic activity of all the knee muscles is the hamstrings (Heise *et al.*, 1996). Hamstring variance might better explain runners who flex their legs (via hamstring activity) earlier and faster at terminal stance than poorer runners do. Earlier and faster flexion at terminal stance would possibly reduce leg extension, maintain momentum—through reduced inertia of a less extended leg—and hence lower vertical oscillation and work done against gravity. Potentially a runner then leaves the ground as the body falls forwards. If the body is accelerating from the gravitational torque and the next step is beginning, there is no need to push-off with the stance leg. In fact, Romanov (2002) is the first to mention pulling the support foot from the ground. If the foot is pulled from the ground, it is also moving in the same direction (upwards) as the elastic recoil of the lower-limb muscles. Elliot and Blanksby (1979) reported maximal biceps femoris activity at terminal stance suggesting rapid knee flexion supporting a potential pulling of the foot from the ground. The concept of pulling the foot from the ground among endurance runners is not common. However, in most sprinters, the knee does not fully extend during stance and rapidly flexes at terminal stance, suggesting the foot is indeed pulled from the ground (Mann and Hagy, 1980; Mann *et al.*, 1986). If the hamstring muscle group flexes the knee at the same time as the muscles experience elastic recoil a coordinated lower-limb/body motion should ensue. If this action is coordinated with the body falling forwards, at this point, the body is rising, which un-weights the foot allowing it to be pulled from the ground. The foot will then essentially be catching up to the body as the runner enters flight.

Flight Phase

During flight the runner falls to the ground under gravity's work (Fenn, 1930) and providing the opposite leg—swing leg—is not driven forwards (via hip flexion) gravity should allow the foot to drop under the centre of mass for the next step cycle to begin again. If the swing leg is driven forwards into the flight phase the swing foot will land in front of the centre of mass at impact reducing horizontal velocity (Bates *et al.*, 1979; Hinrichs *et al.*, 1987). A reasonable assumption is runners are thinking about driving their swing leg forwards at terminal stance, rather than pulling the support foot from the ground. This difference perhaps divides Pose® running from heel-toe running (Romanov, 2002). If the runner is not thinking about pulling the foot from the ground—using the hamstring muscles—as the leg extends, their centre of mass continues to rise via leg extension completing more work against gravity, thus reducing the gravitational torque. Reducing the gravitational torque reduces the take-off velocity, which subsequently reduces running speed.

In summary of the Gravitational hierarchical model that describes the Pose® technique of running, two key concepts emerge: falling under a gravitational torque and pulling the support foot (knee flexion) from the ground via the hamstring muscle group. The

Gravitational hierarchical model has attempted to reflect these concepts while ordering the timing of the forces involved in running. Support presented for gravity being the motive force was the runner could only move forwards once the centre of mass passes the support point (ball of the foot) at mid-stance. Inertia brings the runner's centre of mass after impact to this point (mid-stance), where ground reaction force is maximal, while vertical displacement and horizontal velocity of the centre of mass are minimal. In a flic-flac, there is a clear push-off the ground, but in running the ground reaction force decays from maximal vertical ground reaction force until terminal stance. The decay rate increases with running speed, suggesting increases in the acceleration of the centre of mass (faster angle of deviation) as it leaves the ground. A gravitational torque creates acceleration of the runner from mid-stance, potentially explaining the lack of leg and hip extensor muscle activity. In support, maximum propulsive horizontal ground reaction force occurs after extensor muscle activity ceases. Pulling the foot from the ground as the body is falling, reduces vertical oscillation by potentially decreasing leg extension (Wank *et al.*, 1998), which allows the foot to catch-up with the body more quickly as a result of reduced lower-limb inertia. High Achilles tendon forces at terminal stance, suggest the elastic recoil plays a significant role in reducing work against gravity from mid-terminal stance. During swing, if the ipsilateral leg drops under gravity's influence during flight, and is not driven forwards via the hip flexors, the foot will land under the centre of mass for the cycle to begin again.

3.4 SUMMARY

There are three known forces involved in running (gravity, ground reaction force, muscle force) and potential strain energy. Several deficiencies identified in the current running model include: viewing the constant force of gravity as only active during flight and not relating gravity to forces exerted and the time forces act despite gravity being a constant force. The Gravitational model stated the forces involved in running could hierarchically function when gravity orders their timing and work. A gravitational torque was shown to be the main motive force in running as the body falls forwards. Ground reaction force is not a motive force but operates according to Newton's third law, which simply reflects the forces it receives. The ground can only propel a runner forward via muscle activity. Leg and hip extensor muscles have consistently proven to be silent during the support leg's extension, in contrast to Hay and Reid (1988; pp. 264 and 287-288), who suggest leg extension via ankle, knee and hip musculature is the motive force in running. High Achilles tendon forces at terminal stance suggest the elastic recoil is creating a re-bound effect in the vertical direction thus reducing work against gravity. Gravity is the only external force that can displace the centre of mass from maximal vertical ground reaction force until terminal stance if muscle extensor activity is silent. The Gravitational hierarchical model therefore, identifies gravity's important role in running. Forward movement (falling via a gravitational torque) begins once the centre of mass has passed over the ball of the foot. The flic-flac shows a clear spike in the ground reaction force trace reflecting a push-off, which is completely absent in runners. In fact, the ground reaction force decay rate increases as running speed increases. The decay rate is reflecting the body leaving the ground and not the support limb's muscle activity pushing off the ground because the lower-limb's muscles are silent. The Froude number supports gravity's work in creating running speed, because step length differences from short or long legged runners are proportional to leg length. Muscle force is not a component of the Froude number because step length occurs via a gravitational torque not muscle force. Further, the hip's extension velocity was significantly associated with the support leg's passive extension. This again suggests the body is moving forward of the support limb (via a gravitational torque) and not being pushed forwards via the ankle and knee joints. The hip passively extends because the body moves past the stationary foot extending the lower-limb. In Pose® running the hamstring muscles pull the support foot rapidly from the ground when the foot un-weights with the aid of the stretch-shortening cycle optimised from a short contact time. By pulling the support foot and not driving the swing leg forward of the body via the hip flexors, gravity can drop the swing leg under the body at impact enabling the cycle to begin again. The swing leg's centre of mass must be vertically below the body's centre of mass during flight for this to occur. Driving the swing leg forwards causes the foot to land ahead of the body slowing horizontal velocity of the centre of mass owing to increasing the distance of the centre of mass from the support foot. The Gravitational model, therefore, hierarchically explains the forces involved in running. Gravity causes the muscle system to absorb body weight on landing (maximum ground reaction force), which then produces elastic strain energy in the musculotendinous junctions. As the centre of mass passes over the support limb (at maximum vertical ground reaction force), a gravitational torque is produced as extensor muscle activity ceases. The runner falls forwards while ground reaction force decreases (the body is leaving the ground) and vertical work against gravity is reduced via elastic mechanisms. At terminal stance, as the foot is un-weighted, it is rapidly pulled from the ground (hamstring muscle activity) in order to reduce lower-limb inertia and to catch up with the body during flight. Finally, the runner returns to the ground via gravity during flight. The ability to fall via a gravitational torque and to pull the foot from the ground effectively, potentially divides the two techniques: Pose® and heel-toe running. The Gravitational hierarchical model, therefore, reflects these differences between the two running techniques and potentially offers a quantifiable method to differentiate between the two.

CHAPTER 4

EXPERIMENTAL PROCEDURES

4.1 INTRODUCTION

The research aims are presented with the hypotheses for the main study. A research design for each of the two studies is provided covering sample size, equipment, research variables and treatment of data.

4.2 STATEMENT OF THE PROBLEM

The primary aim of this thesis is to compare the Pose® method technique (Romanov, 2002; Arendse *et al.*, 2004; Dallam *et al.*, 2005) with the heel-toe running technique. Development of a new Gravitational hierarchical model based on the Pose® method using the laws of physics will enable the Pose® technique's systematic evaluation. The Gravitational hierarchical model and the current hierarchical model (Hay and Reid, 1988; p. 282) are reviewed highlighting the different biomechanical theories of running. There are deficiencies with Hay and Reid's model, for example, viewing the constant force of gravity as only active during flight and not relating gravity to forces exerted and the time forces act. Therefore, Hay and Reid's model does not systemise the forces involved in running but acts as general descriptor, whereas, the Gravitational hierarchical model will aim to structure these forces. A comparison of the Pose® and heel-toe running techniques will follow using two experienced male Pose® and heel-toe runners utilising the primary and secondary research variables (study 1; chapter 5) derived from the Gravitational hierarchical model. Upon establishment of the Pose® method technique, a group of male heel-toe recreational runners (study 2; chapter 6) will participate in a repeated measures design. An economy and time trial run will give the participants pre-test baseline physiological measures while the primary research variables will provide a biomechanical profile. The post-test will determine whether there is an improved performance on the economy and 2400 time trial run resulting from the potential biomechanical changes in the Pose® group from a 7-hour Pose® training intervention. A 2 x 2 mixed factorial ANOVA will assess the main effects of group (control vs. treatment) and trial (pre to post changes) on the primary research variables. Tukey's tests of honestly significant differences will be used to assess individual cell differences *post hoc*. A prospective three-month injury study on all the participants post intervention will seek to determine injury incidence between the two running techniques.

4.3 THE HYPOTHESES

The thesis will reject H_o and accept H_1 at $P < 0.05$. Each research and null hypothesis for study 2 are given including a brief explanation. Study 1 was a descriptive study.

4.3.1 Study 2 (Pose® method training study; Chapter 6) hypotheses

The treatment group were heel-toe runners who had 7-hours of Pose® instruction. Fourteen null and research hypotheses derived from the Gravitational hierarchical model's primary research variables are given:

1. Reduced stance time correlates with elite runners and improved economy (Williams and Cavanagh, 1987; Nicol *et al.*, 1991).
- H_1: The treatment group will show a decrease stance time.
- H_o: The treatment group will show no change in stance time.

2. There will be a decrease in vertical ground reaction force between the two groups (Arendse *et al.*, 2004).
- H_1: The treatment group will show a decrease in vertical ground reaction forces.
- H_o: The treatment group will have no change in vertical ground reaction forces.

3. There will be no difference in posterior and anterior ground reaction force between the two groups (Chang *et al.*, 2000).
- H_1: The treatment group will show no change in posterior and anterior ground reaction forces.

- H_o: The treatment group will increase in posterior and anterior ground reaction forces.

4. A decrease in horizontal velocity of the centre of mass at impact to maximal vertical ground reaction force has generally been found in 'poorer' runners (Fenn, 1930; Slocum and Bowerman, 1961; Deshon and Nelson, 1964; Enomoto *et al.*, 1999).

- H_1: At impact, there will be less decrease in the horizontal velocity of the body's centre of mass for the treatment group.
- H_o: At impact, there will be no change in the horizontal velocity of the body's centre of mass for the treatment group.

5. An increase in horizontal velocity of the centre of mass from maximal vertical ground reaction force until terminal stance for the Pose® runners will be used to support gravity's role in forward progression (Keller *et al.*, 1996).

- H_1: From maximal vertical ground reaction force until terminal stance, the treatment group will increase horizontal velocity of the centre of mass.
- H_o: From maximal vertical ground reaction force until terminal stance, the treatment group will have no change in horizontal velocity of the centre of mass.

6. Vertical alignment of the body at impact is associated with faster runners (Deshon and Nelson, 1964; Mann and Herman, 1985).

- H_1: The treatment group will show increased vertical alignment of the body at impact.
- H_o: The treatment group will show no change in vertical alignment at impact.

7. Less horizontal displacement of the centre of mass during stance will reduce stance time (Ferris *et al.*, 1999).

- H_1: The treatment group will show a decrease in horizontal displacement of the centre of mass during stance.
- H_o: The treatment group will show no change in horizontal displacement of the centre of mass during stance.

8. Reduced vertical oscillation of the centre of mass has been associated with 'good' runners (Miura *et al.*, 1973; Williams and Cavanagh, 1986).

- H_1: The treatment group will show a decrease in vertical oscillation of the centre of mass.
- H_o: The treatment group will show no change in vertical oscillation of the centre of mass.

9. Mean knee angular velocity for flexion and extension during stance were significantly correlated with stride length, stride frequency, vertical loading rate and stance time (De Wit *et al.,* 2000). A decrease in knee angular velocity for flexion and extension may reflect lower muscle activity.

- H_1: The treatment group will show a decrease in mean angular knee flexion and extension velocity during stance.
- H_o: The treatment group will show no change in angular knee flexion and extension velocity during stance.

10. Increased mean knee flexion angular velocity from terminal stance until maximum swing shows a faster leg recovery, which correlates with faster running (Heise *et al.*, 1996).

- H_1: The treatment group will show an increase in mean knee flexion angular velocity terminal stance until maximum swing.
- H_o: The treatment group will show no change in mean knee flexion angular velocity terminal stance until maximum swing.

11. Increased step length can cause braking of the runner's horizontal velocity and potentially increase injuries (Volishin and Wosk, 1982; Hunter *et al*., 2005).

- H_1: The treatment group will show a decrease in step length.
- H_o: The treatment group will show no change step length.

12. Increased step frequency is associated with Pose® running (Romanov, 2002; Arendse *et al*., 2004).

- H_1: The treatment group will show an increase in step frequency.
- H_o: The treatment group will show no change step frequency.

13. An increase in running speed for Pose® runners in the post-test 2400 m time trial will establish the Pose® method enables faster running.

- H_1: The Pose® group will show an increase in speed for the post-test time trial.
- H_o: The Pose® group will show no change in speed for the post-test time trial.

14. An improved economy for Pose® runners in the post-test 2400 m economy run will establish the Pose® method enables more economical running.

- H_1: The Pose® group will show an increase (improvement) in economy for the post-test economy run.
- H_o: The Pose® group will show no change in economy for the post-test economy run.

4.4 RESEARCH DESIGN

4.4.1 Introduction

On completion of the new Gravitational hierarchical model, two studies will assess the Pose® technique. Comparison of two experienced male Pose® and heel-toe runners will complete study 1 using the primary and secondary research variables from the Gravitational hierarchical model. A pre and post-test design using sixteen male recreational heel-toe runners, where eight will be trained in Pose® running, from a 7-hour intervention over one-week, will be compared using inferential statistics on the primary research variables.

4.4.2 Sample size and selection criteria

Study 1: Experienced Pose® and heel-toe runner's study

Only two suitably experienced male Pose® runners were prepared to travel to the UK for testing. No experienced Pose® runners lived in the UK at the time of data collection. Two experienced heel-toe runners who matched the Pose® runners in age, stature, weight and experience were recruited for the study. Descriptive statistics compared and evaluated the two running techniques using the primary and secondary research variables.

Study 2: Pose® method training study

A population of local runners and triathletes recruited from Loughborough University served as volunteers for study 2. The main criteria for participant selection included that: (a) all subjects were males; (b) were of a competitive age of 18-30 years old; (c) were sub-elite and had been running for at least two-years (10-km personal best time 37-45 min equating to 6 to 7 min per mile pace) who were distance runners (5-km-marathons). Sub-elite runners were selected owing to their availability over elite athletes. (d) They also had not read or heard of the Pose® method of running; (e) landed on their heel first when running; (f) were willing to change their running technique for the testing period; (g) had been without injury in the past 3-months and finally (h) were able to make the study research dates.

These criteria were selected to give the study internal and external validity, which would allow the results to be generalised to a population of recreational male endurance runners/triathletes. Selection of this population was based on them having the largest number of participants relative to the total running population. The emphasis was on a minimum and maximum age and ability, which reduced inter-participant variance in scores. All participants were heel-toe runners, which represented eighty percent of the endurance running population (Kerr *et al*., 1983). Using pilot data and data from the literature a power test was calculated giving $n = 16$ for the desired sample size for 99% confidence of rejecting the null hypothesis when it is true.

4.4.3 Equipment and design

Study 1: Experienced Pose® and heel-toe runner's study

A force plate and a three-dimensional analysis system collected the research variables derived from the Gravitational hierarchical model for the two running techniques. Descriptive statistics described the two techniques.

Study 2: Pose® method training study

A force plate, portable gas analyser, heart rate monitor and a three-dimensional analysis system were used to quantify the changes between the heel-toe and Pose® groups for the laboratory experiment and the field-tests. Both heel-toe and Pose® groups completed a pre-test economy run and time trial of 2400 m involving a portable gas analyzer

(Cosmed, K4 b2) and a heart rate monitor. They also completed a laboratory pre and post-test using a force plate and a three-dimensional analysis system for five trials run at 3.35 $m \cdot s^{-1}$. The Pose® group received 60 min of instruction in the Pose® method from a qualified Pose® coach for 7-days. Immediately following the intervention, both groups were administered the post-tests using the same instrumentation.

4.4.4 Identification of the research variables

Study 1: Selection of research variables

Variables derived form the Gravitational hierarchical model (primary research variables) were used to assess differences between two experienced Pose® and heel-toe runners.

1. Stance time (ms).
2. Posterior and anterior ground reaction force (BW).
3. Maximum vertical ground reaction force (BW).
4. Centre of mass horizontal velocity from impact to maximum vertical ground reaction force ($cm \cdot s$-^{1}).
5. Centre of mass horizontal velocity from maximum vertical ground reaction force until terminal stance ($cm \cdot s^{-1}$).
6. Centre of mass behind the toe marker (horizontal difference at 25 ms) (cm).
7. Centre of mass horizontal displacement during stance (cm).
8. Vertical oscillation of centre mass (cm).
9. Mean knee flexion angular velocity for stance ($rad \cdot s^{-1}$).
10. Mean knee extension angular velocity for stance ($rad \cdot s^{-1}$).
11. Mean knee flexion angular velocity from terminal stance to maximum swing angle ($rad \cdot s^{-1}$).
12. Step length for right foot (cm).
13. Step frequency (Hz).

Secondary research variables aided the analysis of the two running techniques.

I. Time to maximum braking and propulsive ground reaction force (percentage of stance).
II. Time to maximum vertical ground reaction force (percentage of stance).
III. Centre of mass horizontal velocity from terminal stance until maximum swing ($cm \cdot s^{-1}$).
IV. Centre of mass at terminal stance forward of the support foot (horizontal difference) (cm).
V. Centre of mass horizontal velocity at terminal stance ($cm \cdot s^{-1}$).
VI. Horizontal velocity of the centre of mass from maximum vertical ground reaction force until terminal stance minus horizontal velocity of the centre of mass from impact until maximum vertical ground reaction ($cm \cdot s^{-1}$).
VII. Centre of mass and toe marker angle at terminal stance (rad).
VIII. Knee flexion from impact until mid-stance (rad).
IX. Knee extension from mid-stance until terminal stance (rad).
X. Knee flexion from terminal stance until maximum swing (rad).

XI. Knee angle at impact (rad).
XII. Knee angle at maximum vertical ground reaction force (rad).
XIII. Flight time (ms).
XIV. Time of maximum horizontal acceleration of the centre of mass ($cm\cdot s^{-2}$).

Study 2: Selection of research variables

The research variables derived form the Gravitational hierarchical model (primary research variables) were used to assess differences between a group of sixteen heel-toe runners where eight participants were trained in Pose® running technique from a 7-hour intervention.

1. Stance time (ms).
2. Posterior and anterior ground reaction force (BW).
3. Maximum vertical ground reaction force (BW).
4. Centre of mass horizontal velocity from impact to maximum vertical ground reaction force ($cm\cdot s\text{-}^{1}$).
5. Centre of mass horizontal velocity from maximum vertical ground reaction force until terminal stance ($cm\cdot s^{-1}$).
6. Centre of mass behind the toe marker (horizontal difference at 25 ms) (cm).
7. Centre of mass horizontal displacement during stance (cm).
8. Vertical oscillation of centre mass (cm).
9. Mean knee flexion angular velocity for stance ($rad\cdot s^{-1}$).
10. Mean knee extension angular velocity for stance ($rad\cdot s^{-1}$).
11. Mean knee flexion angular velocity from terminal stance to maximum swing angle ($rad\cdot s^{-1}$).
12. Step length for right foot (cm).
13. Step frequency (Hz).
14. Time for 2400 m time trial (s).
15. Oxygen consumption (ml).

Secondary research variables aided the analysis of the two running techniques.

I. Time to maximum braking and propulsive ground reaction force (percentage of stance).
II. Time to maximum vertical ground reaction force (percentage of stance).
III. Centre of mass horizontal velocity from terminal stance until maximum swing ($cm.s^{-1}$).
IV. Centre of mass at terminal stance forward of the support foot (horizontal difference) (cm).
V. Centre of mass and toe marker angle at terminal stance (rad).
VI. Knee flexion from impact until mid-stance (rad).
VII. Knee extension from mid-stance until terminal stance (rad).
VIII. Knee flexion from terminal stance until maximum swing (rad).
IX. Knee angle at impact (rad).
X. Knee angle at maximum vertical ground reaction force (rad).
XI. Flight time (ms)

4.4.5 Treatment of collected data

Study 1: Experienced Pose® and heel-toe runner's study

Descriptive statistical procedures compared the two running techniques. Discussion focused on differences supported by the primary and secondary research variables and running research.

Study 2: Pose® method training study

A power test for a repeated measures ANOVA statistical procedure was conducted to determine the probability of detecting a 'true' effect when it exists. Using proc power in SAS statistical software (version 9.1) sample size was calculated. Selected power was 0.8 at $P < 0.05$ (Cohen, 1988). Step length was selected as the variable since it generically describes the gait cycle because it is the direct result of the kinetic and kinematic motions of the runner. Using heel-toe runner's pilot data for the sample mean (mean step length 97 cm), the literature was used to determine the population mean (mean step length 119 cm; Cavanagh and Kram, 1985) and standard deviation (14 cm; Cavanagh and Kram, 1985) at the test running speed of 3.35 $m \cdot s^{-1}$ enabling sample size to be calculated. Proc power requires the following information in order to do the power analysis: a) the number of levels (or groups = 2), b) the means for each level (119, 97), c) the common group standard deviation (14), d) the alpha level ($P < 0.05$) and e) the power (0.8). For $n = 16$ the calculated power was 0.99.

A 2 x 2 mixed factorial ANOVA assessed the main effects of group (control vs. treatment) and trial (pre to post changes) on the primary research variables. Tukey's tests of honestly significant differences were used to assess individual cell differences *post hoc*. Data analysis was completed using the Minitab (version 14) statistical analysis package. An alpha level of $P < 0.05$ was used to establish statistical significance for the inferential procedures.

Assumptions

Assumptions were satisfied for the inferential statistical analysis and are given below. Significance is taken at $P = 0.05$.

1. Independence: In this study, the two groups contain separate individuals so the data are independent.
2. Scale of measurement: The scale of measurement was ratio.
3. Normality:

Table 4.4.1 Ryan-Joiner's (similar to Shapiro-Wilk) normality test ($N = 16$).

Variable	Ryan-Joiner normality test
Stance time	0.1
Anterior-posterior GRF (brak)	0.1
Vertical GRF	0.1
Anterior-posterior GRF (prop)	0.1
Centre of mass horizontal velocity (brak)	0.1
Centre of mass horizontal velocity (prop)	0.1
Centre of mass to toe-marker at 25 ms	0.1
Centre of mass displacement during stance	0.1
Vertical oscillation	0.1
Knee flexion angular velocity	0.08
Knee extension angular velocity	0.1
Knee flexion angular velocity swing	0.1
Step length	0.1
Step frequency	0.07
Time trial	0.08
Oxygen consumption	0.15

4. Homogeneity:

The variances between each group was examined using Levene's test for homogeneity of variances.

Table 4.4.2 Levene's test for homogeneity of variance (N = 16).

Variables		Levene Statistic	Significance
Stance time	Based on Mean	2.25	0.16
Anterior-posterior GRF (brak)	Based on Mean	2.42	0.14
Vertical GRF	Based on Mean	4.29	0.60
Anterior-posterior GRF (prop)	Based on Mean	0.14	0.70
Centre of mass horizontal velocity (brak)	Based on Mean	0.03	0.09
Centre of mass horizontal velocity (prop)	Based on Mean	0.30	0.60
Centre of mass to toe-marker at 25 ms	Based on Mean	7.91	0.07
Centre of mass displacement during stance	Based on Mean	2.59	0.13
Vertical oscillation	Based on Mean	1.45	0.24
Knee flexion angular velocity	Based on Mean	2.03	0.18
Knee extension angular velocity	Based on Mean	0.93	0.35
Knee flexion angular velocity swing	Based on Mean	1.21	0.29
Step length	Based on Mean	0.36	0.56
Step frequency	Based on Mean	1.01	0.33
Time trial	Based on Mean	1.46	0.25
Oxygen Consumption	Based on Mean	0.05	0.80

Table 4.4.3 Interactions for the primary research variables for the 2*2 mixed factorial ANOVA for P = 0.05 (N = 16).

Variables	***F value***	***P value***
Stance time		
Treatment * Group	7.28	**0.012**
Anterior-Posterior GRF (Brak)		
Treatment * Group	0.0	0.960
Vertical GRF		
Treatment * Group	0.22	0.642
Anterior-Posterior GRF (Prop)		
Treatment * Group	0.53	0.472
Centre of mass velocity (brak)		
Treatment * Group	1.20	0.282
Centre of mass velocity (Prop)		
Treatment * Group	0.00	0.983
Centre of mass at 25 ms		
Treatment * Group	6.88	**0.014**
Centre of mass displacement		
Treatment * Group	6.88	**0.030**
Vertical Oscillation		
Treatment * Group	1.62	0.213
Knee flexion angular velocity		
Treatment * Group	1.27	0.269
Knee extension angular velocity		
Treatment * Group	2.49	0.126
Knee flexion angular velocity (swing)		
Treatment * Group	0.51	0.481
Step length		
Treatment * Group	1.50	0.231
Step frequency		
Treatment * Group	9.37	**0.005**
Time trial		

Treatment * Group	0.31	0.582
Oxygen consumption Treatment * Group	0.652	0.652

Table 4.4.4 Tukey *post hoc* tests for the 2*2 mixed factorial ANOVA on the primary research variables (treatment pre test is 1 and post is 2; the control heel-toe group is 3 and the Pose® treatment group is 4) (*N* = 16).

Variables	Treatment	Group	*P-value*
Stance Time Interactions among Levels of Treatment*Group Treatment = 1 Group = 3 subtracted from:	1	4	0.9991
	2	3	0.8457
	2	4	**0.0006**
Stance Time Treatment = 1 Group = 4 subtracted from:	2	3	0.7763
	2	4	**0.0004**
Anterior-Posterior GRF (Brak) Interactions among Levels of Treatment*Group Treatment = 1 Group = 3 subtracted from:	1	4	0.9999
	2	3	0.4904
	2	4	0.4904
Anterior-Posterior GRF (Brak) Treatment = 1 Group = 4 subtracted from:	2	3	0.4486
	2	4	0.4486
Vertical GRF (Brak) Interactions among Levels of Treatment*Group Treatment = 1 Group = 3 subtracted from:	1	4	0.9975
	2	3	0.8187
	2	4	0.5417
Vertical GRF (Brak) Treatment = 1 Group = 4 subtracted from:	2	3	0.7145
	2	4	0.4298
Anterior-Posterior GRF (Prop) Interactions among Levels of Treatment*Group Treatment = 1 Group = 3 subtracted from:	1	4	0.8421
	2	3	0.9968
	2	4	1.0000
Anterior-Posterior GRF (Prop) Treatment = 1 Group = 4 subtracted from:	2	3	0.9252
	2	4	0.8421
Centre of mass horizontal velocity (Brak) Interactions among Levels of Treatment*Group Treatment = 1 Group = 3 subtracted from:	1	4	0.9966
	2	3	0.9217
	2	4	0.8924
Centre of mass horizontal velocity (Brak) Treatment = 1 Group = 4 subtracted from:	2	3	0.9749
	2	4	0.7940
Centre of mass horizontal velocity (Prop) Interactions among Levels of Treatment*Group Treatment = 1 Group = 3 subtracted from:	1	4	0.7612
	2	3	1.00000
	2	4	0.7187
Centre of mass horizontal velocity (Prop) Treatment = 1 Group = 4	2	3	0.7855

subtracted from:			
	2	4	0.9998
Centre of mass at 25 ms Interactions among Levels of Treatment*Group Treatment = 1 Group = 3 subtracted from:	1	4	0.9689
	2	3	0.8047
	2	4	0.1092
Centre of mass at 25 ms Treatment = 1 Group = 4 subtracted from:	2	3	0.9692
	2	4	**0.0420**
Centre of mass horizontal displacement Interactions among Levels of Treatment*Group Treatment = 1 Group = 3 subtracted from:	1	4	0.9820
	2	3	0.5374
	2	4	**0.0002**
Centre of mass horizontal displacement Treatment = 1 Group = 4 subtracted from:	2	3	0.7607
	2	4	**0.0005**
Vertical oscillation Interactions among Levels of Treatment*Group Treatment = 1 Group = 3 subtracted from:	1	4	0.9986
	2	3	0.9994
	2	4	0.2766
Vertical oscillation Treatment = 1 Group = 4 subtracted from:	2	3	0.9925
	2	4	0.3516
Knee flexion angular velocity (Stance) Interactions among Levels of Treatment*Group Treatment = 1 Group = 3 subtracted from:	1	4	0.9928
	2	3	0.2679
	2	4	**0.0046**
Knee flexion angular velocity (Stance) Treatment = 1 Group = 4 subtracted from:	2	3	0.4017
	2	4	**0.0091**
Knee extension angular velocity (Stance) Interactions among Levels of Treatment*Group Treatment = 1 Group = 3 subtracted from:	1	4	0.9817
	2	3	0.8669
	2	4	0.7017
Knee extension angular velocity (Stance) Treatment = 1 Group = 4 subtracted from:	2	3	0.9785
	2	4	0.4746
Knee flexion angular velocity (Swing) Interactions among Levels of Treatment*Group Treatment = 1 Group = 3 subtracted from:	1	4	0.9815
	2	3	0.2998
	2	4	**0.0180**
Knee flexion angular velocity (Swing) Treatment = 1 Group = 4 subtracted from:	2	3	0.5023
	2	4	**0.0430**
Step Length Interactions among Levels of Treatment*Group Treatment = 1 Group = 3 subtracted from:	1	4	0.5978
	2	3	0.9154
	2	4	**0.0058**

Step Length Treatment = 1 Group = 4 subtracted from:	2	3	0.9287
	2	4	0.1046
Step Frequency Interactions among Levels of Treatment*Group Treatment = 1 Group = 3 subtracted from:	1	4	0.9999
	2	3	0.9937
	2	4	**0.0016**
Step Frequency Treatment = 1 Group = 4 subtracted from:	2	3	0.9887
	2	4	**0.0019**
Time Trial Interactions among Levels of Treatment*Group Treatment = 1 Group = 3 subtracted from:	1	4	0.9997
	2	3	0.9999
	2	4	0.8760
Time Trial Treatment = 1 Group = 4 subtracted from:	2	3	0.9989
	2	4	0.8344
Oxygen Consumption Interactions among Levels of Treatment*Group Treatment = 1 Group = 3 subtracted from:	1	4	0.8473
	2	3	0.6391
	2	4	0.5372
Oxygen Consumption Treatment = 1 Group = 4 subtracted from:	2	3	0.9815
	2	4	09475

4.4.6 Limitations

The limitations of this thesis are given below in no particular order.

- Only two experienced Pose® runners were available, making definitive statements on Pose® running preliminary.
- The runway length of 15.66 m possibly restricted the participants on the force plate because they were thinking of slowing down owing to a brick-wall 7 m away.
- Predominantly, the heel-toe intervention was unsuccessfully applied owing to participant non-compliance, making the heel-toe group a control group without an intervention.

CHAPTER 5

EXPERIENCED POSE® AND HEEL-TOE RUNNER'S STUDY

5.1 INTRODUCTION

A clear method of running would be advantageous in the identification of an 'ideal' running technique. A universal standard of what is 'good' technique needs identifying to make authoritative recommendations. The Pose® method (Romanov, 2002) has made theoretical claims of being a universal technique that applies the laws of physics to running, whereas the heel-toe technique is the most popular technique with endurance runners. This study therefore seeks to quantify the differences between experienced Pose® and heel-toe runners using the Gravitational hierarchical model. Firstly, a review of how the two techniques are presently distinguished is given. Secondly, using the primary and secondary variables from the Gravitational hierarchical model, the two techniques of running are compared.

5.2 THEORETCIAL BACKGROUND

Skill, technique and style are terms used to describe human movement patterns (Kreighbaum and Barthels, 1996). Skill is defined as a general movement pattern that is adapted to the constraints of a particular sport, such as high jumping, which is a skill within the general movement pattern of jumping (Kreighbaum and Barthels, 1996). Technique represents the actions of internal and external forces on the human body, which determine how the parts of the human body move during the performance of the movement pattern (Hay and Reid, 1988). Following the high jump example, the Fosbury flop and straddle are two high jump techniques. Style refers to individual adaptations of a technique, such as a curved or straight run-up towards the high jump bar. Skills, techniques and styles develop because of the constraints or limitations associated with a particular sport. In running, the environment (forces of nature, hills, opponents and visibility) and the human body (size, strength, power and endurance) are constraints (Kreighbaum and Barthels, 1996). Heel-toe running is the predominant technique in endurance runners (Kerr *et al.*, 1983). However, a new technique (Pose®) has made claims that it is an effective way to run. To compare the two running techniques, the Gravitational hierarchical model (see chapter 3) will be employed.

Pose® runners have shown a distinct biomechanical profile in comparison to heel-toe runners. Two studies took heel-toe runners and trained them in Pose® with a seven and half-hour and twelve-hour intervention respectively (Arendse *et al.*, 2004; Dallam *et al.*, 2005). A consistent finding is stride length is lower in Pose® runners compared to heel-toe runners yet stride frequency increases in Pose® runners (Arendse *et al.*, 2004; Dallam *et al.*, 2005). As running speed is a combination of stride length multiplied by stride frequency, an endurance runner with a 2 m stride holding two strides·s^{-1} has a speed of 4 m·s^{-1}. If stride length increased to 2.5 m while holding the same cadence, running speed will be 5 m·s^{-1}. Alternatively, if stride length remains at 2 m and stride frequency increased to three strides·s^{-1}, running speed will be 6 m·s^{-1}. If the increase to three strides·s^{-1} were accompanied by a decrease in stride length to 1.5 m, the running speed would be only 4.5 m·s^{-1} (Hay and Reid, 1988). These measurements are obviously correct, however, clarity on how to reduce internal muscle force in relation to producing stride length and stride frequency in combination with the external forces of nature is not currently lucid.

Cavanagh and Kram (1985) in a descriptive study found at speeds of 3 m·s^{-1} to 4.2 m·s^{-1}, stride length increased as opposed to stride frequency. An increase in stride frequency potentially requires greater muscle activity during a shorter time in stance (Kyrolainen *et al.*, 2000). This possibly explains why endurance runners increase stride length over stride frequency up to 7 m·s^{-1}, but around 7 m·s^{-1} stride length maximises (Cavanagh and Kram, 1990). An increase in stride length can involve a reciprocal increase in leg extension (Williams, 1985), although this finding is not universal (Mann *et al.*, 1986). Clarke *et al.* (1985) identified tibial accelerations increased by taking longer strides, giving circumstantial evidence that increased stride length results in an increased impact force. Stride frequency increases over stride length above 7 m·s^{-1} lacks a clear biomechanical explanation (Luhtanen and Komi, 1978). The Gravitational hierarchical model seeks to offer a clear explanation of why stride length maximises at running speeds above 7 $m \cdot s^{-1}$.

A second finding is vertical oscillation of the centre of mass decreased in Pose® runners (Arendse *et al.*, 2004; Dallam *et al.*, 2005). Vertical oscillation of the centre of mass decreases in runners generally as running speed increases (Luhtanen and Komi, 1978; Mero *et al.*, 1992). Further, knee extension of the support leg correlates with increased vertical oscillation of the centre of mass after mid-stance (Wank *et al.*, 1998). However, knee extension decreases as running speed increases (Mann *et al.*, 1986). Logically, excessive vertical oscillation would be ineffective for horizontal displacement (Williams, 1985) yet, many individuals run economically despite high vertical oscillation (Williams and Cavanagh, 1987). Vertical oscillation is maximal at terminal stance or just after coinciding with maximal leg extension of the support limb (Fenn, 1930). Dallam *et al.* (2005) found that the hip to ankle distance at impact reduced as well as stance time in Pose® runners. It would be reasonable to assume that joint angles, impact patterns and the position of the centre of mass at impact and terminal stance influence vertical oscillation by virtue of the kinematic chain (Mero *et al.*, 1992). The increased body angles at take-off and impact found at faster speeds may be associated with potential skill differences. Changes in the body angle at take-off affects performance owing to a change in the gravitational torque on the runner's centre of mass in relation to their support limb (see chapter 3). In addition, at impact, a more vertical alignment of the centre of mass to the support limb reduces losses in horizontal velocity (Cavanagh *et al.*, 1977; Bates *et al.*, 1979; Girardin and Roy, 1984). Further study of these body positions using these variables from the Gravitational hierarchical model will aim to clarify biomechanical differences between heel-toe and Pose® runners.

Williams *et al.* (2000) identified that heel-toe and forefoot runners differed in knee flexion at impact and knee flexion excursion during stance. Arendse *et al.* (2004) also found an increased knee flexion in preparation for and at initial contact in Pose® runners as opposed to when they were heel-toe runners. Williams *et al.* (2000) found peak knee flexion moment, knee power absorption and negative work at the knee differed between heel-toe and forefoot runners. Arendse *et al.* (2004) also measured less eccentric work at the knee and more eccentric work at the ankle in Pose® runners compared with heel-toe running. The position of the torso during the gait cycle may explain the reduced knee eccentric work and increased ankle eccentric work in Pose® running compared with their heel-toe running. Arendse *et al.* (2004) recommended that the position of the torso and the centre of mass should be included in future studies of running technique modification.

Transition from walking to running occurs at a critical speed of 2.2 $m \cdot s^{-1}$ or a similar Froude number, rather than at a critical stride rate or length (Alexander and Jayes, 1983; Hreljac, 1995). This suggests the centre of mass's horizontal velocity determines the walk-run transition rather than a particular stride length or stride rate. A change in the centre of mass's horizontal velocity would obviously reflect work by an external force. Pose® running technique suggests the external force is a gravitational torque. Therefore, falling forwards as the centre of mass passes over the support limb's foot causes a gravitational torque while the support foot is pulled rapidly from the ground represents the Pose® technique. The Pose® and heel-toe running techniques differ theoretically, in which external force is motive. Pose® technique emphasises a gravitational torque as the motive force in running, whereas heel-toe running suggest leg extension via increased ground reaction force increases running speed. The aim therefore, using the primary and secondary variables is to compare the two techniques of running using the new Gravitational hierarchical model with two skilled heel-toe and Pose® runners.

5.3 METHODS

Participants

Two experienced male Pose® runners were recruited for this study (aged: 28 yrs and 51 yrs, stature: 1.74 m and 1.86 m, mass: 75.5 kg and 71.4 kg and 10-km personal best times of 42 min and 29 min) and were matched (in mass, stature and age) with two experienced male heel-toe runners (aged: 24 yrs and 47 yrs, stature: 1.76 m and 1.95 m, mass: 72.5 kg and 71.4 kg and 10-km personal best times of 34 min). Written informed consent and ethical approval from Sheffield Hallam University were obtained. All participants had no history of surgical intervention, chronic pain, orthotic use or current pathology of the lower extremity. Each participant wore his normal running shoes. All shoes were qualitatively assessed for rigidity of the heel counter and compliance of the cushioning element of the rear section of the shoe.

Experimental protocol

All participants were pre-selected before the testing date through personal contact. All respondents were selected based on the following criteria: 1) they had been without injury in the past 12 months, 2) were male, 3) competitive athletes and 4) were experienced in their respective styles of running and were similar in age, experience, stature and weight. After their individual warm up, each participant run across a force plate at 2.5 $m \cdot s^{-1}$, 3.35 $m \cdot s^{-1}$, 4 $m \cdot s^{-1}$ and 4.5 $m \cdot s^{-1}$ while simultaneously recording kinematic data.

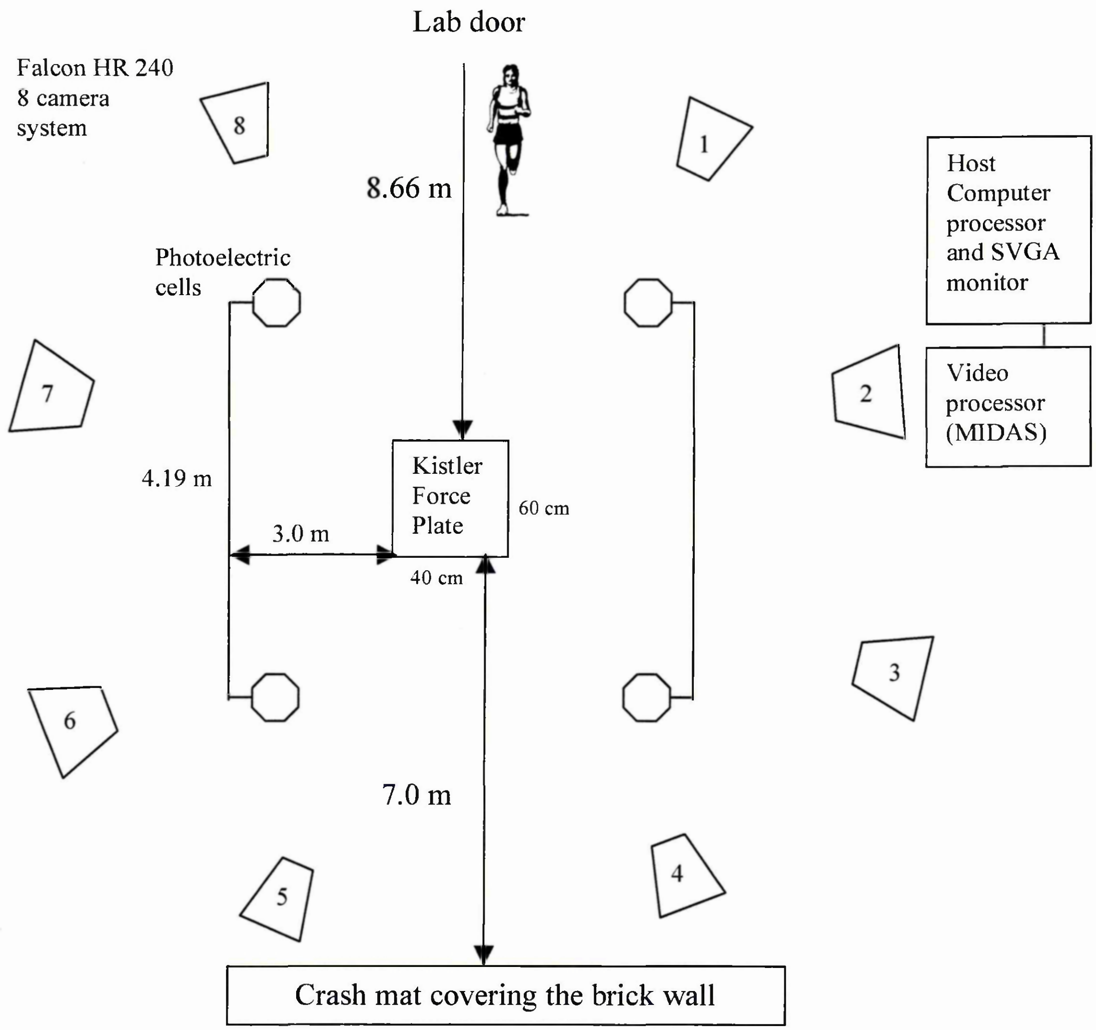


Figure 5.3.1 Measurement set-up for laboratory data collection

Collection and processing of ground reaction force data

Biomechanical data were collected using a piezoelectric transducer force plate with eight output signals, which were sampled at 1200 Hz (9281-CA Kistler Instruments Corporation, Winterthur, Switzerland). The plate was mounted flush with the running surface on a 15.66 m runway. The force plate was 8.66 m from the start position and measured 40 by 60 cm (figure 5.3.1). Participants were instructed to run normally while aligning their run-up to land with their right foot on the force plate. Each participant was allowed as many practice trials as needed to achieve 'normal' foot contact with the plate in their regular running shoes, with five trials collected. After each trial, the data was visually inspected to ensure that the footfall was 'normal' and centred on the force plate. After data collection the ground reaction force analogue data was processed through Matlab 6 software to convert volts into Newtons. In accordance with Munro *et al.* (1987), ground reaction force data were normalised to the participant's body weight. Initial contact of the foot with the ground was identified from the ground reaction force data. Foot contact began once the vertical ground reaction force data exceeded 20 N and ended as it went below 20 N (Bobbert *et al.*, 1991; Wright *et al.*, 1998; Tirosh and Sparrow, 2003).

Collection and processing of kinematic data

A modified Helen Hayes marker set (22-markers) was used to collect their three-dimensional trajectories for computing kinematic data. Retroflective spheres of a diameter of 2 cm (4.4 g) were applied to their bodies in order to define a model comprised of twelve body segments: two segments for feet, lower legs, upper legs, forearm, upper arm and two single segments comprising the head/neck and trunk. These markers were applied directly onto the skin using athletic tape on the acromion processes, elbow and radiocarpal joints, sacrum, anterior superior iliac spines, lateral femoral condyles, lateral malleolus, and the dorsim of the feet between the second and third metatarsals. Two lateral wands were used to calculate the medial knee and ankle markers during the dynamic trials. The two lateral wands were 10 cm long and attached using athletic tape to the thigh, midway between the hip and knee joints, and for the shank, midway between the knee and ankle joints. Both wands were vertically aligned with the relevant joints. The attachment and length of the wands were such that oscillations of the marker at the tip of the wands were insignificant. An off-set marker placed on the right scapula precipitated software marker recognition through body asymmetry. Video data were collected using a VPAT 310 video recorder and an eight-camera (Falcon HR 240) motion analysis system recording at 120 Hz (Motion Analysis Corporation, Santa Rosa, California) which collected data for one step of the right leg while running in the positive X direction. The cameras were zoomed in as far as possible to a volume of 3.6 m in x (fore-aft axis) by 1.4 m in y (medio-lateral axis) and 2 m in z (vertical axis) with the centre of the base corresponding to the centre of the force plate.

The laboratory (global) orthogonal coordinate system followed the right hand rule and had the positive *x*-direction orientated in the direction of forward progression, the positive *y*-direction orientated to the left and the positive *z*-direction orientated vertically upward. The volume was calibrated before data collection using a cube and a 500 mm wand associated with EvaRT 3.2 data collection software (Motion Analysis Corporation, Santa Rosa, California). During data collection, the experienced heel-toe and Pose® runners ran at 2.5 $m \cdot s^{-1}$, 3.35 $m \cdot s^{-1}$, 4 $m \cdot s^{-1}$ and 4.5 $m \cdot s^{-1}$. Running speeds were measured by two photoelectric cells 4.19 m apart and 3 m from the centre of the force plate, and mounted so the participant's waist triggered the photoelectric cells. Up to five trials were recorded at each speed, and only trials in which 'good' foot contact with a steady stride and speeds within 5% of the measured speed were analysed. The three dimensional coordinate data were filtered using a 2nd order low-pass Butterworth filter; a cut-off frequency of 6-8 Hz was used and was selected through visual inspection of the fit (Winter, 1987). Video and analogue data were time synchronised using impact, recorded when vertical ground reaction force exceeded 20 N. Following the filtering process in EvaRT 3.2, the filtered video data were extracted using OrthoTrak 5 software. Coordinate and angular data were calculated according to the method used by Winter (1990) from the filtered raw data.

Statistical analysis

Descriptive statistical comparisons between Pose® and heel-toe running were undertaken.

5.4 RESULTS

Ground reaction force variables

Vertical and posterior-anterior ground reaction forces for both techniques of running are compared at each speed (figures 5.4.1-5.4.8). The Pose® runners elicit similar ground reaction force traces to forefoot runners, whereas the heel-toe runners match their traditional heel-toe counterparts. The first and second graph will always be the same runner in both techniques for all speeds.

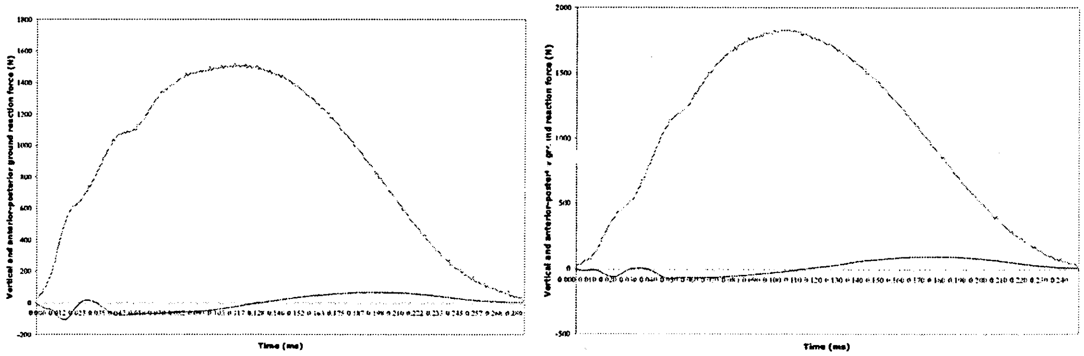


Figure 5.4.1 Vertical and posterior-anterior ground reaction force for the Pose® runners at 2.5 m·s^{-1}.

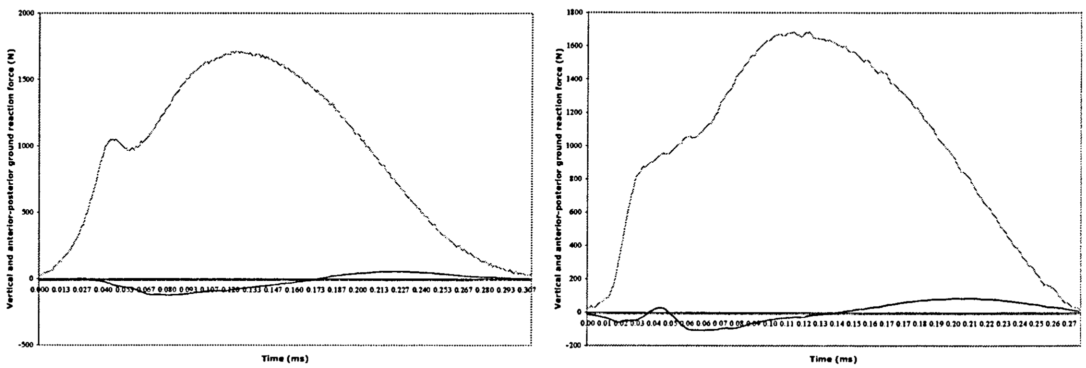


Figure 5.4.2 Vertical and posterior-anterior ground reaction force for the heel-toe runners at 2.5 m·s^{-1}.

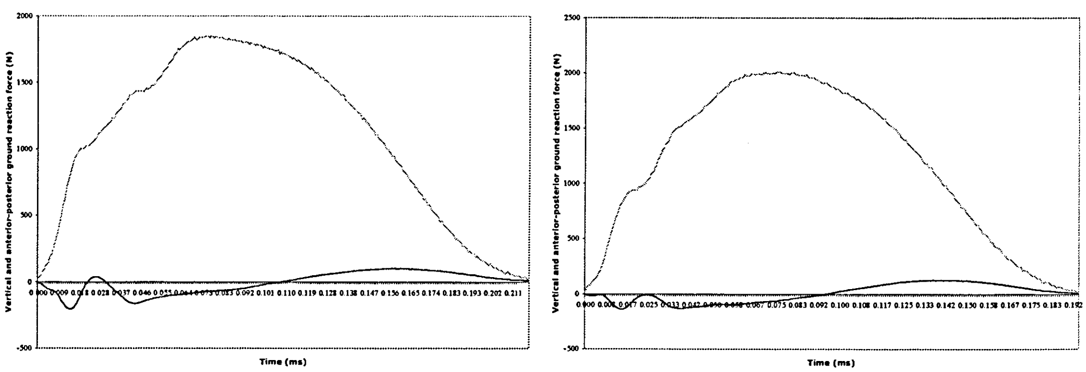


Figure 5.4.3 Vertical and posterior-anterior ground reaction force for the Pose® runners at 3.35 m·s^{-1}.

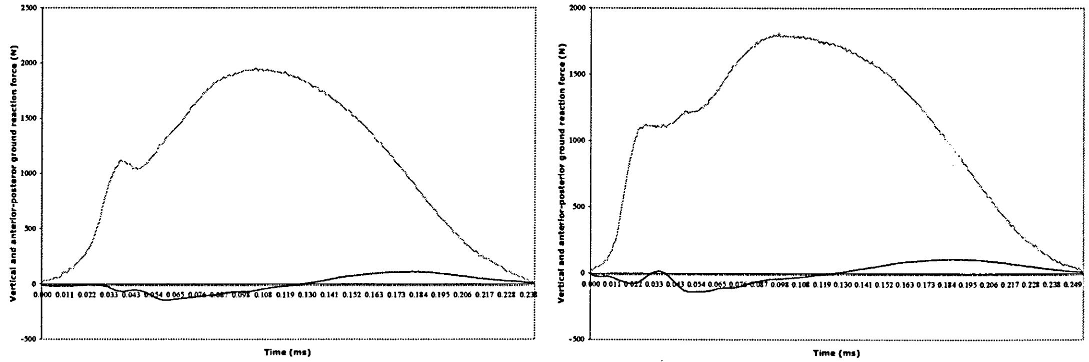


Figure 5.4.4 Vertical and posterior-anterior ground reaction force for the heel-toe runners at 3.35 m·s^{-1}.

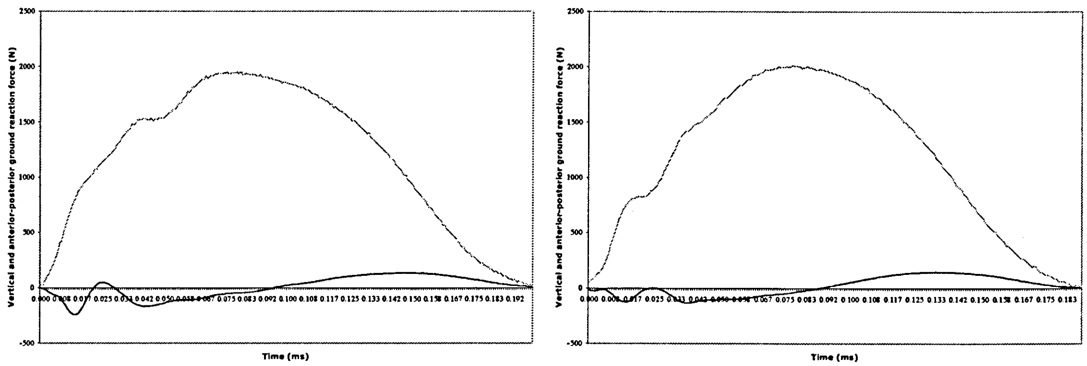


Figure 5.4.5 Vertical and posterior-anterior ground reaction force for the Pose® runners at 4.0 m·s^{-1}.

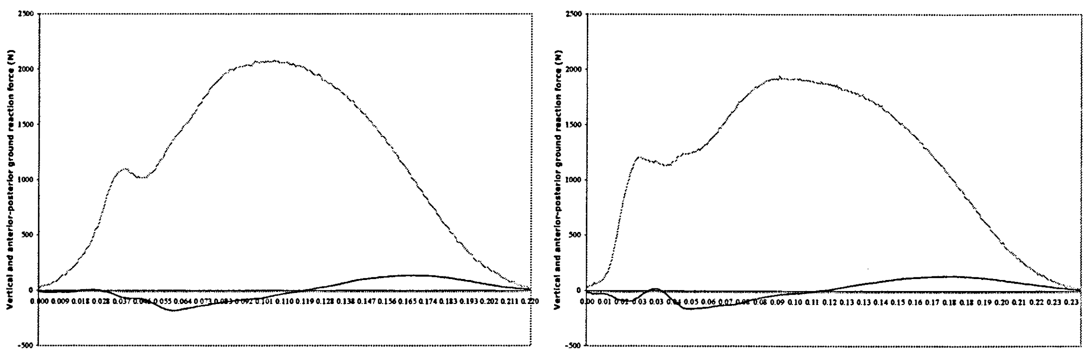


Figure 5.4.6 Vertical and posterior-anterior ground reaction force for the heel-toe runners at 4.0 m·s^{-1}.

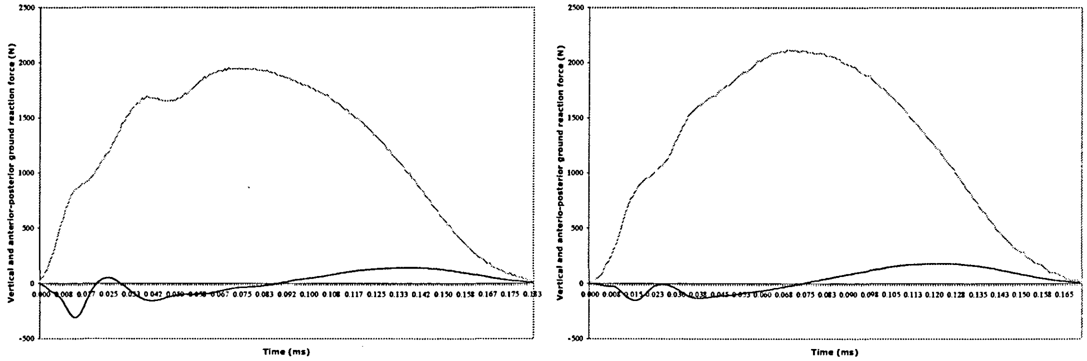


Figure 5.4.7 Vertical and posterior-anterior ground reaction force for the Pose® runners at 4.5 m·s^{-1}.

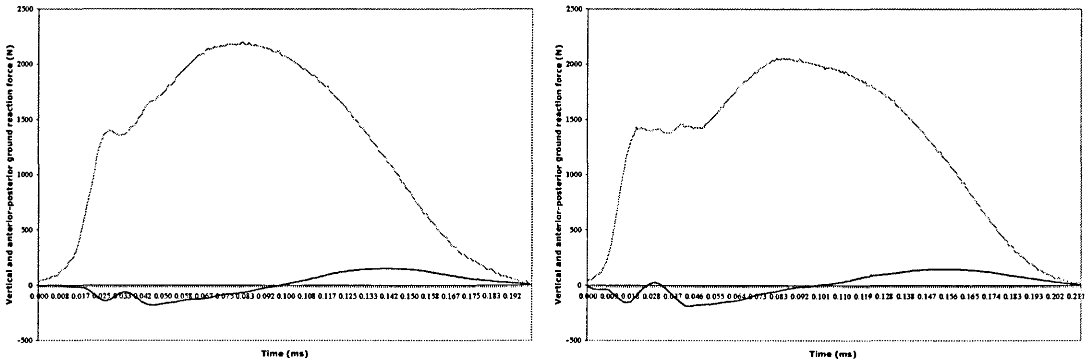


Figure 5.4.8 Vertical and posterior-anterior ground reaction force for the heel-toe runners at 4.5 m·s^{-1}.

Motion analysis variables

Flexion-extension, abduction-adduction for the right (support) knee and hip plus vertical oscillation of the centre of mass (figures 5.4.9-5.4.40) are graphed in the sagittal plane at each running speed. Each graph begins at impact with the vertical line representing terminal stance. The graph finishes at maximum swing angle for the right leg.

Hip angles represent the thigh relative to the pelvis (figures 5.4.9-16). Larger hip flexion angles occur for all speeds in the Pose® runners at impact. At terminal stance, the heel-toe runners exhibit hip extension, whereas the Pose® runners do not extend the hip or do so much less.

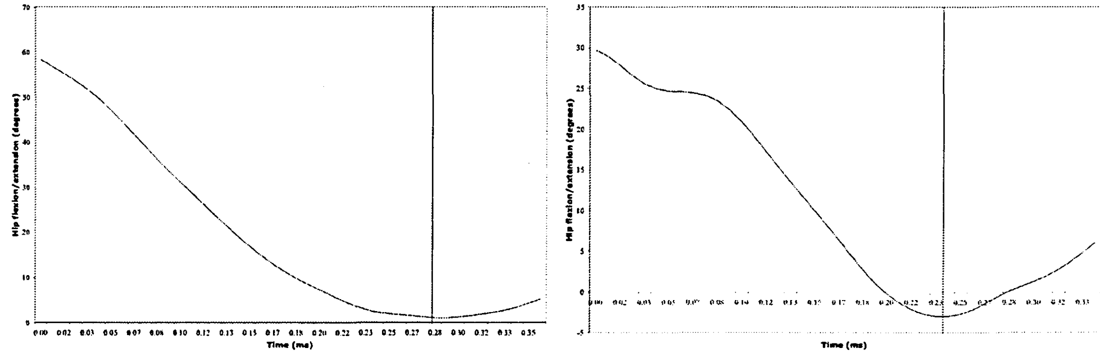


Figure 5.4.9 Hip flexion and extension for the Pose® runners at 2.5 m·s^{-1}.

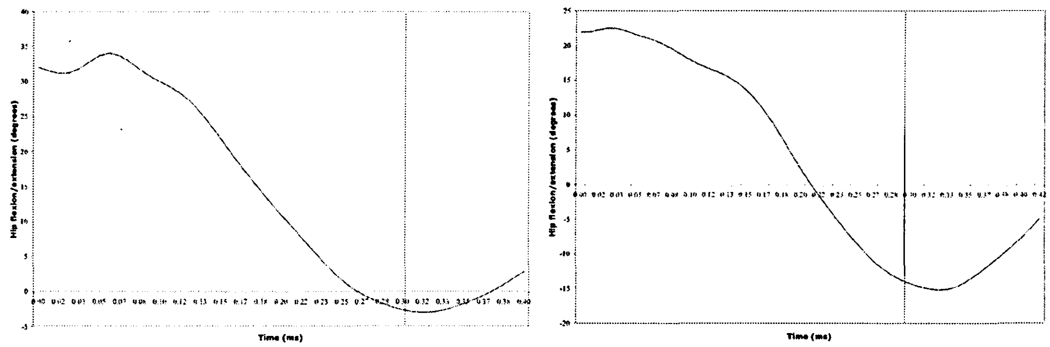


Figure 5.4.10 Hip flexion and extension for the heel-toe runners at 2.5 m·s^{-1}.

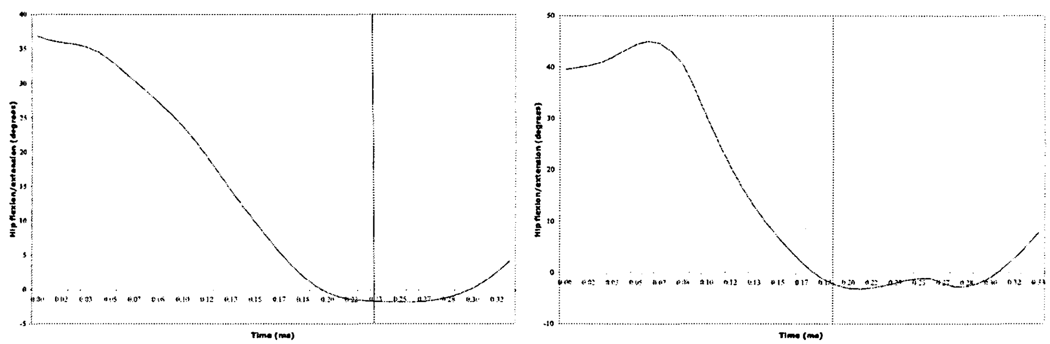


Figure 5.4.11 Hip flexion and extension for the Pose® runners at 3.35 m·s^{-1}.

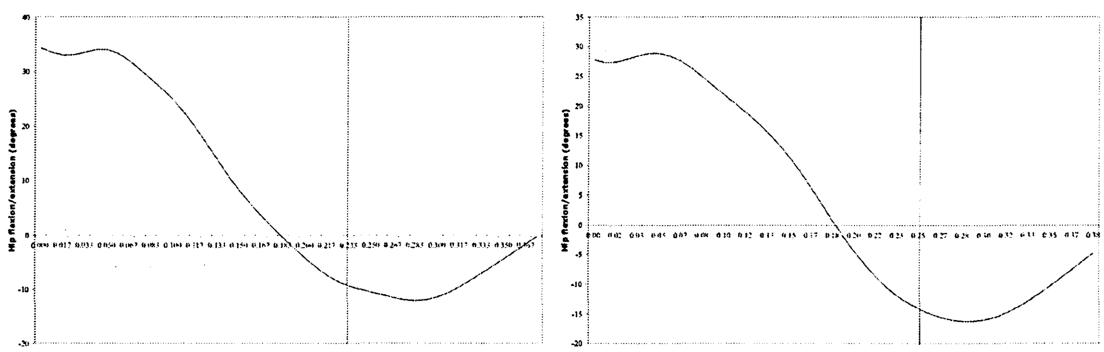


Figure 5.4.12 Hip flexion and extension for the heel-toe runners at 3.35 m·s^{-1}.

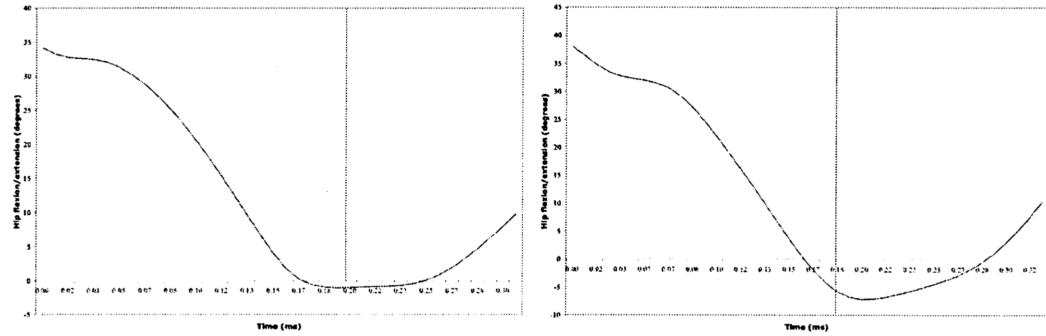


Figure 5.4.13 Hip flexion and extension for the Pose® runners at 4.0 m·s^{-1}.

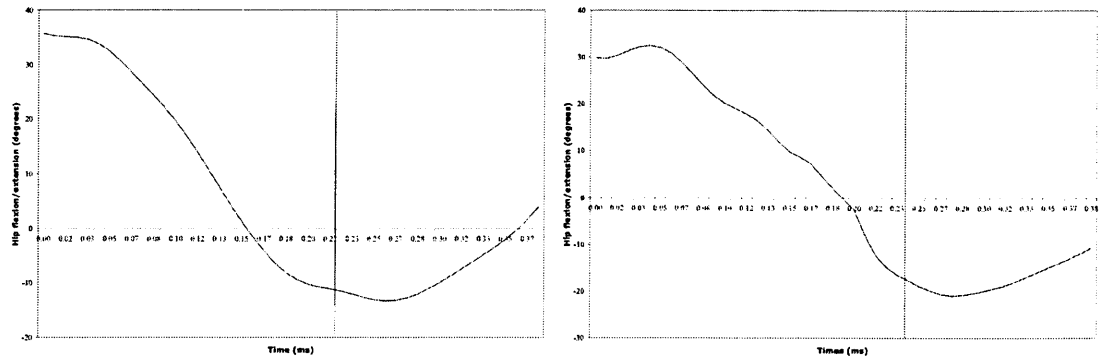


Figure 5.4.14 Hip flexion and extension for the heel-toe runners at 4.0 m·s^{-1}.

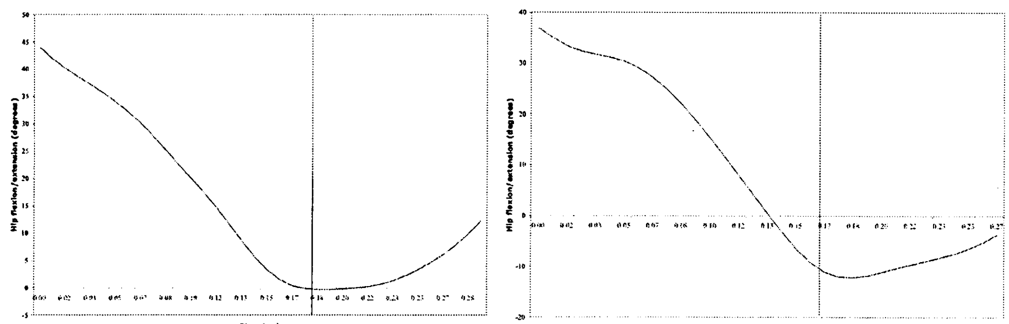


Figure 5.4.15 Hip flexion and extension for the Pose® runners at 4.5 m·s^{-1}.

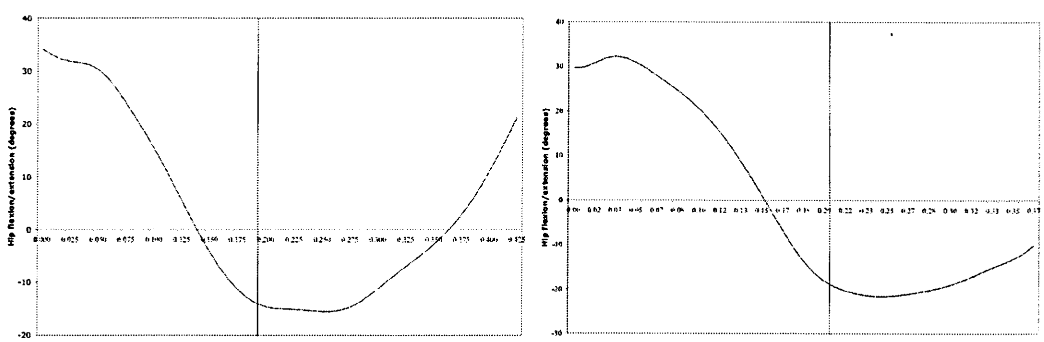


Figure 5.4.16 Hip flexion and extension for the heel-toe runners at 4.5 m·s^{-1}.

Vertical oscillation (figures 5.4.17-5.4.24) is lower in Pose® runners for all speeds. The vertical path of the centre of mass follows a similar pattern for both techniques of running. However, from maximum vertical ground reaction force until terminal stance there is an increase in vertical oscillation of the centre of mass in the heel-toe runners compared to the Pose® participants.

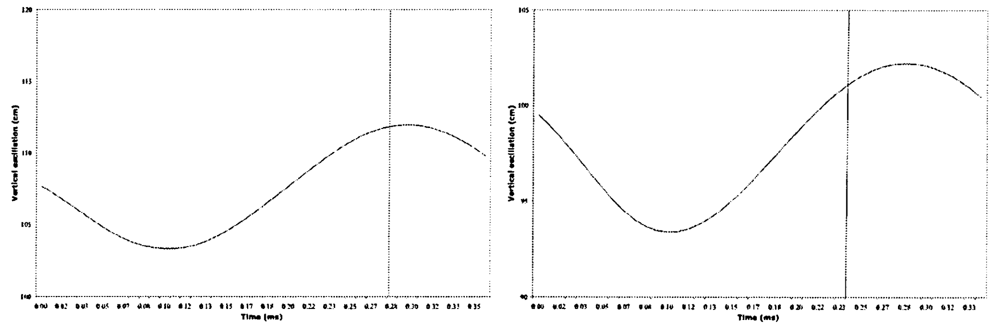


Figure 5.4.17 Vertical oscillation for the Pose® runners at 2.5 m·s^{-1}.

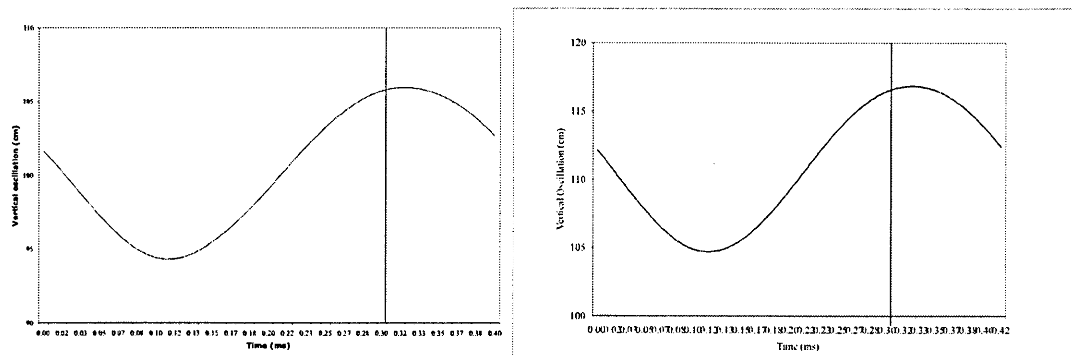


Figure 5.4.18 Vertical oscillation for the heel-toe runners at 2.5 m·s^{-1}.

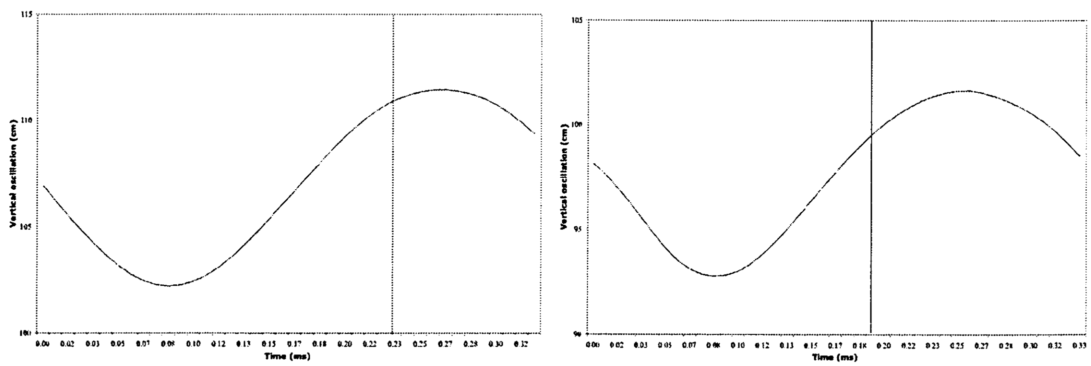


Figure 5.4.19 Vertical oscillation for the Pose® runners at 3.35 m·s^{-1}.

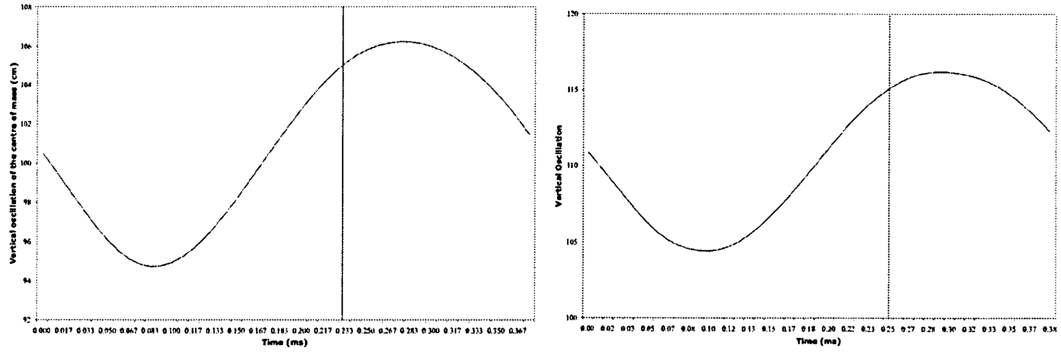


Figure 5.4.20 Vertical oscillation for the heel-toe runners at 3.35 $m \cdot s^{-1}$.

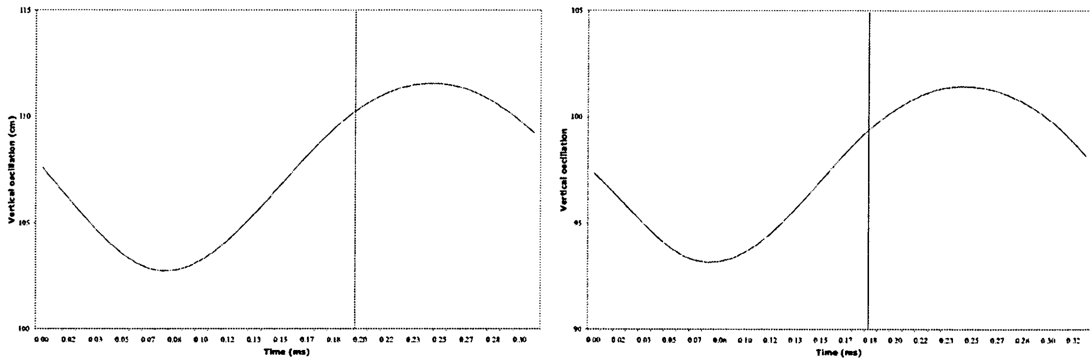


Figure 5.4.21 Vertical oscillation for the Pose® runners at 4.0 $m \cdot s^{-1}$.

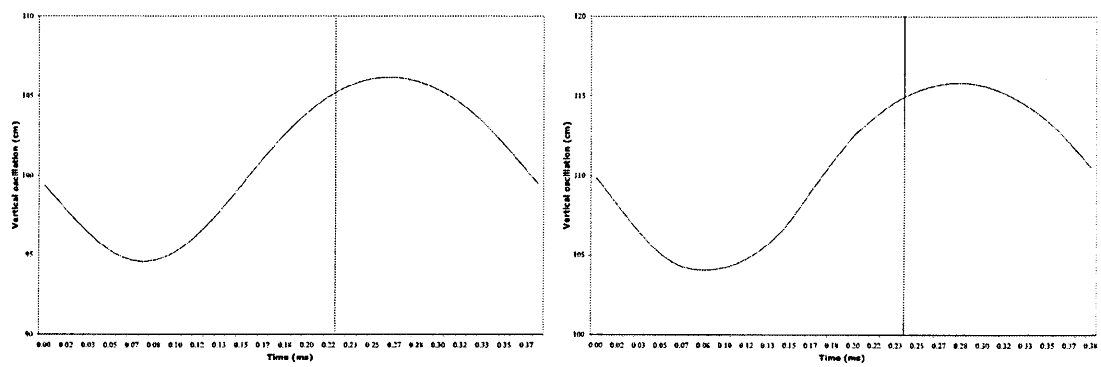


Figure 5.4.22 Vertical oscillation for the heel-toe runners at 4.0 $m \cdot s^{-1}$.

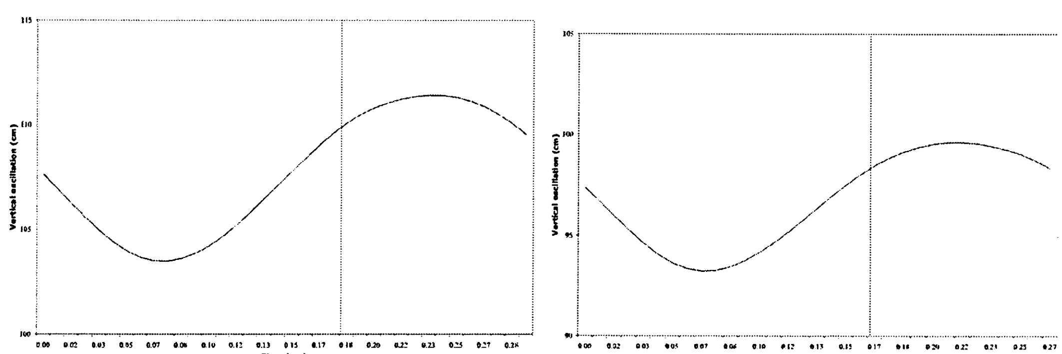


Figure 5.4.23 Vertical oscillation for the Pose® runners at 4.5 $m \cdot s^{-1}$.

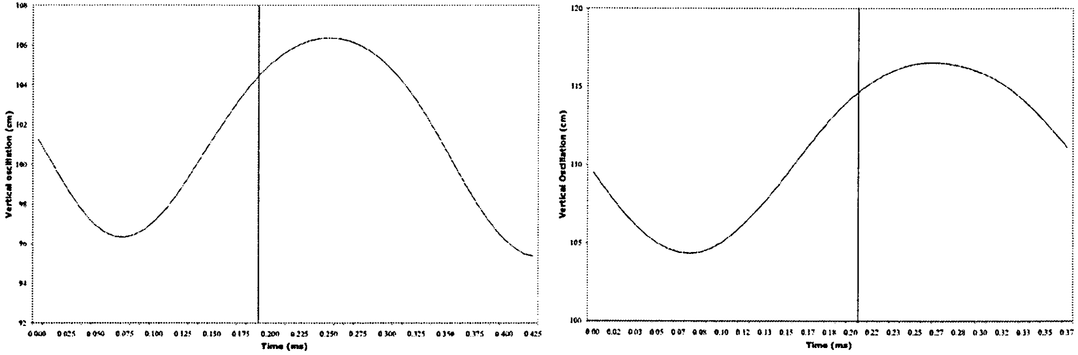


Figure 5.4.24 Vertical oscillation for the heel-toe runners at 4.5 m·s^{-1}.

Knee angular displacements

Right knee (support leg) abduction and adduction angles are recorded in figures 5.4.25-5.4.32. They verify accuracy of the marker and motion analysis system. Acceptable accuracy was determined by abduction and adduction knee angles under 14° (Kadaba *et al.* 1989). All runners for all speeds remained under 14° except the first Pose® runner from terminal stance until maximum swing at 2.5 m·s^{-1}, 3.5 m·s^{-1} and 4 m·s^{-1}.

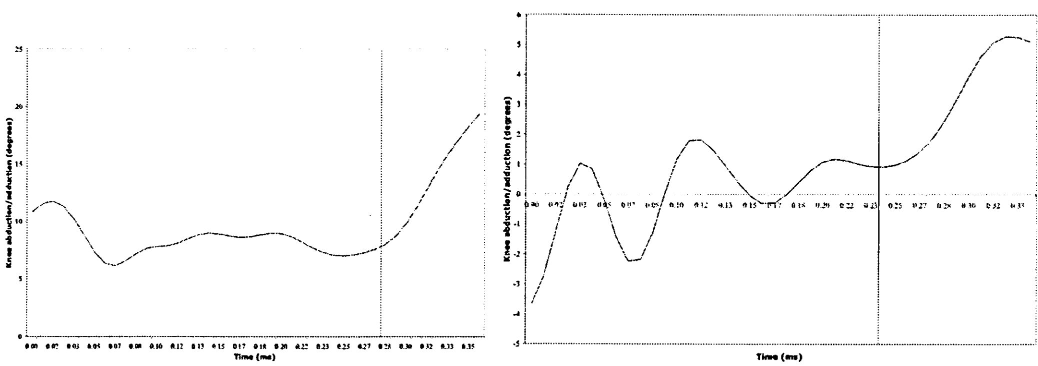


Figure 5.4.25 Knee adduction and abduction for the Pose® runners at 2.5 m·s^{-1}.

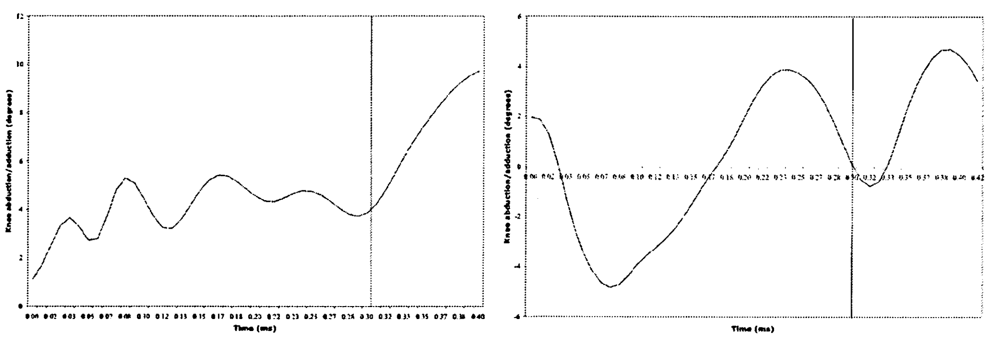


Figure 5.4.26 Knee adduction and abduction for the heel-toe runners at 2.5 m·s^{-1}.

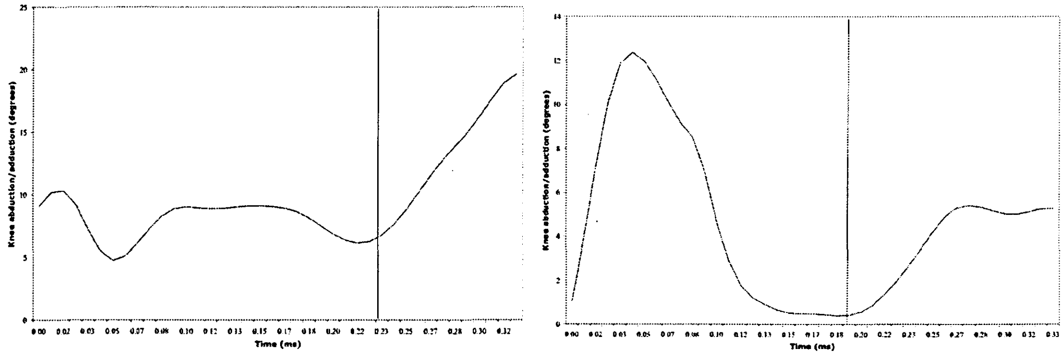


Figure 5.4.27 Knee adduction and abduction for the Pose® runners at 3.35 m·s^{-1}.

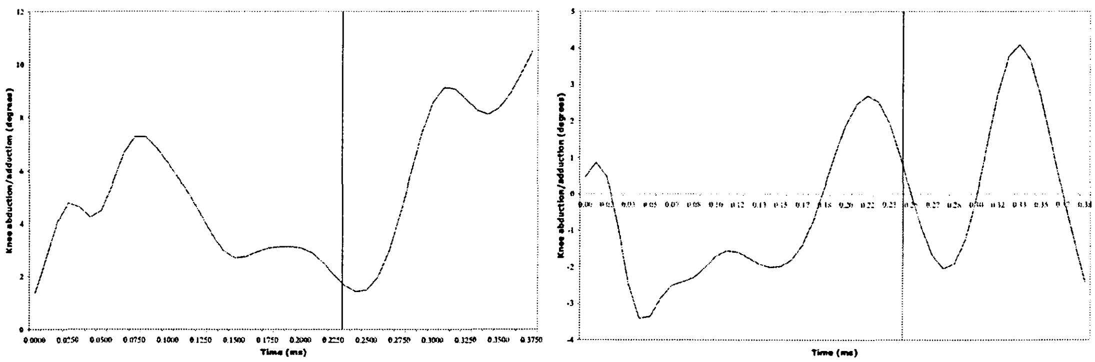


Figure 5.4.28 Knee adduction and abduction for the heel-toe runners at 3.35 m·s^{-1}.

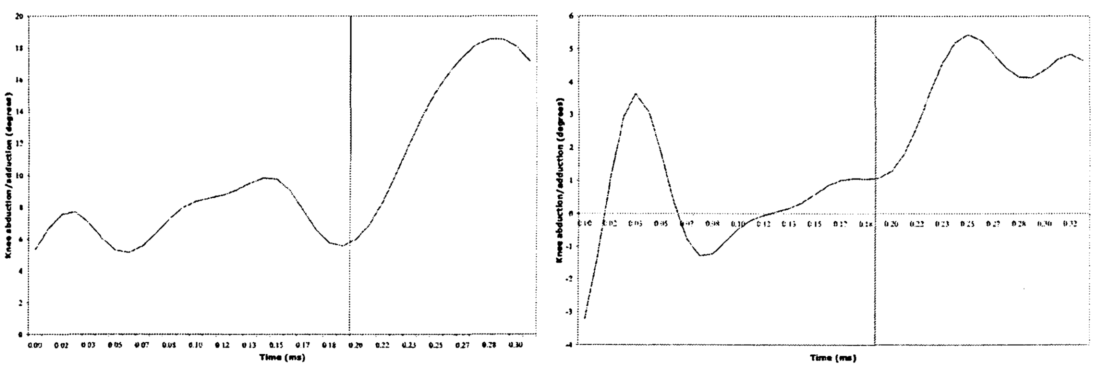


Figure 5.4.29 Knee adduction and abduction for the Pose® runners at 4.0 m·s^{-1}.

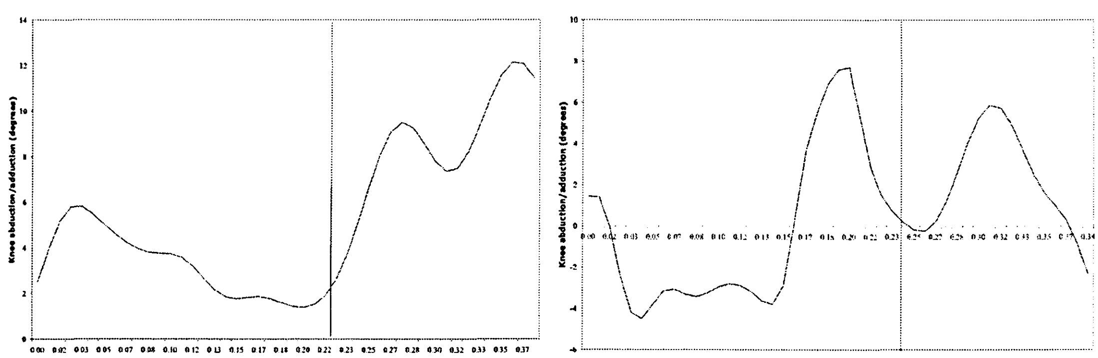


Figure 5.4.30 Knee adduction and abduction for the heel-toe runners at 4.0 m·s^{-1}.

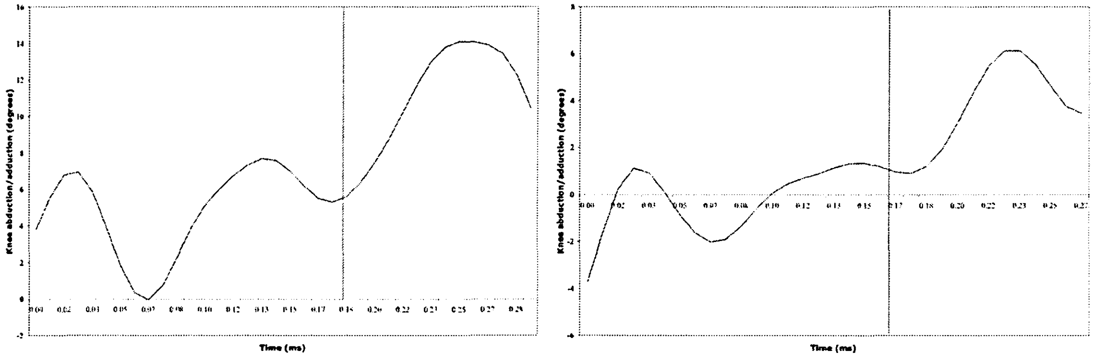


Figure 5.4.31 Knee adduction and abduction for the Pose® runners at 4.5 m·s^{-1}.

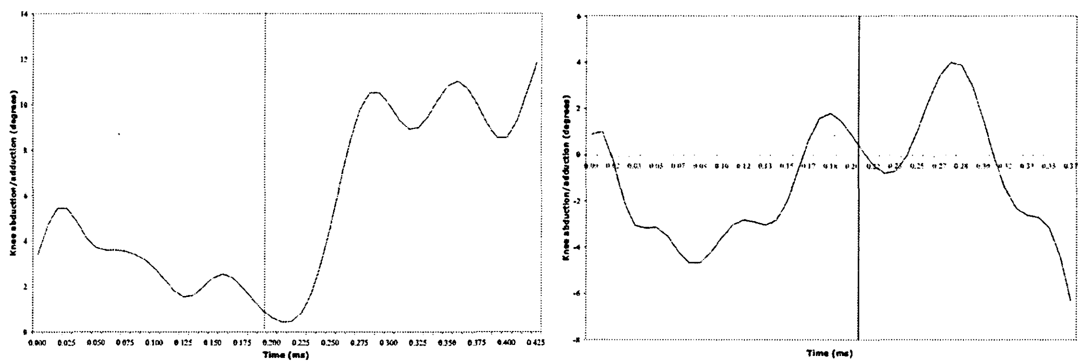


Figure 5.4.32 Knee adduction and abduction for the heel-toe runners at 4.5 m·s^{-1}.

Knee flexion and extension follow similar patterns for all four runners. Differences in the knee during impact, maximum vertical ground reaction force and swing are recorded in table 5.4.2. Increased knee extension from maximum vertical ground reaction force until terminal stance in the heel-toe runners, correlates with their increased vertical oscillation of their centre of mass (Wank *et al.*, 1998).

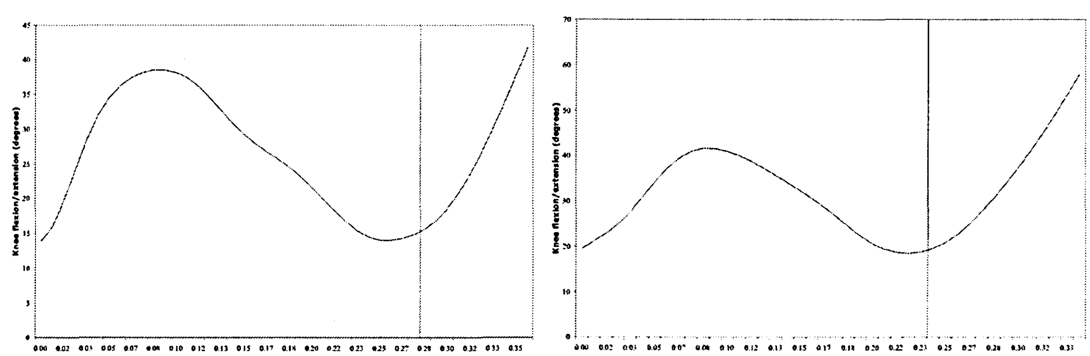


Figure 5.4.33 Knee flexion and extension for the Pose® runners at 2.5 m·s^{-1}.

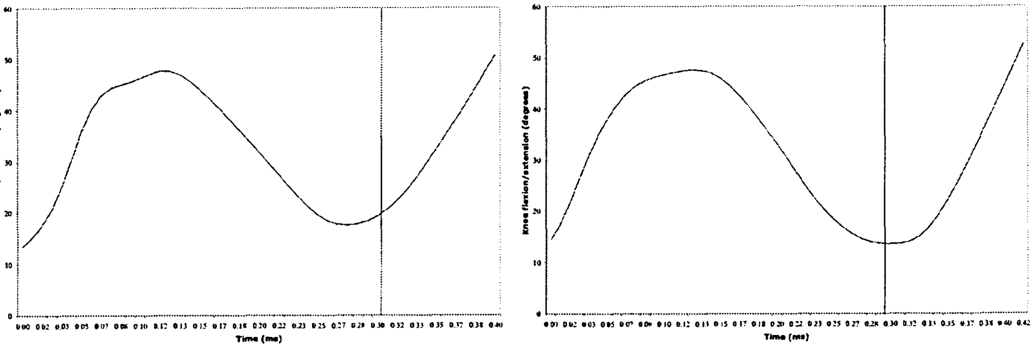


Figure 5.4.34 Knee flexion and extension for the heel-toe runners at 2.5 m·s^{-1}.

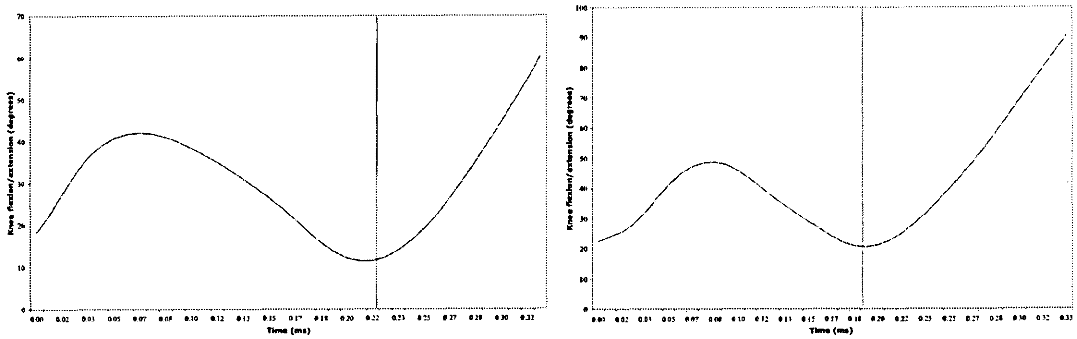


Figure 5.4.35 Knee flexion and extension for the Pose® runners at 3.35 m·s^{-1}.

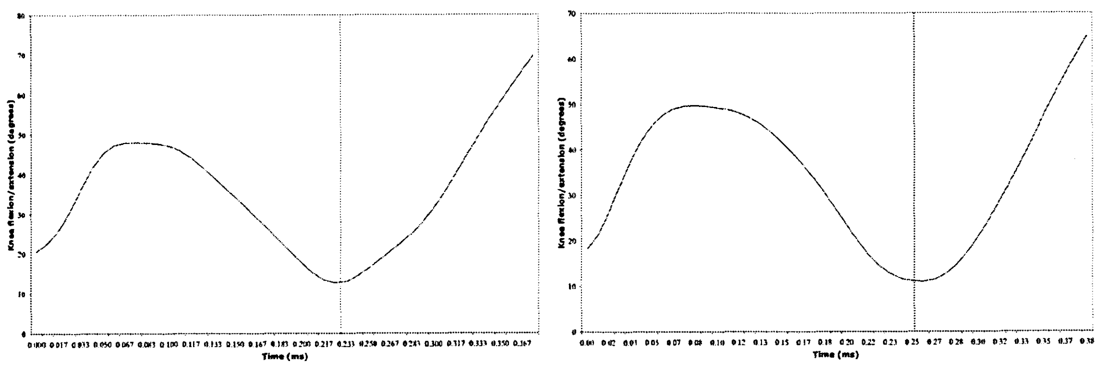


Figure 5.4.36 Knee flexion and extension for the heel-toe runners at 3.35 m·s^{-1}.

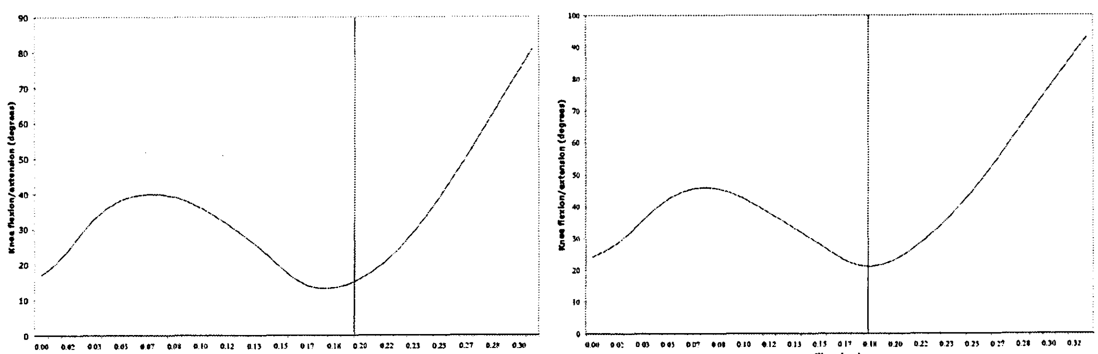


Figure 5.4.37 Knee flexion and extension for the Pose® runners at 4.0 m·s^{-1}.

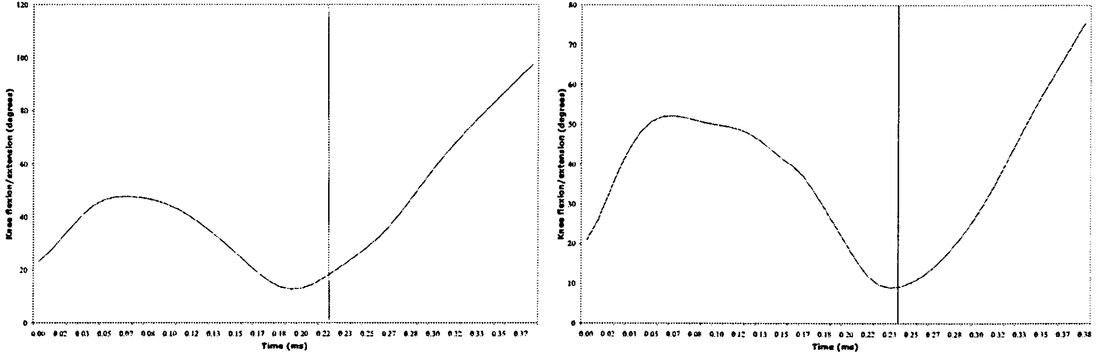


Figure 5.4.38 Knee flexion and extension for the heel-toe runners at 4.0 m·s^{-1}.

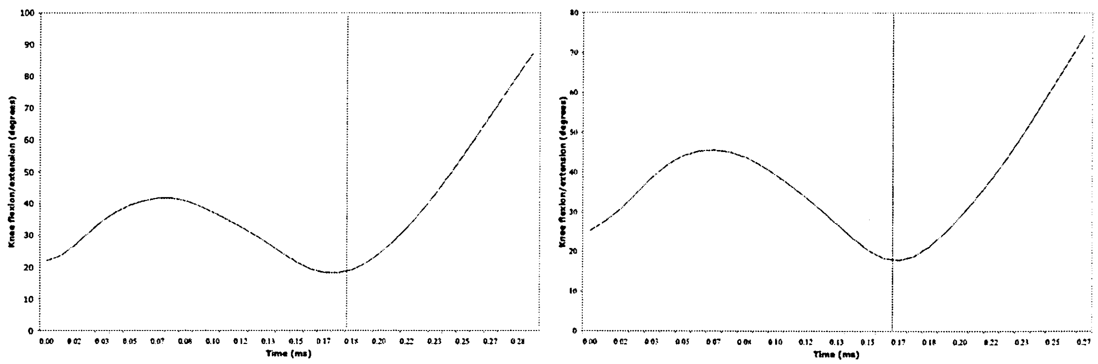


Figure 5.4.39 Knee flexion and extension for the Pose® runners at 4.5 m·s^{-1}.

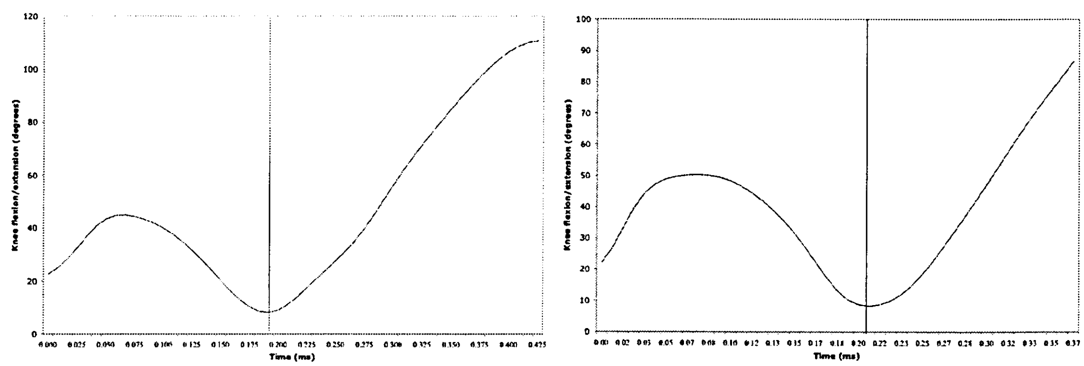


Figure 5.4.40 Knee flexion and extension for the heel-toe runners at 4.5 m·s^{-1}.

The running gait for one Pose® and heel-toe runner at each test speed are given (figures 5.5.41-5.5.49). Each still frame was taken for every five frames at a frame rate of 120 frames·s^{-1}. At impact, the ball of the foot is the first point of contact for the Pose® runner, in contrast to the heel for the heel-toe runners. The Pose® runner has a more vertically aligned body at impact plus he leaves the ground without fully extending his leg in contrast to the heel-toe runners. Heel-toe runners had greater range of motion for the lower-limb—knee flexion and extension—during stance than the Pose® runners. Knee flexion was similar for both techniques from terminal stance to maximum swing (Table

5.4.2). Knee flexion and extension angular velocity during stance was higher in the heel-toe runners. However, swing knee flexion angular velocity was much higher in the Pose® runners. The horizontal displacement of the centre of mass during stance was less for the Pose® runners. The horizontal displacement of the centre of mass for flight was still lower in Pose® runners but not as marked as actual step length. For example, Pose® runners displaced their centre of masses during flight 18.7 cm, 41.6 cm, 49 cm and 55.7 cm for each test speed beginning at 2.5 $m \cdot s^{-1}$. The heel-toe runners displaced their centre of masses during flight for 26.5 cm, 42.1 cm, 57.3 cm and 69.3 cm beginning at 2.5 $m \cdot s^{-1}$. Figures 5.4.41-5.4.49 allow visual inspection of these biomechanical differences for the Pose® and heel-toe runners.

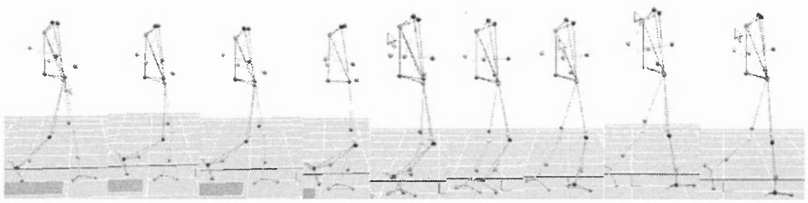


Figure 5.4.41 Pose® runner at 2.5 $m \cdot s^{-1}$ for one step.

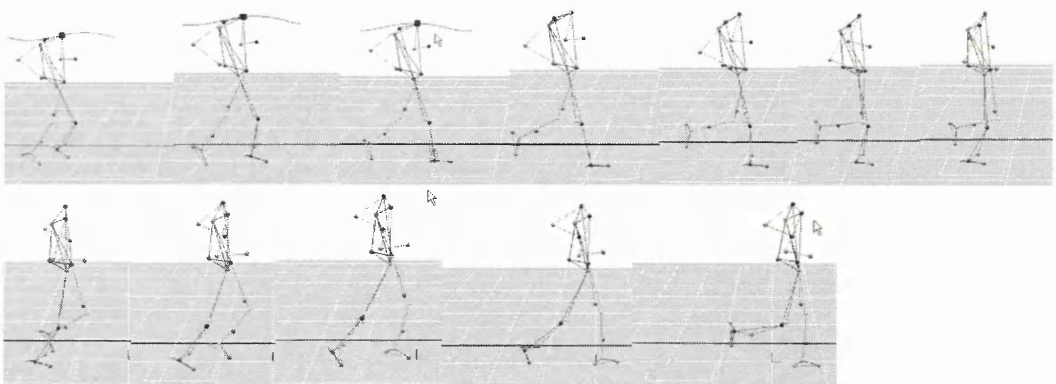


Figure 5.4.42 Pose® runner at 3.35 $m \cdot s^{-1}$ for one stride.

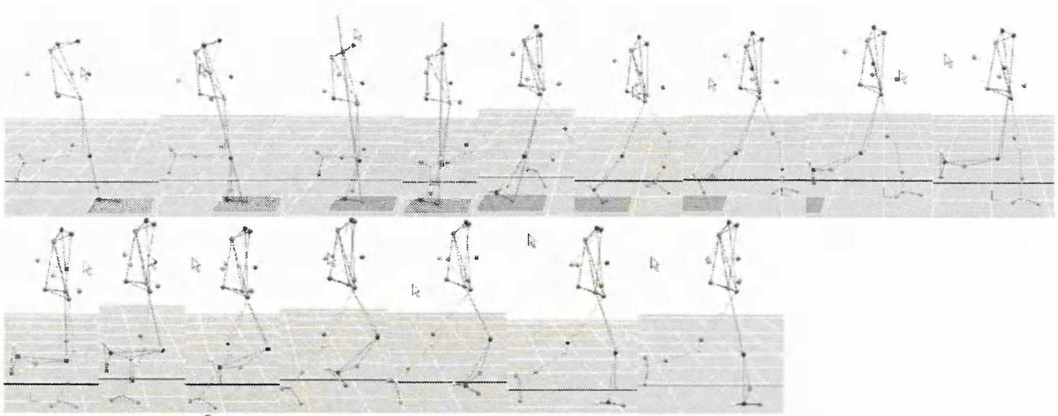


Figure 5.4.43 Pose® runner at 4.0 $m \cdot s^{-1}$ for one stride.

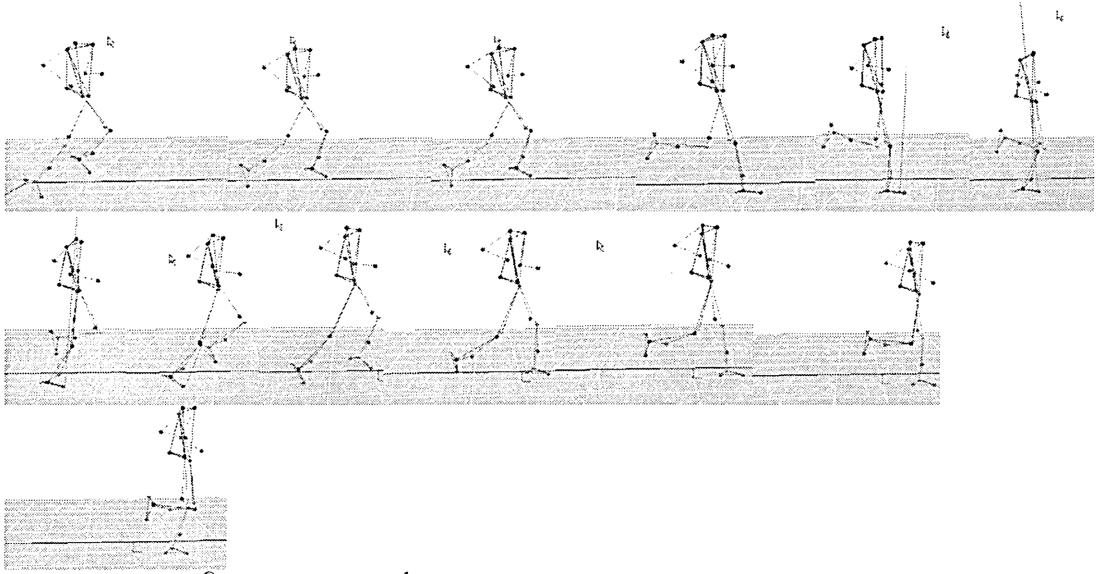


Figure 5.4.44 Pose® runner at 4.5 m·s^{-1} for one stride.

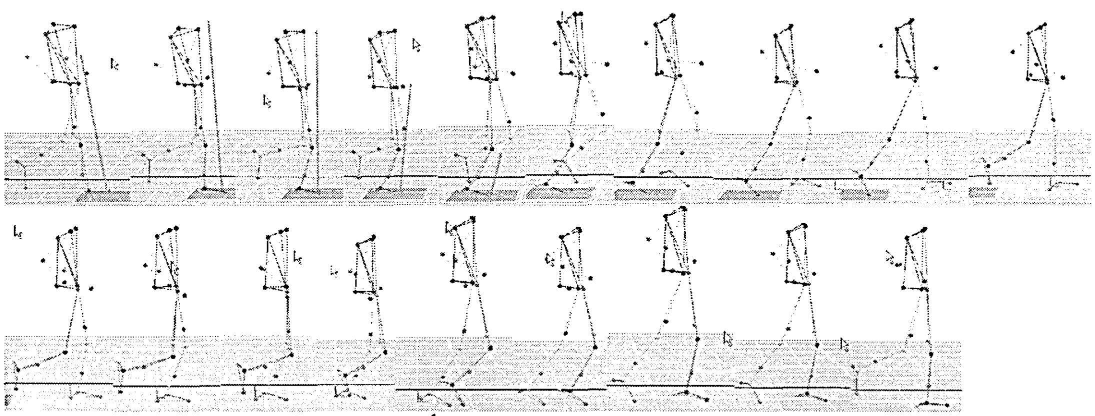


Figure 5.4.45 Heel-toe runner at 2.5 m·s^{-1} for one stride.

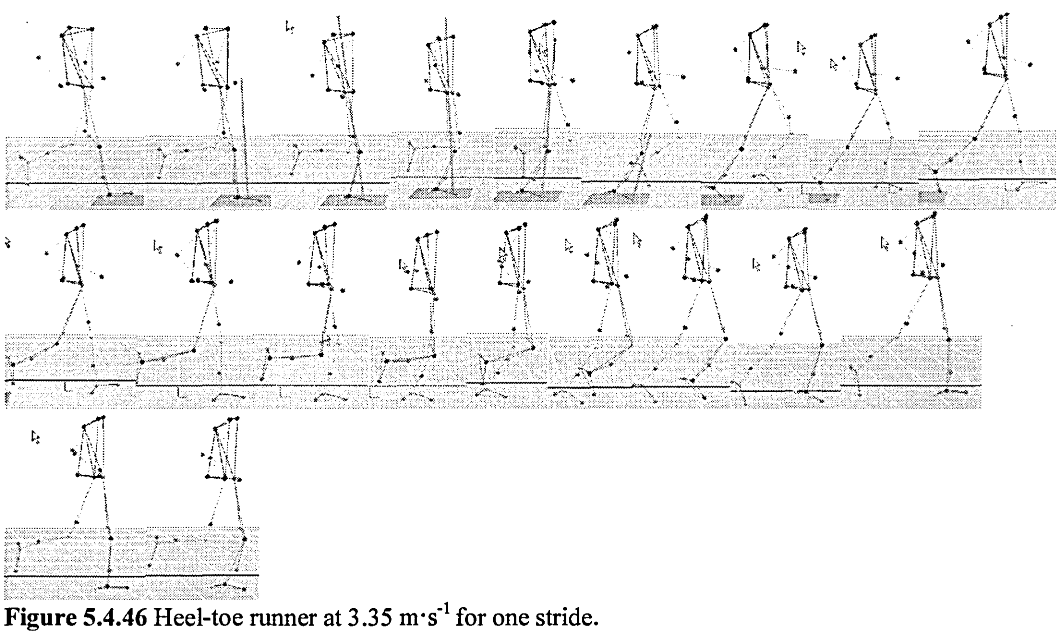


Figure 5.4.46 Heel-toe runner at 3.35 m·s^{-1} for one stride.

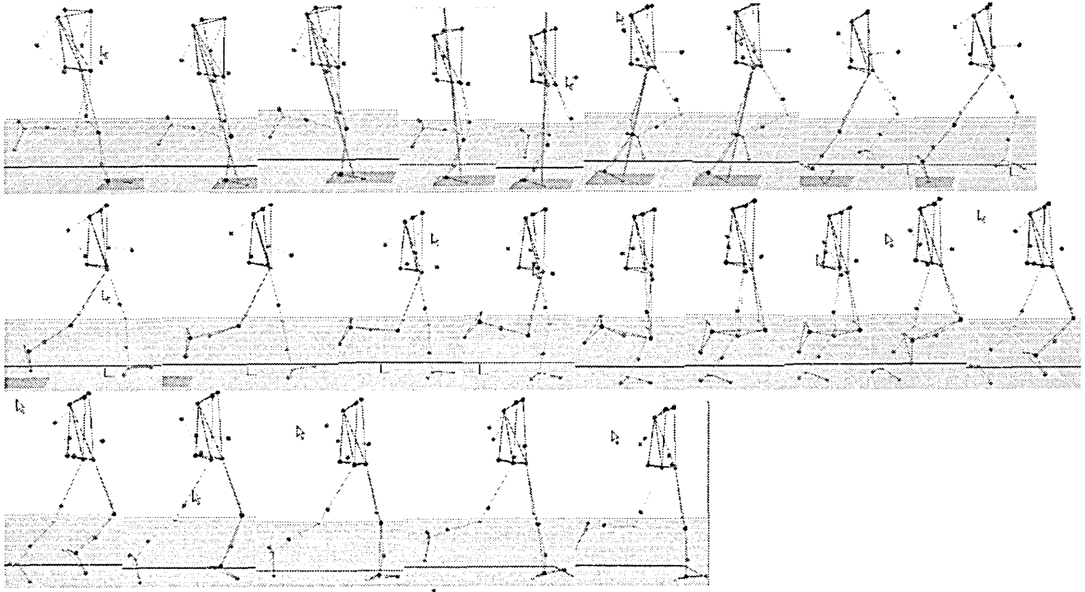


Figure 5.4.47 Heel-toe runner at 4.0 m·s^{-1} for one stride.

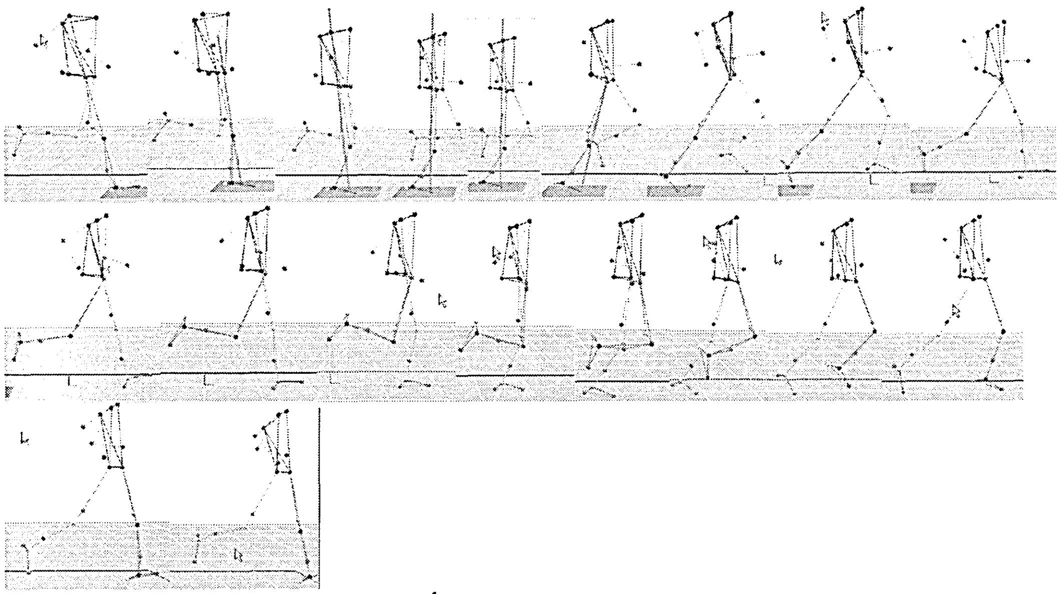


Figure 5.4.48 Heel-toe runner at 4.5 m·s^{-1} for one stride.

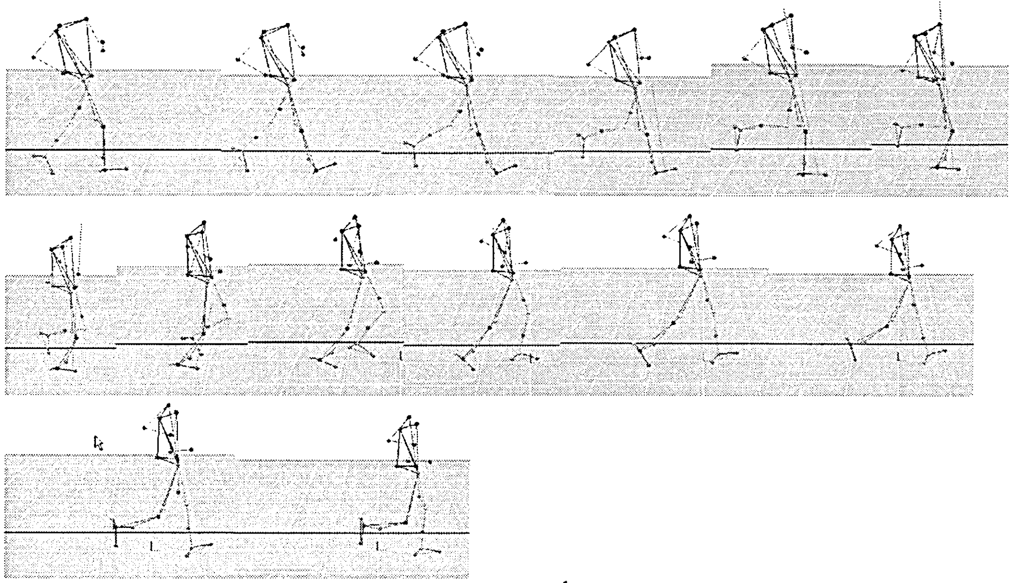
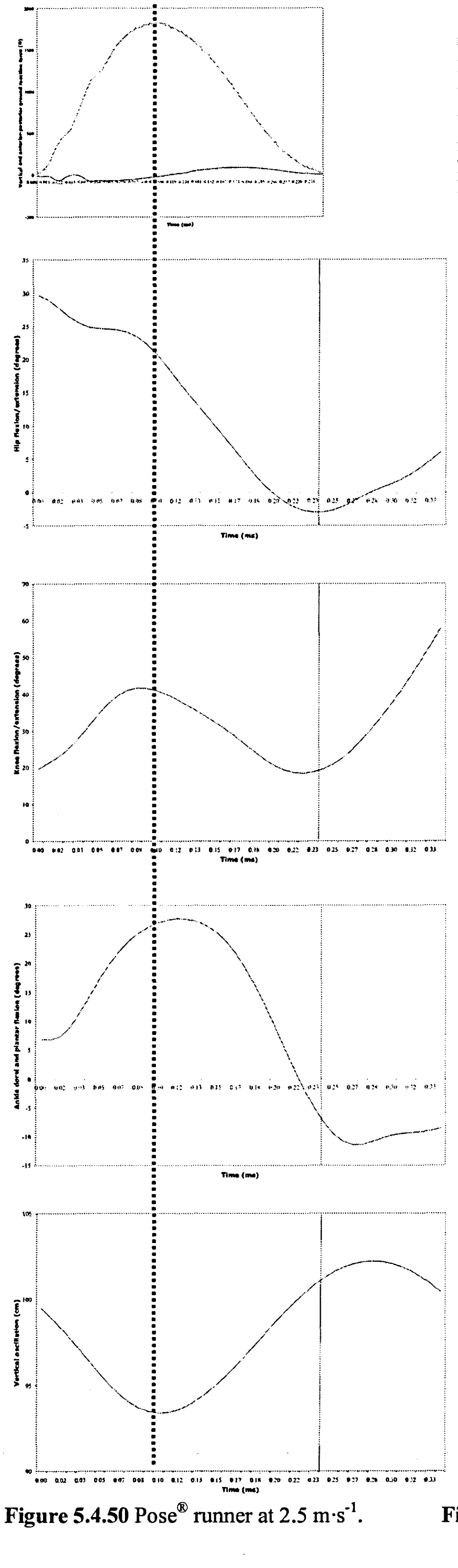


Figure 5.4.49 The second heel-toe runner at 3.35 $m \cdot s^{-1}$ for one stride.

Figures 5.4.50-5.4.57 time-align the support leg's hip, knee and ankle joint flexion and extension with maximum vertical ground reaction force. Vertical oscillation is also included to highlight the centre of mass displacement. The graphs illustrate at maximum vertical ground reaction force for the Pose® runner the hip begins to extend or has been extending depending upon running speed. The knee and ankle follow in sequence each extending after the hip, proceeding maximum vertical ground reaction force. The heel-toe runner at all speeds has begun to extend the hip at maximum vertical ground reaction force, but the knee has also begun its extension. Vertical oscillation of the centre of mass changes direction from downwards to upwards at maximum vertical ground reaction force. In the heel-toe runner the centre of mass has just began to rise at maximum vertical ground reaction force. This rise of the centre of mass probably correlates with the knee extension (Wank *et al.*, 1998).



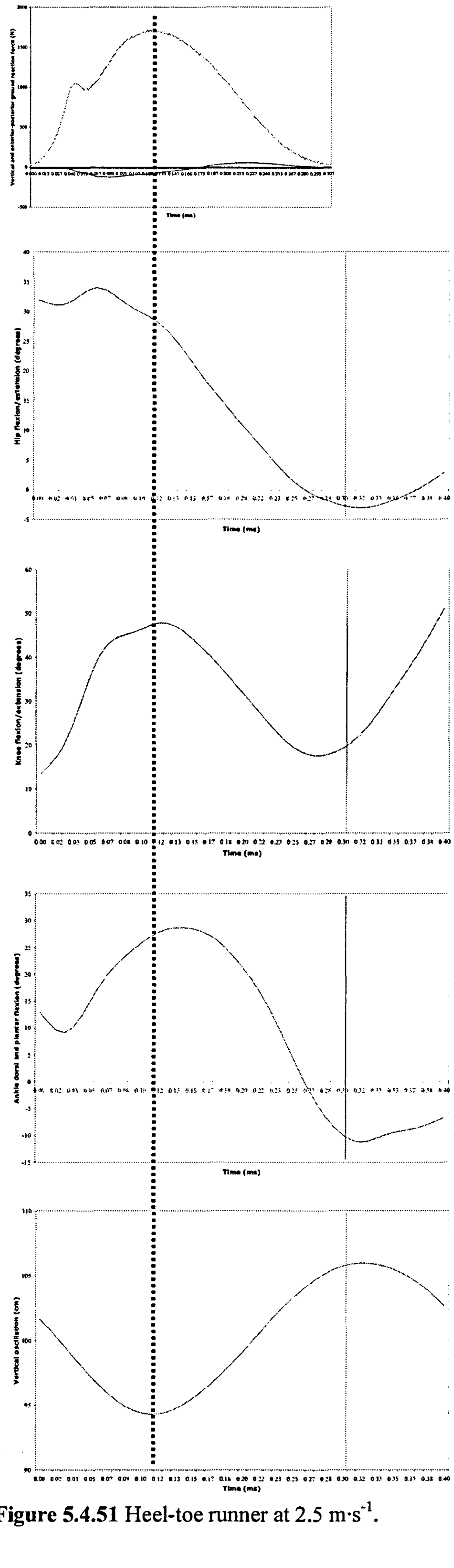


Figure 5.4.50 Pose® runner at 2.5 m·s^{-1}.

Figure 5.4.51 Heel-toe runner at 2.5 m·s^{-1}.

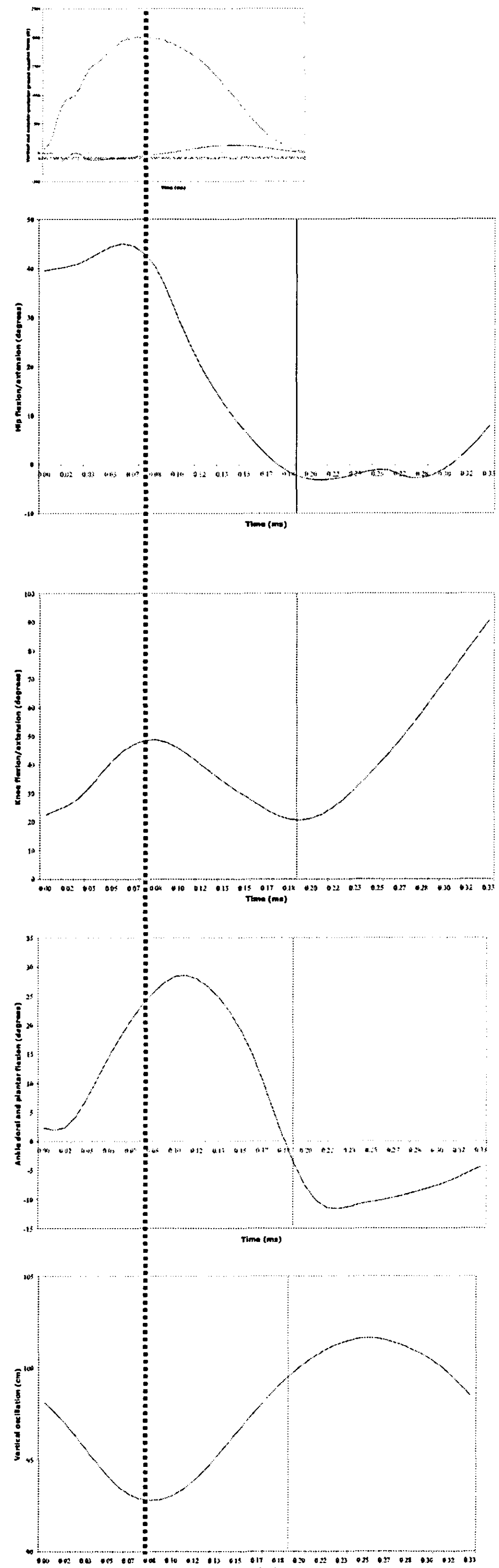


Figure 5.4.52 Pose® runner at 3.35 m·s^{-1}.

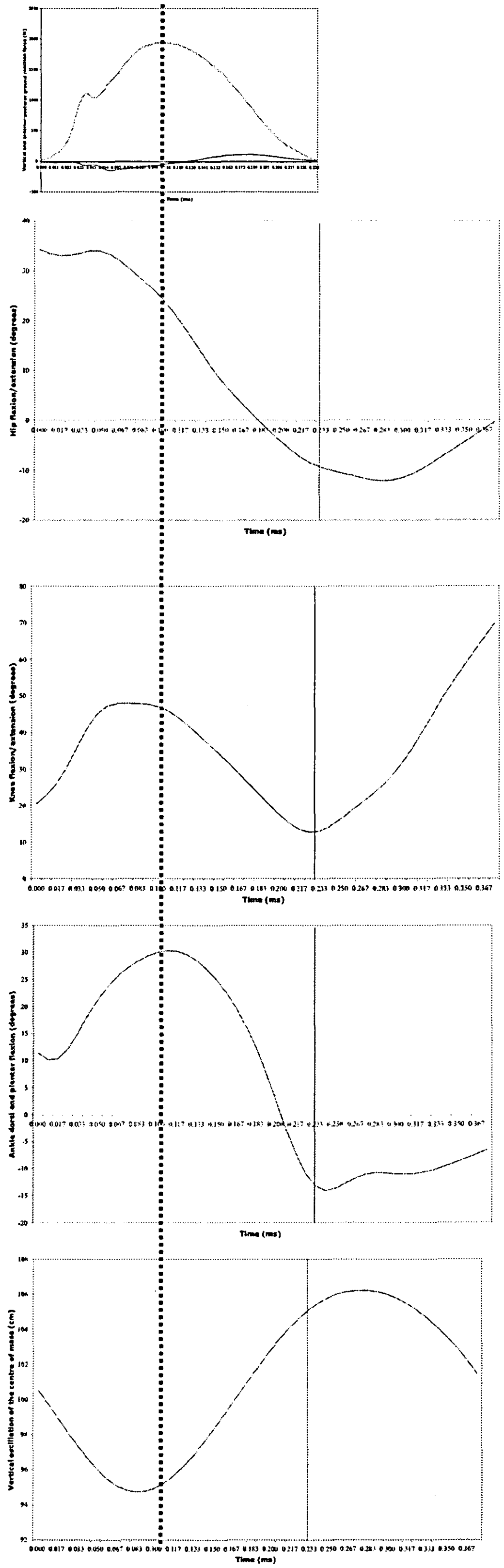


Figure 5.4.53 Heel-toe runner at 3.35 m·s^{-1}.

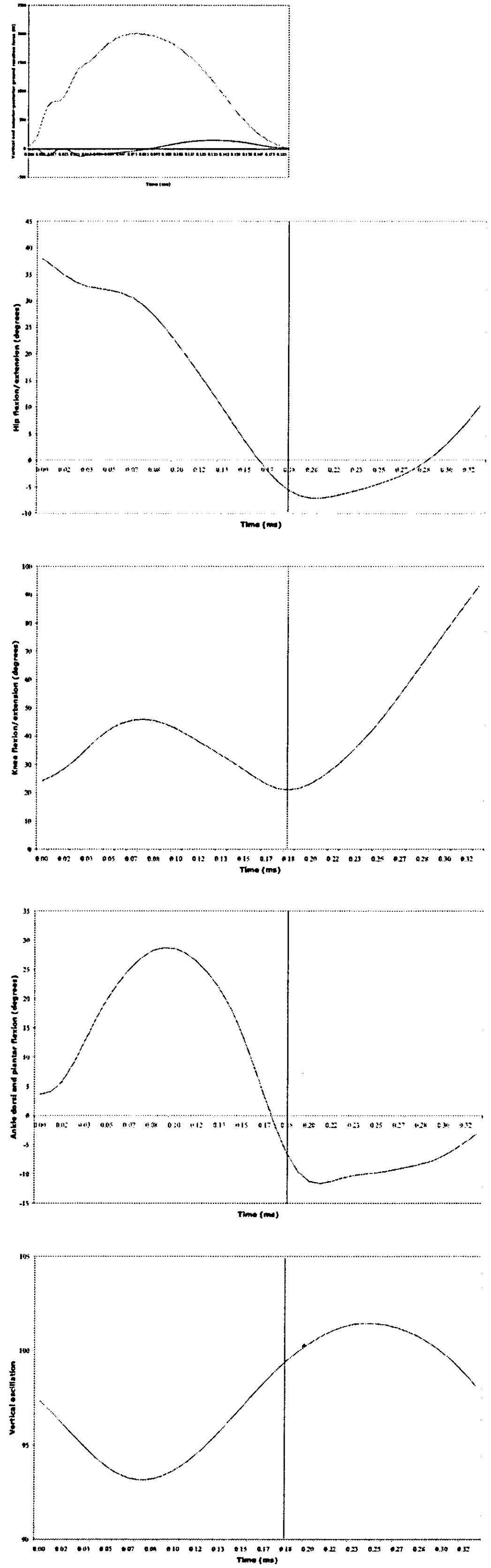


Figure 5.4.54 Pose® runner at 4.0 m·s^{-1}.

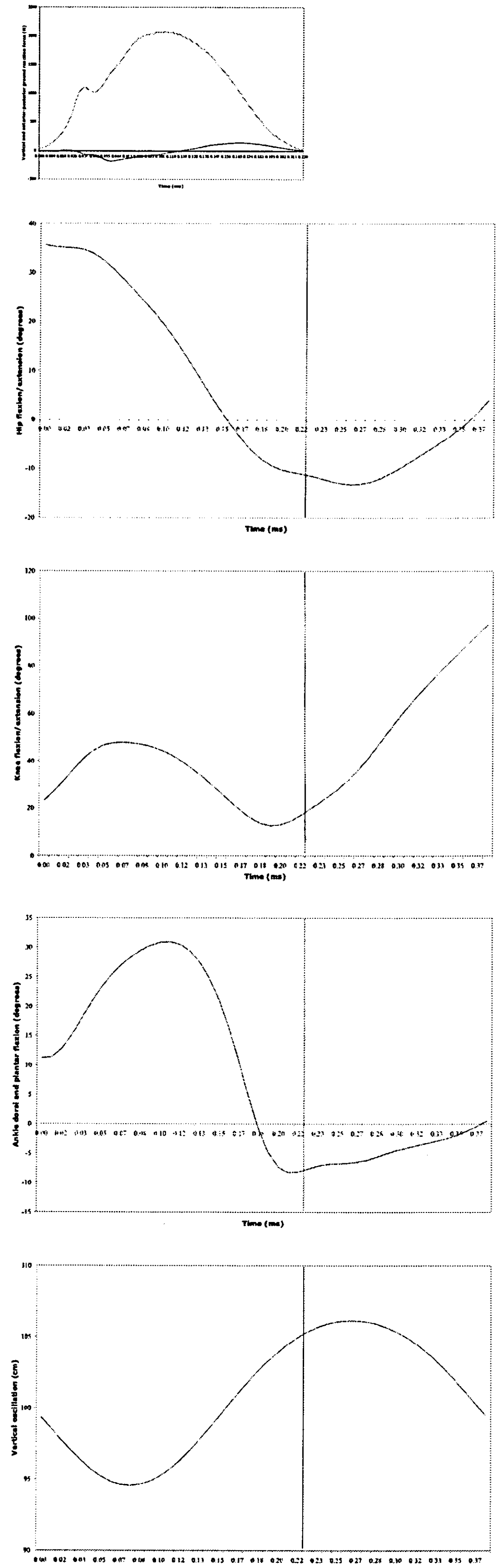


Figure 5.4.55 Heel-toe runner at 4.0 m·s^{-1}.

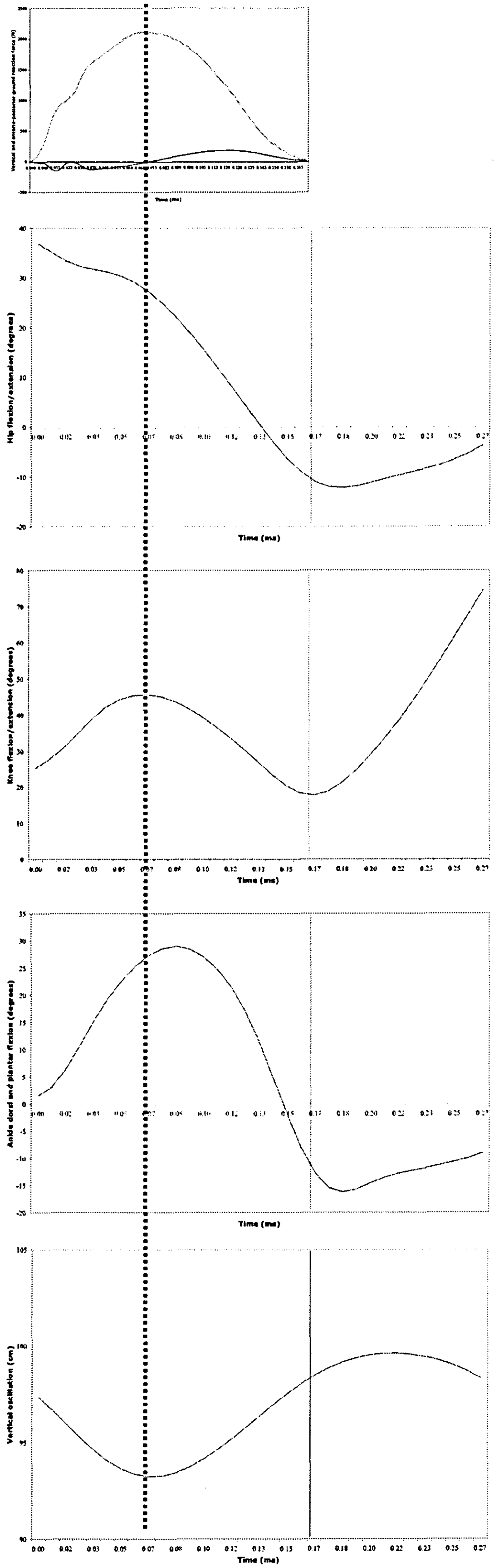


Figure 5.4.56 Pose® runner at 4.5 m·s^{-1}.

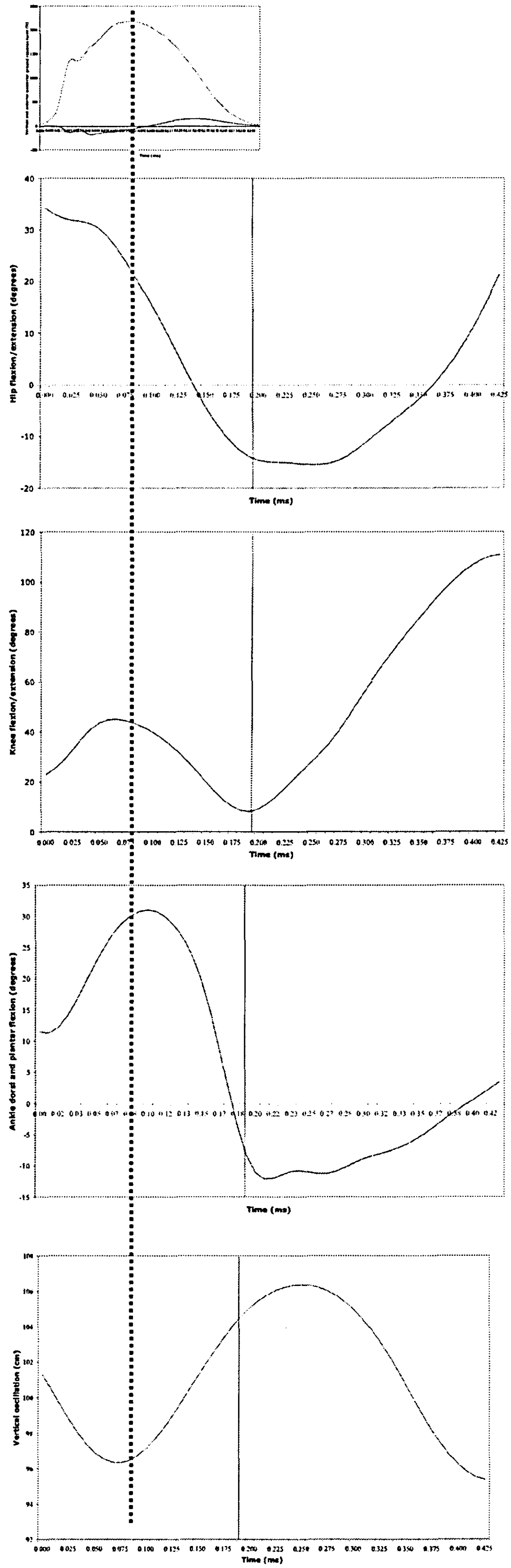
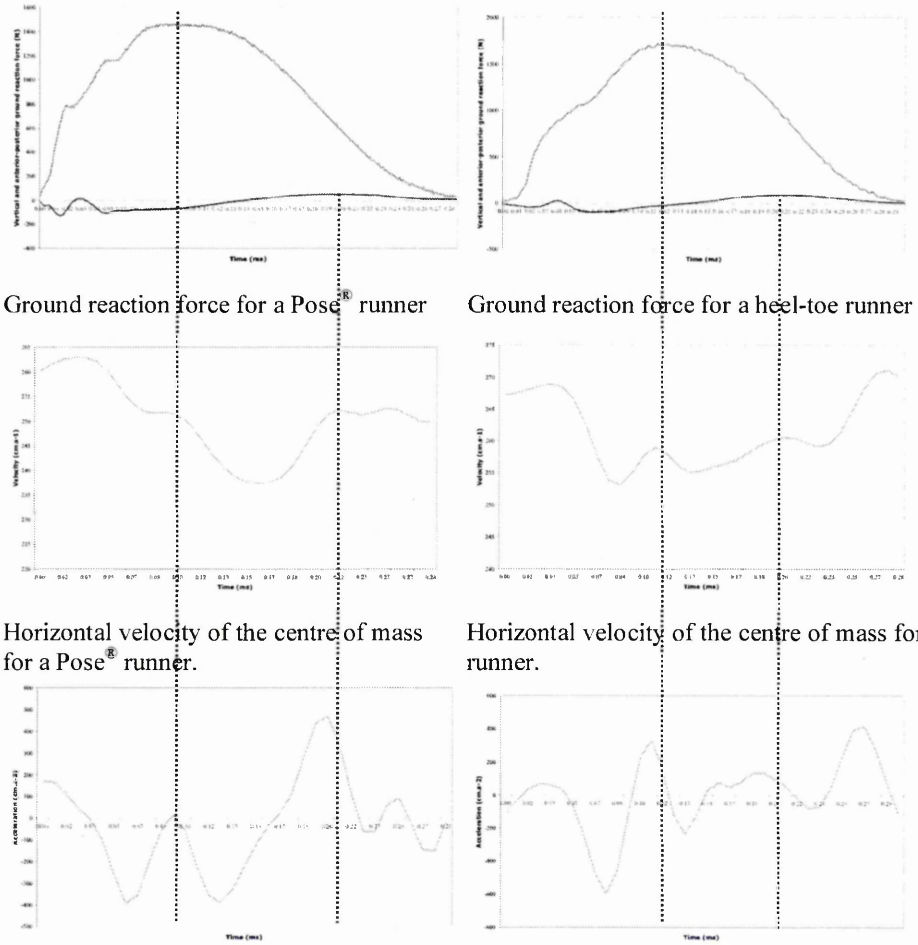


Figure 5.4.57 Heel-toe runner at 4.5 m·s^{-1}.

Figures 5.4.58-61 have vertical lines running from maximum vertical and anterior (propulsive) ground reaction force through the horizontal velocity and acceleration graphs. Maximum horizontal acceleration of the centre of mass occurs before maximum horizontal propulsive ground reaction force. Only one heel-toe and Pose® runner at 2.5 $m \cdot s^{-1}$ had a horizontal acceleration after the propulsive horizontal ground reaction force (figure 5.4.58). Table 5.4.1 gives the maximum values for vertical and anterior ground reaction force and maximum horizontal acceleration of the centre of mass and percentages of stance time. Pose® runners consistently had higher horizontal acceleration of the centre of mass during the propulsive phase of stance.



Ground reaction force for a Pose® runner

Ground reaction force for a heel-toe runner

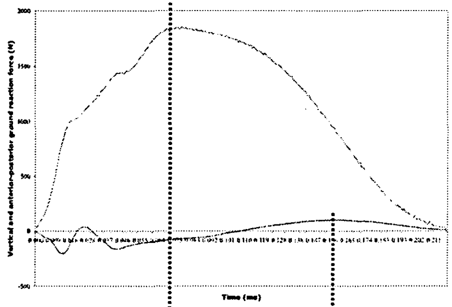
Horizontal velocity of the centre of mass for a Pose® runner.

Horizontal velocity of the centre of mass for a heel-toe runner.

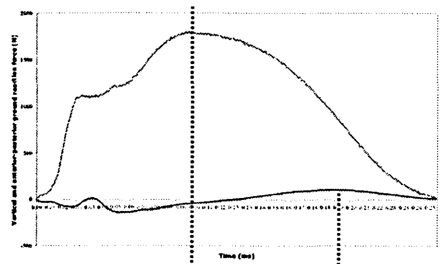
Horizontal acceleration of the centre of mass for a Pose® runner.

Horizontal acceleration of the centre of mass for a heel-toe runner.

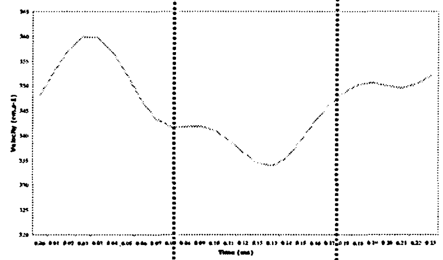
Figure 5.4.58 Ground reaction force, horizontal velocity and acceleration of the centre of mass for a Pose® and heel-toe runner at 2.5 $m \cdot s^{-1}$.



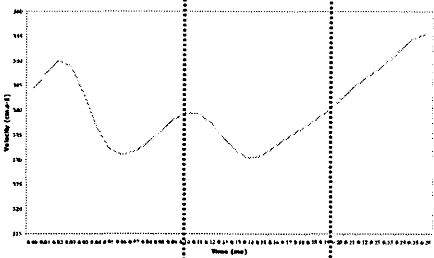
Ground reaction force for a Pose® runner



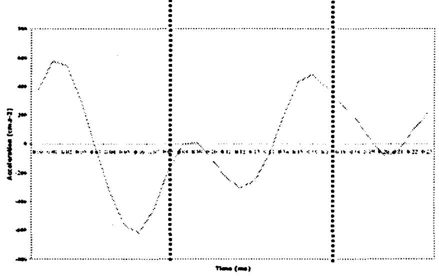
Ground reaction force for a heel-toe runner



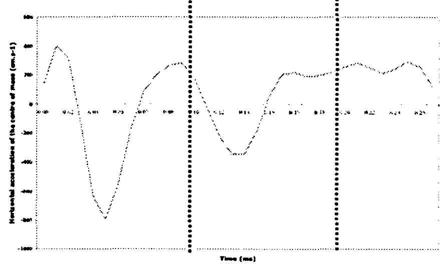
Horizontal velocity of the centre of mass for a Pose® runner.



Horizontal velocity of the centre of mass for a heel-toe runner.

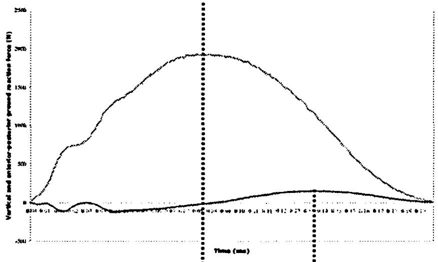


Horizontal acceleration of the centre of mass for a Pose® runner.

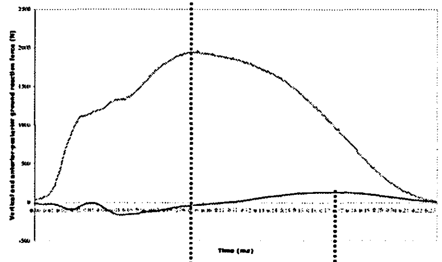


Horizontal acceleration of the centre of mass for a heel-toe runner.

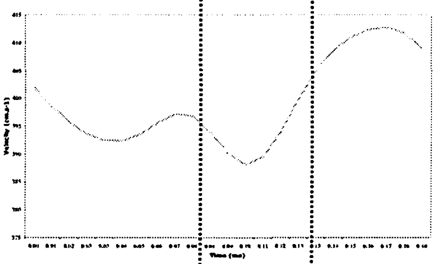
Figure 5.4.59 Ground reaction force, horizontal velocity and acceleration of the centre of mass for a Pose® and heel-toe runner at 3.35 $m \cdot s^{-1}$.



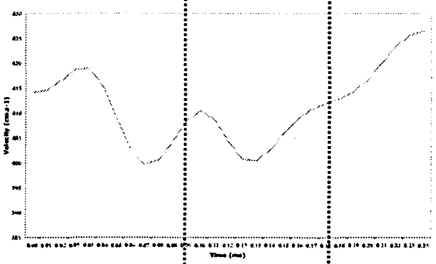
Ground reaction force for a Pose® runner



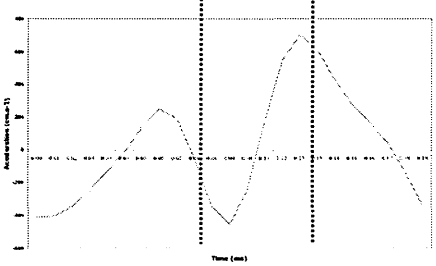
Ground reaction force for a heel-toe runner



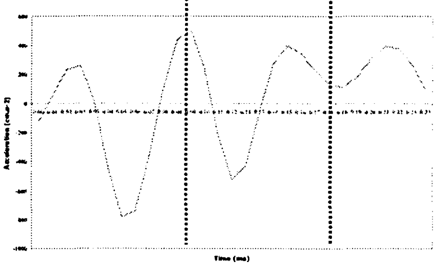
Horizontal velocity of the centre of mass for a Pose® runner.



Horizontal velocity of the centre of mass for a heel-toe runner.

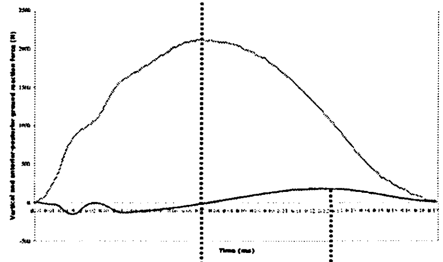


Horizontal acceleration of the centre of mass for a Pose® runner.

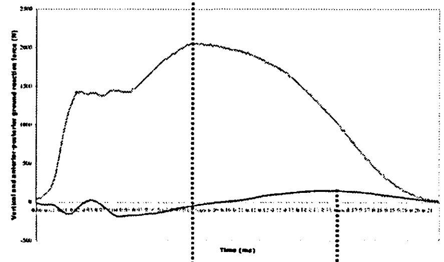


Horizontal acceleration of the centre of mass for a heel-toe runner.

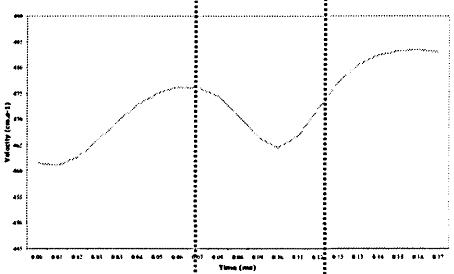
Figure 5.4.60 Ground reaction force, horizontal velocity and acceleration of the centre of mass for a Pose® and heel-toe runner at 4.0 $m \cdot s^{-1}$.



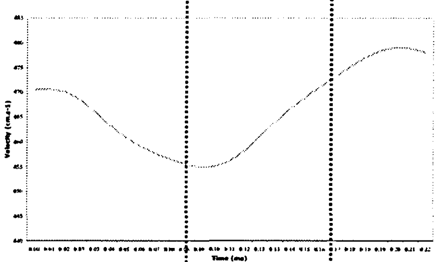
Ground reaction force for a Pose® runner



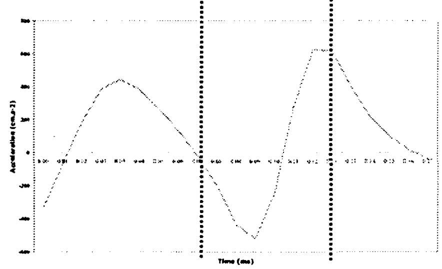
Ground reaction force for a heel-toe runner



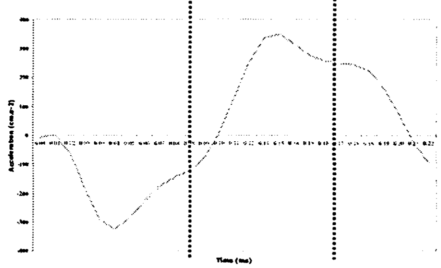
Horizontal velocity of the centre of mass for a Pose® runner.



Horizontal velocity of the centre of mass for a heel-toe runner.



Horizontal acceleration of the centre of mass for a Pose® runner.



Horizontal acceleration of the centre of mass for a heel-toe runner.

Figure 5.4.61 Ground reaction force, horizontal velocity and acceleration of the centre of mass for a Pose® and heel-toe runner at 4.5 $m \cdot s^{-1}$.

Table 5.4.1 Maximum vertical and anterior ground reaction force are recorded as a percentage of stance and compared with maximum horizontal acceleration of the centre of mass. Each value is a mean of three trials (*N* = *4*).

Participant run speeds	**Time of maximum vertical ground reaction force (%)**	**Time of maximum anterior ground reaction force (%)**	**Time of maximal horizontal acceleration of the centre of mass (%)**
1 Pose® 2.5 $m{\cdot}s^{-1}$	36	71	69
1 Pose® 3.35 $m{\cdot}s^{-1}$	37	72	65
1 Pose® 4.0 $m{\cdot}s^{-1}$	40	74	72
1 Pose® 4.5 $m{\cdot}s^{-1}$	43	74	65
2 Pose® 2.5 $m{\cdot}s^{-1}$	38	70	71
2 Pose® 3.35 $m{\cdot}s^{-1}$	41	65	50
2 Pose® 4.0 $m{\cdot}s^{-1}$	43	71	66
2 Pose® 4.5 $m{\cdot}s^{-1}$	40	71	70
1 Heel-toe 2.5 $m{\cdot}s^{-1}$	42	75	88
1 Heel-toe 3.35 $m{\cdot}s^{-1}$	48	73	70
1 Heel-toe 4.0 $m{\cdot}s^{-1}$	40	74	63
1 Heel-toe 4.5 $m{\cdot}s^{-1}$	43	74	63
2 Heel-toe 2.5 $m{\cdot}s^{-1}$	41	72	67
2 Heel-toe 3.35 $m{\cdot}s^{-1}$	44	74	66
2 Heel-toe 4.0 $m{\cdot}s^{-1}$	45	74	59
2 Heel-toe 4.5 $m{\cdot}s^{-1}$	46	74	58

Primary and secondary variables for both the heel-toe and Pose® runners at all the test speeds are given in Table 5.4.2. Similar to other studies, stance time for both styles of running decreases with increases in running speed (Williams, 1985). All the ground reaction force variables increase with running speed (Miller, 1990). Stride length also increased as running speed increased. However, stride frequency increased as running speed increased for the Pose® runners in contrast with all other research on endurance running speeds, whereas the heel-toe runners followed conventional patterns of no increase (Patla *et al.,* 1989). Vertical oscillation reduced with running speed but more significantly in Pose® runners. Horizontal velocities for the centre of mass—braking and propulsion—were consistent across the speed range in the heel-toe runners but at 4 $m{\cdot}s^{-1}$ and 4.5 $m{\cdot}s^{-1}$, the Pose® runners had significant reductions in braking.

Table 5.4.2 Two experienced heel-toe and Pose® runner's mean scores across all collected speeds. The primary research variables are in bold ($N = 4$).

Variables	Model	2.5 m•s^{-1}	3.35 m•s^{-1}	4.0 m•s^{-1}	4.5 m•s^{-1}
ST (ms)	HT	272	260	230	209
	P	262	216	195	174
M A-P GRF (brak) (BW)	HT	-0.16	-0.20	-0.25	-0.30
	P	-0.14	-0.23	-0.25	-0.28
M V GRF (BW)	HT	2.46	2.58	2.84	2.93
	P	2.32	2.63	2.77	2.84
M A-P GRF (prop) (BW)	HT	0.108	0.15	0.19	0.25
	P	0.084	0.16	0.2	0.24
T A-P GRF (brak)	HT	23.7	23.8	23.4	25.1
(% of stance)	P	12.5	8.4	13.6	7.7
T V GRF	HT	41.3	44.1	42.5	44.8
(% of stance)	P	37.8	37.9	39.9	40.6
T A-P GRF (prop)	HT	73.7	73.3	74.4	74.7
(% of stance)	P	69.9	71.2	72.7	72.9
CM (brak) (cm·s^{-1})	HT	-18.3	-22.7	-16.9	-18.3
	P	-12.1	-15.3	-2.2	-3.0
CM (prop) (cm·s^{-1})	HT	12.2	20.4	18.5	22.2
	P	9.7	17.7	8.3	12.9
CM diff (cm·s^{-1})	HT	-6.1	-2.3	1.6	3.9
	P	-2.4	2.4	6.1	9.9
HVTO (m·s^{-1})	HT	2.64	3.50	4.13	4.6
	P	2.51	3.6	4.12	4.8
CM S (cm·s^{-1})	HT	-16.0	-18.9	-33.3	-36.3
	P	-10.8	-27.3	-14.8	-13.7
CM 25 (cm)	HT	35.5	37.2	38.4	37.8
	P	29.8	32.7	33.2	32.1
CM TO (cm)	HT	32.9	40.5	46.0	50.1
	P	34.3	36.8	43.1	45.5
CM θ (rad)	HT	0.30	0.35	0.40	0.44
	P	0.27	0.34	0.37	0.42
CM dis (cm)	HT	75.1	89.3	91.4	94.5
	P	64.4	75.6	78.2	82.9
SHA (cm)	HT	15.6	16.6	12.9	11.3
	P	7.95	8.0	5.2	2.8
VO (cm)	HT	12.0	11.9	11.95	11.1
	P	8.5	9.3	8.5	7.2
KF (rad)	HT	0.57	0.55	0.51	0.45

	P	0.42	0.44	0.39	0.33
KE (rad)	HT	0.56	0.64	0.69	0.69
	P	0.39	0.48	0.45	0.46
KSW (rad)	HT	1.2	1.5	1.8	1.9
	P	1.2	1.6	1.7	1.8
KTD (rad)	HT	0.25	0.34	0.36	0.41
	P	0.26	0.32	0.36	0.43
KVGRF (rad)	HT	0.83	0.87	0.84	0.83
	P	0.67	0.74	0.75	0.75
KFV (rad·s^{-1})	HT	5.0	5.4	6.1	5.5
	P	4.4	5.3	6.1	4.2
KEV (rad·s^{-1})	HT	3.1	4.1	4.9	5.2
	P	2.7	3.5	4.1	4.8
KFVS (rad·s^{-1})	HT	5.4	6.4	7.5	7.95
	P	6.2	7.7	9.1	10.1
SL (cm)	HT	103.0	130.8	153.0	170.3
	P	84.8	119.2	130.3	141.8
FT (ms)	HT	110.0	120.0	150.0	150.0
	P	90.0	120.0	120.0	110.0
SF (Hz)	HT	2.5	2.7	2.6	2.8
	P	2.9	3.0	3.2	3.5

Technique: P = Pose® and HT = heel-toe, ST = stance time (ms) right foot, M A-P GRF (brak) = maximum posterior ground reaction force (braking) (BW), M V GRF = maximum vertical ground reaction force (BW), M A-P GRF (prop) = maximum anterior ground reaction force (propulsive) (BW), T A-P GRF (brak) = time of posterior ground reaction force (braking) (% of stance), T V GRF = time of maximum vertical ground reaction force (% of stance), T A-P GRF (prop) = time of anterior ground reaction force (propulsion) (% of stance), CM (brak) = centre of mass horizontal velocity largest decrease after impact until maximum vertical ground reaction force (cm·s^{-1}), CM (prop) = centre of mass horizontal velocity largest increase from maximum vertical ground reaction force until terminal stance (cm·s^{-1}), CM diff = horizontal velocity of the centre of mass from maximum vertical ground reaction force until terminal stance minus horizontal velocity of the centre of mass from impact until maximum vertical ground reaction (cm·s^{-1}), HVTO = horizontal velocity of the centre of mass at terminal stance (m·s^{-1}), CM S = centre of mass horizontal velocity decrease between terminal stance and maximum swing (flexion) for the right leg during flight (cm·s^{-1}), CM 25 = centre of mass behind the toe-marker (horizontal difference at 25 ms) (cm), CM TO = centre of mass forward of the toe-marker (horizontal difference at terminal stance) (cm), CM θ = centre of mass and toe-marker angle at terminal stance from the vertical axis going clockwise (rad), CM dis = centre of mass displacement during stance (cm), SHA = shoulder, hip, and ankle marker difference in vertical alignment at 25 ms (cm), VO = vertical oscillation of the centre of mass (cm), KF = knee flexion range during stance (rad), KE = knee extension during stance (rad), KSW = knee flexion from terminal stance to maximum swing (rad), KTD = knee angle at impact (rad), KV GRF = knee angle at maximum vertical ground reaction force (rad), KFV = mean knee flexion angular velocity for stance (rad·s^{-1}), KEV =

mean knee extension angular velocity for stance (rad·s^{-1}), KFVS = mean knee flexion angular velocity from terminal stance to maximum swing angle (rad.s^{-1}), SL = step length for right foot (cm), FT = flight time (ms), SF= step frequency (Hz).

The primary and secondary variables are grouped in table 5.4.3 as similar, lower or higher for the Pose® runners compared with the heel-toe runners.

Table 5.4.3 Variables are grouped as similar, lower and higher for the Pose® runners compared with the heel-toe runners (*N* = 4).

Similar	Lower	Higher
M V GRF	T A-P GRF (brak)	KFVS
M A-P GRF (brak)	T V GRF	SF
M A-P GRF (prop)	CM (brak)	CM diff
T A-P GRF (prop)	CM (prop)	H accel. CM
CM θ	CM S	Hip flexion
KSW	CM 25	
KTD	CM TO	
HVTO	CM disp (stance)	
	SHA	
	VO	
	KF	
	KE	
	KVGRF	
	KEV	
	KFV	
	ST	
	SL	
	FT	
	Hip ext.	
	Ankle flexion at impact	
	CM disp (flight)	

The experienced heel-toe runners were compared with the literature where possible to ensure they accurately represented the recreational endurance running population.

Table 5.4.4 Variables for the heel-toe runners (*N* = 2) are matched with the literature at similar speeds. Any minor speed differences are noted after the reference. The thesis research variables fall within one standard deviation of the literature. Over-ground running studies were selected over treadmill running where possible owing to some kinetic and kinematic differences (Wank *et al.*, 1998).

RV	($m \cdot s^{-1}$)	HT	Literature	Sources
ST (ms)	2.5	272	283 (22)	Martin (1985)
	3.35	260	258 (18)	Munro *et al.* (1987)
	4.0	230	229 (14)	Munro *et al.* (1987)
	4.5	209	214 (13)	Munro *et al.* (1987)
M A-P GRF (brak) (BW)				
	2.5	-0.16		
	3.35	-0.20	-0.17 (0.03)	Munro *et al.* (1987)
	4.0	-0.25	-0.21 (0.02)	Munro *et al.* (1987)
	4.5	-0.30	-0.24 (0.02)	Munro *et al.* (1987)
M V GRF (BW)				
	2.5	2.46		
	3.35	2.58	2.52 (0.19)	Williams and Cavanagh (1987) at 3.57 $m \cdot s^{-1}$
	4.0	2.84	2.72 (.17)	Munro *et al.* (1987)
	4.5	2.93	2.79 (.18)	Munro *et al.* (1987)
M A-P GRF (prop) (BW)				
	2.5	0.108		
	3.35	0.15	0.16 (0.01)	Munro *et al.* (1987)
	4.0	0.19	0.20 (0.01)	Munro *et al.* (1987)
	4.5	0.25	0.23 (0.02)	Munro *et al.* (1987)
T A-P GRF (brak) (% of stance)				
	2.5	23.7		
	3.35	23.8		
	4.0	23.4	21.48	Hamill *et al.* ((1983)
	4.5	25.1		
T V GRF (% of stance)				
	2.5	41.3		
	3.35	44.1	40.1 (3.7)	Frederick and Hagy (1986)
	4.0	42.5	42.3 (3.5)	Frederick and Hagy (1986) at 3.83 $m \cdot s^{-1}$
	4.5	44.8	42.1 (4.1)	Frederick and Hagy (1986) at 4.47 $m \cdot s^{-1}$
T A-P GRF (prop) (% of stance)				
	2.5	73.7		
	3.35	73.3		
	4.0	74.4	73.05	Hamill *et al.* ((1983)
	4.5	74.7		
CM (brak) ($cm \cdot s^{-1}$)				
	2.5	-18.3		
	3.35	-22.7		
	4.0	-16.9		
	4.5	-18.3	-18.0	Cavanagh and LaFortune (1980)
CM (prop) ($cm \cdot s^{-1}$)				
	2.5	12.2		
	3.35	20.4		
	4.0	18.5		
	4.5	22.2	27.0	Cavanagh and LaFortune (1980)
VO (cm)				
	2.5	12.0		
	3.35	11.9	11.6 (1.2)	Collins *et al.* (2000)
	4.0	11.95		
	4.5	11.1	11.8 (1.1)	Collins *et al.* (2000)
KF (rad)				
	2.5	0.57	0.57 (0.09)	Christina *et al.* (2001) at 2.9 $m \cdot s^{-1}$
	3.35	0.55		
	4.0	0.51		

4.5	0.45		
KSW (rad)			
2.5	1.2		
3.35	1.5		
4.0	1.8	1.85	Nilsson and Thorstensson (1985) at 3.83 $m \cdot s^{-1}$
4.5	1.9		
KTD (rad)			
2.5	0.25		
3.35	0.34		
4.0	0.36	0.24 (0.09)	Diss (2001)
4.5	0.41		
KVGRF (rad)			
2.5	0.83		
3.35	0.87	0.78 (0.06)	Morgan *et al.* (1990)
4.0	0.84		
4.5	0.83		
KFV ($rad \cdot s^{-1}$)			
2.5	5.0	5.2 (1.03)	Martin (1985)
3.35	5.4		
4.0	6.1		
4.5	5.5		
SL (cm)			
2.5	103.0		
3.35	130.8	119.5 (0.14)	Cavanagh and Kram (1985)
4.0	153.0	152.0 (.07)	Wank *et al.* (1998)
4.5	170.3		
FT (ms)			
2.5	0.11		
3.35	0.12	0.093 (0.025)	Martin (1985)
4.0	0.15		
4.5	0.15		
SF (Hz)			
2.5	2.5	2.6 (0.07)	Kyolainen *et al.* (1995)
3.35	2.7	2.7 (0.09)	Kyolainen *et al.* (1995)
4.0	2.6	2.72 (0.10)	Kyolainen *et al.* (1995)
4.5	2.8		

5.5 DISCUSSION

Discernable differences between the two running techniques were identified. Both techniques utilise the same external (gravity and ground reaction force) and internal force (muscle force), however differences occur from the timing of these forces resulting in different displacements of the runner's body and lower-limbs. Discussion of these differences follows the Gravitational hierarchical model. The Gravitational hierarchical model is included for ease of reference from chapter 3.

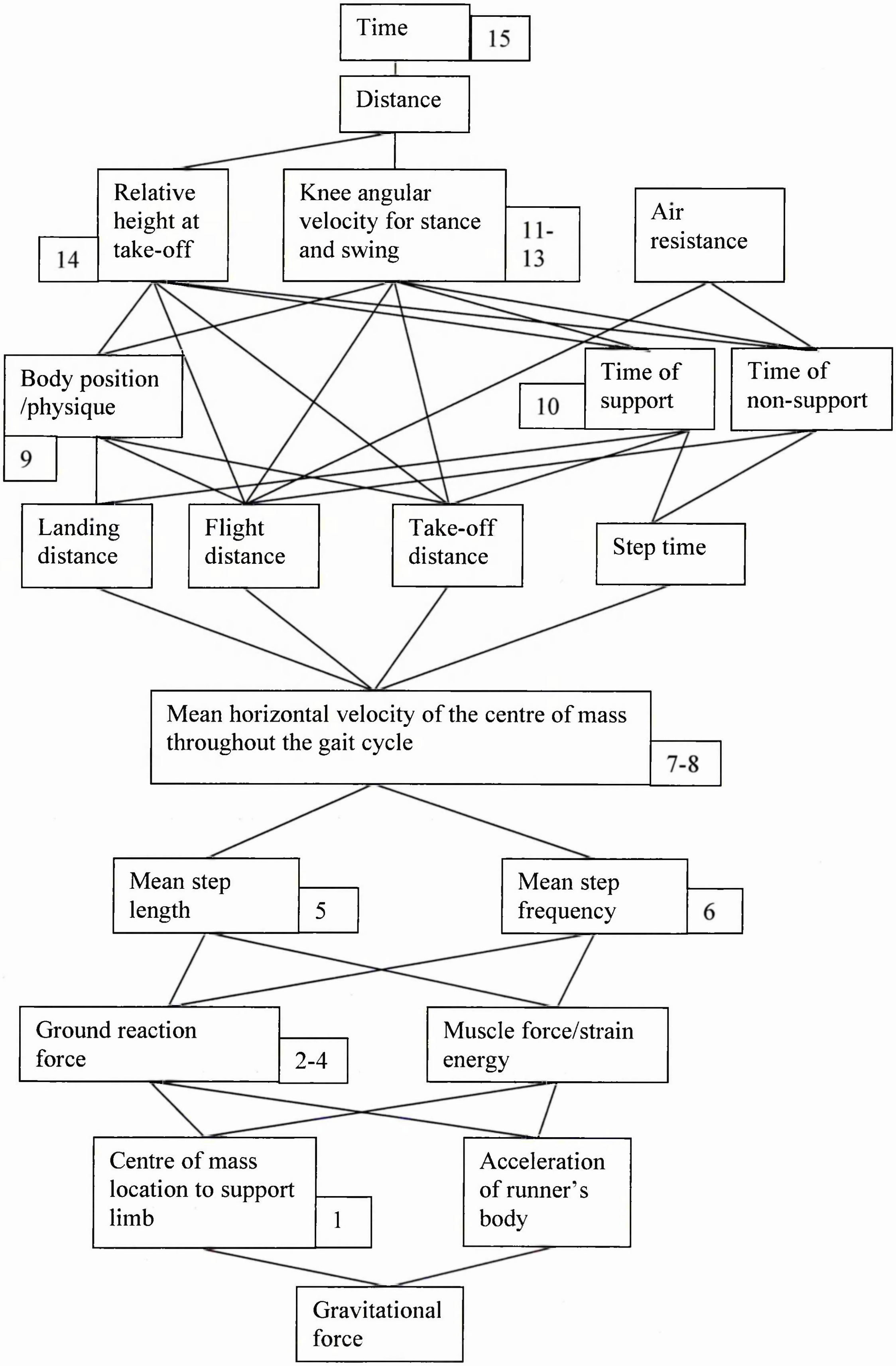


Figure 5.5.1 The Gravitational hierarchical model. A gait cycle is right foot contact to right foot toe contact of the same foot.

5.5.1 Comparison of the two running techniques using the Gravitational hierarchical model

The heel-toe runners exhibited similar profiles to those already established (see table. 5.4.4). For example, Munro *et al.*'s (1987) ground reaction force data were similar to this study at the same test running speeds. All the variables in table 5.4.4 for the experienced heel-toe runners were within one standard deviation of those found within the literature. Owing to the similarities between the experienced heel-toe runners and the literature, it seems reasonable to suggest the two experienced heel-toe participants were a good representation of the male recreational heel-toe endurance running population. The two experienced Pose® runners are also a good example of Pose® running. Arendse *et al.* (2004) recorded similar characteristics from their Pose® runners as this study's experienced Pose® runners. For example, the experienced Pose® runners were similar to Arendse *et al.* (2004) for vertical oscillation, stance time and step length.

Comparison of running techniques across the four speeds illustrates clear differences between the heel-toe and Pose® runners (table 5.4.2). Running is a full body activity so thirty-four kinetic and kinematic variables (fourteen primary research and twenty secondary research variables) were used to describe both running techniques. Table 5.4.3 depicts these variables for the Pose® runners as similar, lower or higher than the heel-toe technique. Vertical and posterior-anterior ground reaction forces and take-off velocity at terminal stance have similar maximums. The time of the propulsive ground reaction force is also similar as well as the angle of inclination of the centre of mass from the vertical axis at terminal stance. Finally, knee angle at impact and maximum swing were similar. Only five variables are higher in the Pose® runners: knee flexion angular velocity from terminal stance to maximum swing, the difference between braking and propulsive horizontal velocity of the centre of mass, horizontal acceleration of the centre of mass, hip flexion at impact plus step frequency. Twenty-one kinematic variables were lower for the Pose® runners. The proceeding discussion using the Gravitational hierarchical model highlights these differences between heel-toe and Pose® running.

Distance and time

Time measures how long it takes to run the distance for a particular event and is the performance criterion. The performance criterion is the measure used to evaluate the level of success in the performance of a sports skill (Bartlett, 1999). Notice that the hierarchical model is relevant for any running event from sprinting to marathons. The Pose® method claims to be a technique that both sprinters and marathon runners can use because both still experience a gravitational torque, whereas endurance runners predominantly use the heel-toe technique with sprinters landing on the forefoot.

Air resistance

Air resistance was not measured in-line with most other gait research (Anderson, 1996). However, strong winds change runner's technique by causing them to lean into the wind (Davies, 1980). Interestingly, Pose® running suggests forward movement is the result of a gravitational torque; by leaning forward in the wind, the torque increases via an increased moment arm.

Relative height at take-off

Vertical oscillation was 3.4 cm lower on average in Pose® runners for the mean of all the test speeds. As running speed increased vertical oscillation decreases for both techniques in-line with other research (Luhtanen and Komi, 1980; Mann and Hagy, 1980; Ito *et al.*, 1983a). Knee flexion from impact to maximum vertical ground reaction force was also lower in Pose® runners, which suggests decreased knee flexion accounts for reduced vertical oscillation. Less knee extension also correlates with lower vertical oscillation (Wank *et al.*, 1998). As the body passively extends the support knee (Mann *et al.*, 1986), having the support foot remain longer on the ground potentially increases vertical oscillation in heel-toe runners. Stance time was less in Pose® runners and knee extension was lower, possibly supporting this concept. As running speed increased, vertical oscillation of the centre of mass decreased, again suggesting leg extension is not related to running speed increases (Hunter *et al.*, 2005). In fact, the Pose® technique recorded no increases in leg extension across the endurance run speeds of 3.35-4.5 $m \cdot s^{-1}$. The heel-toe runners extend their knee and increase their vertical oscillation after maximal vertical ground reaction force until terminal stance, but they do not increase knee extension as running speed increases (4.0-4.5 $m \cdot s^{-1}$). Pose® runners have increased mean knee angular velocity from terminal stance until maximum swing as they rapidly pull the foot from the ground yet they have lower mean knee extension angular velocity during stance. This may explain why heel-toe runner's knees extend more, because they are not thinking about pulling their foot from the ground, and hence their knee passively extends further, increasing vertical oscillation. The Gravitational hierarchical model illustrates the relationship of vertical oscillation with knee flexion and extension angular velocity owing to it being on the same level in the model.

Knee flexion and extension angular velocity during stance

Enomoto *et al.* (1999) using an effective index for mechanical energy tested thirty-two participants. They found less knee flexion in the first half of stance, and lower vertical oscillation correlated with smaller reductions in horizontal velocity of the centre of mass ($P \leq 0.01$). Their fastest runners exhibited these traits (less knee flexion, lower vertical oscillation and less braking of the centre of mass horizontal velocity), which matched this study's Pose® runners. In support, Lee and Farley (1998) stated stance-limb impact angle and virtual stance-limb compression both play important roles in determining the trajectory of the centre of mass. In agreement, figure 5.5.2 clearly shows the different centre of mass's vertical displacements of the two techniques, highlighting the affect gravity has on certain body geometry. Arendse *et al.* (2004) identified ankle position also distinguished between the two techniques at impact, with the ankle dorsiflexed (-18.3° ±9.8°) in heel-toe and neutral (-0.4° ±4.9°) in Pose® running. Low work values were also found at the knee and high eccentric work values for the ankle 6.91 J/kg (±1.93) compared to 5.85 J/kg (±1.39) as heel-toe runners. This suggests the magnitude of the moment arm at the ankle in Pose® running is greater than at the knee during eccentric loading. Arendse *et al.* (2004) proposed this might be owing to a combination of the lower-limb geometry and the position of the torso at impact. Positioning of the torso over the supporting limb at impact may influence the direction of the ground reaction force in relation to the lower-limb joint centres thus increasing eccentric work at the ankle in Pose® runners. Whether running barefoot in Arendse *et al.*'s (2004) study caused increased eccentric work at the ankle in the Pose® technique or the technique itself, requires further investigation, which is outside the scope of this thesis.

Increasing running speed via knee extension lacks support (Mann *et al.*, 1986). Instead, the propulsive phase of stance is attributed to hip motion. Belli *et al.* (2002) measured peak joint ankle, knee and hip power for nine male endurance runners at speeds of 4.0 $m \cdot s^{-1}$ to 6.0 $m \cdot s^{-1}$ and at their maximal running speed. Ankle and knee joint power increased with running speed, but the highest changes were for the hip (327 ±203 W at 4.0 $m \cdot s^{-1}$ and 1642 ±729 W at maximal speed). They concluded that hip extensors are the prime forward movers as running speed increases in contrast to the knee and ankle. In support, power generation at the knee was significantly lower in Pose® runners (5.01

W/kg ±2.49) than heel-toe runners (6.27 W/kg ±1.44) (Arendse *et al.*, 2004). Arendse *et al.* (2004) found no significant increase in ankle power generation and concentric work in Pose® runners. They suggested the hip is the source of power for forward propulsion, which was likely increased in Pose® running. Novacheck (1996) noted that the contribution of knee and ankle power is minimised as running speed increases. The concept that the hip extends leading the knee and ankle joints from maximum ground reaction force to initiate or enable forward movement is actually well documented (figures 5.4.50-57; McClay *et al.*, 1990; Montgomery *et al.*, 1994; Pink *et al.*, 1994; Belli *et al.*, 2002; Hunter *et al.*, 2005). Leg extension by the forward progression of the hip passively extending the knee seems a plausible explanation. In confirmation, the hip, knee and ankle reach their maximum moments just after maximum vertical ground reaction force in sprinters and these moments were associated with impact (Mann, 1981; Biewener *et al.*, 2004). After maximum vertical ground reaction force, they decreased. This suggests joint moments are associated with impact and are not propulsive per se.

The Pose® technique suggests the body is falling via a gravitational torque from maximum vertical ground reaction force, because leg and hip muscle extensors are silent, and ground reaction force is decaying (see chapter 3). Knee extension angular velocity is lower in Pose® runners while the hip is leading the lower-limb joints extension seen clearly in figures 5.4.50-57 which time aligned the lower-limb. The Pose® technique proposes it is body weight (via a gravitational torque) leading the propulsive movement as the runner falls forwards after mid-stance, reflected by hip extension, hence the lower knee extension angular velocity in the Pose® runners.

Figures 5.5.50-57 show the two techniques time aligned. A consistent observation is knee extension has just begun at maximum vertical ground reaction force in the heel-toe runners, whereas the knee is at maximum flexion in Pose® runners. In both heel-toe and Pose® runners, the hip has consistently begun to extend before the knee, but in heel-toe runners the knee extends earlier. Perhaps the early knee extension in the heel-toe runners increases work against gravity as stated earlier through increased vertical oscillation. Leg extension of the support limb however, should be passive by using the elastic recoil and forward movement of the body. Mann *et al.* (1986) in support states: "*Knee extension which occurs during the toe-off phase of support during jogging and running is the result of the forward movement of the body over the fixed foot and tibia.*" Passive leg extension would complement the Pose® method's concept of pulling the foot from the ground rather than trying to extend the leg via the 'push-off' foot-ground contact.

Knee flexion angular velocity from terminal stance to maximum swing

Knee flexion angular velocity from just before or at terminal stance until maximum knee swing angle was higher in Pose® runners for all speeds, but particularly at the faster speeds. At the two faster running speeds, Pose® runners had 121% and 127% greater mean angular knee flexion velocity than the heel-toe runners. Pose® runners significantly increased their mean angular knee flexion velocity from terminal stance to maximum swing potentially via pulling their foot from the ground. This would bring the foot closer to a faster moving body during flight, potentially reducing angular inertia of the lower-limb (Enomoto *et al.*, 1999). Knee flexion angles are similar for both techniques at maximum swing, yet the Pose® runners reach this position with greater angular velocity, which supports a lower rotational inertia of the leg from terminal stance. The Gravitational hierarchical model therefore, attempts to reflect the lower-limb's key relationship to the centre of mass's horizontal velocity and the forces that cause their motion.

Step time

Step time consists of flight and stance time and both were less in the Pose® runners compared to the heel-toe runners. Increased stance time has correlated positively (r = 0.4; P = 0.05) with poorer running economy (Williams and Cavanagh, 1986; Williams and Cavanagh, 1987). As endurance runners become fatigued, stance times increases (Nicol *et al.*, 1991), possibly reflecting reduced elastic energy in the muscle mechanisms (Zatsiorsky, 1995; Paavolainen *et al.*, 1999a). Nicol *et al.* (1991) suggest that a time delay between the muscle stretch and the shortening action may widen when fatigued possibly reducing elastic energy. The Pose® runner's body geometry and lower-limb range of motion appear to reduce stance time, which may potentially enhance elastic energy.

Distance travelled (landing, flight and take-off distance)

Landing distance, flight distance and take-off distance represent one-step length in the hierarchical model. Several primary variables represent these distances, landing distance matches the centre of mass displacement in the horizontal direction during stance, flight distance is step length and the centre of mass horizontal displacement at terminal stance to the support limb is take-off distance. All distances were less in Pose® runners. The centre of mass horizontal displacement for Pose® runners during stance was 12.3 cm less on average across the speed range. Possibly the increased horizontal displacement travelled by the heel-toe runners decreases their horizontal velocity for their centre of mass owing to different body geometry at impact and terminal stance than the Pose® runners. Step length is lower in Pose® runners, however horizontal velocity of the centre of mass at terminal stance were similar, with a mean for all test speeds of 3.75 $m \cdot s^{-1}$ and 3.73 $m \cdot s^{-1}$ for Pose® and heel-toe runners respectively. In a legless projectile a similar horizontal take-off velocity, would produce a similar horizontal displacement. It appears heel-toe runners are extending their leg at impact to increase step length. Further, increases in the distance between the support limb and the centre of mass at impact decrease horizontal velocity, which impedes the runner's progress (Mann *et al.*, 1986). Importantly, increased stride length correlates with increased ground reaction force (Clarke *et al.*, 1985) cited as a potential injury risk (Volishin and Wosk, 1982) although not evident in this study. The Gravitational hierarchical model attempts to connect the horizontal velocity of the centre of mass and the lower-limb with the forces that cause stride length, potentially leading to a better understanding of running injury mechanisms.

Mean horizontal velocity of the centre of mass throughout the gait cycle

The mean horizontal velocity of the centre of mass for the gait cycle is divided into three phases: impact to maximum vertical ground reaction force (braking) and from this point until terminal stance (propulsion), then from terminal stance to maximum swing knee flexion angle. The heel-toe runners had consistent braking in their progression across all speeds. The Pose® runners brake less at 2.5 $m \cdot s^{-1}$ and 3.35 $m \cdot s^{-1}$ by -0.2 $cm \cdot s^{-1}$ and -7.2 $cm \cdot s^{-1}$. At 4.0 $m \cdot s^{-1}$ and 4.5 $m \cdot s^{-1}$, the differences were more marked at -14.7 $cm \cdot s^{-1}$ and -15.3 $cm \cdot s^{-1}$ respectively. Pose® runners at 4.0 $m \cdot s^{-1}$ and 4.5 $m \cdot s^{-1}$ were only braking their forward progression of their centre of mass by -2.2 $cm \cdot s^{-1}$ and -3.0 $cm \cdot s^{-1}$ respectively, compared with -12.1 $cm \cdot s^{-1}$ and -15.3 $cm \cdot s^{-1}$ at the lower speeds of 2.5 $m \cdot s^{-1}$ and 3.35 $m \cdot s^{-1}$. The more aligned position of the support limb and the centre of mass at impact, especially at the faster speeds, may explain these differences, along with the vertical alignment of the shoulder, hip and ankle in the Pose® runners. In support, Bates *et al.* (1979) showed their 400 m runner with the largest deceleration during stance also had the largest distance from the ankle to their centre of mass at impact of 0.27 m compared with 0.14 m for their runner with the least deceleration. The timing of the maximum braking force is also earlier in Pose® runners suggesting accelerations of the body in the horizontal direction are different between the two techniques at impact. Bobbert *et al.* (1992) found a backward acceleration of the lower-limb segments relative to the rest of the body just before impact. The knee marker's velocity became horizontal in the forward direction at impact, as it rotated around the now stationary ankle, because the ankle can no longer move forwards while the foot is on the ground. Further, the hip's tangential acceleration remained positive, indicating it lead the lower-limb through stance owing to the body's inertia. A lower braking effect on the horizontal velocity of the Pose® runners may reflect their distinct body geometry at impact (shoulder, hip and ankle vertical alignment).

The propulsive horizontal velocity from maximum vertical ground reaction force until terminal stance was higher at all speeds for the heel-toe runners. The differences were much larger again at the faster speeds of 4 $m \cdot s^{-1}$ and 4.5 $m \cdot s^{-1}$ with heel-toe runners having 10.2 $cm \cdot s^{-1}$ and of 9.3 $cm \cdot s^{-1}$ higher propulsive velocity respectively. An increased propulsive horizontal velocity in the heel-toe runners may reflect their swing leg being driven forwards, discussed later. Driving the swing leg forwards owing to its large mass will have a significant affect on the centre of mass's velocity. Interestingly, horizontal velocity at terminal stance was similar between both techniques. A possible explanation is the propulsive horizontal velocity—change between maximum vertical ground reaction force and terminal stance—masks a rapid acceleration in the Pose® runners as they fall utilising the gravitational torque more effectively via less vertical oscillation. In support, figures 5.4.58-5.4.61 consistently show higher horizontal accelerations of the centre of mass in the Pose® runners during the propulsive phase of stance. Further, when the differences between braking and propulsion of the centre of mass's horizontal velocity were calculated, Pose® runners show better overall propulsion, suggesting movement that is more efficient. The mean propulsive horizontal velocity (difference between braking and propulsion) across the four speeds was 16 $cm \cdot s^{-1}$ and -2.9 $cm \cdot s^{-1}$ for the Pose® and heel-toe runners respectively. By braking less, the overall horizontal velocity was positive in Pose® runners. It would seem reasonable to suggest this is more efficient, because the heel-toe runners needed to generate higher increases in horizontal velocity after maximum vertical ground reaction force potentially via driving their swing legs forwards.

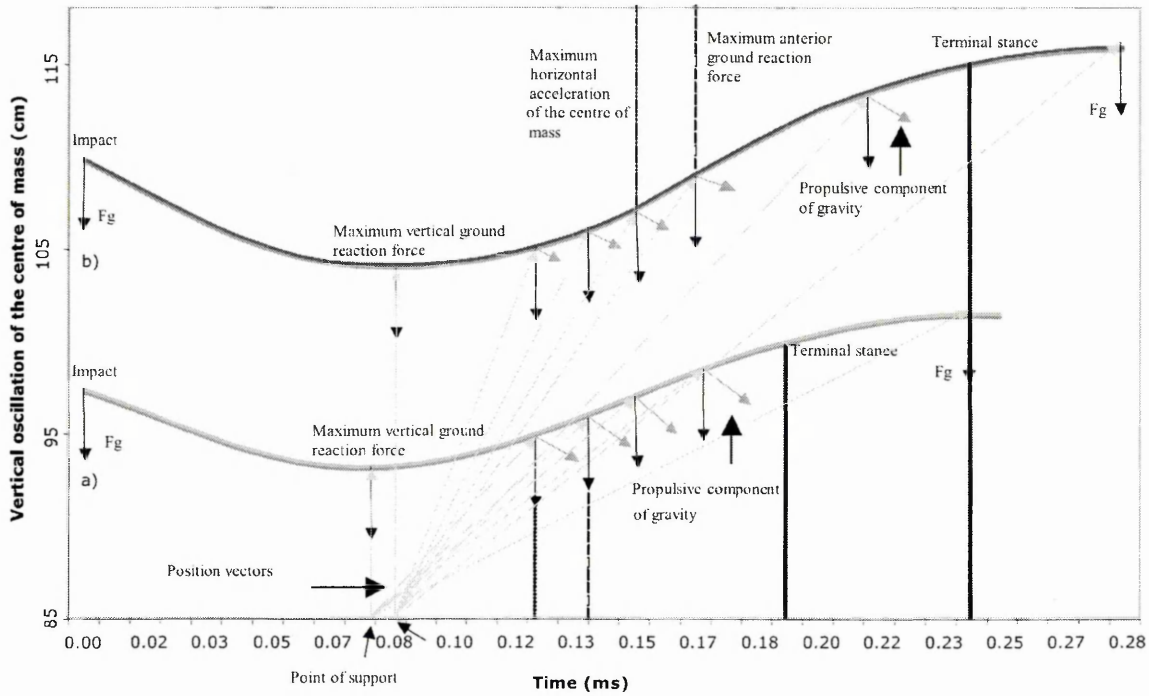


Figure 5.5.2 a) represents the vertical oscillation of a Pose® runner at 4.0 m·s^{-1}. b) represents a heel-toe runner at 4.0 m·s^{-1}.

Figure 5.5.2 illustrates gravity's acceleration on the two runners using the vertical oscillation of their centre of masses. Gravity has no affect on the horizontal velocity of the centre of mass during flight. However, while the support foot is on the ground a propulsive gravitational torque occurs from maximum vertical ground reaction force until terminal stance. The runner's vertical oscillation is from impact until maximum vertical height reached during flight. The support foot's position to the centre of mass is drawn beneath maximum vertical ground reaction force to certain points on the path of the centre of mass (light grey arrow). Both runners have their actual time of maximum horizontal acceleration of their centre of mass (dotted line) and their maximum anterior ground reaction force (dashed line) marked. Gravity's work (black arrow) on the centre of mass as it rises from maximum vertical ground reaction force via elastic mechanisms and body geometry (see chapter 3) until terminal stance is constant. However, gravity's propulsive component (dark grey arrow) changes depending upon the position of the centre of mass to the support foot (vector product: sine of the angle between gravity and the position vector). It is evident that the Pose® runner is able to utilise gravity more effectively for horizontal progression via less vertical oscillation compared to the heel-toe runner, owing to the larger propulsive component of gravity (dark grey arrow).

The maximal horizontal acceleration of the centre of mass at all speeds for the Pose® runners was higher, possibly reflecting a more effective use of the gravitational torque. Table 5.4.1 consistently shows the maximal horizontal acceleration of the centre of mass occurs before the maximum horizontal ground reaction force. This suggests the gravitational torque is the only other possible force (only two external forces in running) that could cause this maximum horizontal acceleration of the centre of mass. Further research should determine the horizontal acceleration of the centre of mass during stance using accelerated running, at a frame rate of at least 240 frames·s^{-1}. This should verify the Pose® technique and whether the Gravitational hierarchical model effectively explains running. However, the Gravitational hierarchical model does reflect the complex inter-relationship of the effects of force and body kinematics on the horizontal velocity of the centre of mass.

Mean step length and step frequency

Stride length and stride frequency commonly evaluate individual runners and their differences at various running speeds (Hogberg, 1952; Cavanagh and Williams, 1982; Martin, 1985; Patla *et al.*, 1989). Both running techniques increase their step length as running speed increases in-line with other studies (for example, Patla *et al.,* 1989). The Pose® runners have shorter step lengths than the heel-toe runners for all speeds, with the faster running speeds—4.0 and 4.5 m·s^{-1}—differences being 22.7 cm and 28.5 cm respectively. At running speeds of 2.5 m·s^{-1} and 3.35 m·s^{-1}, the differences were 19.0 cm and 11.6 cm respectively, whereas step frequency was higher at all speeds for the Pose® runners. Heel-toe runner's step frequency is similar to other gait studies (for example, Wank *et al.*, 1998; table 5.4.4). Pose® runners increased step length by 167% from 2.5-4.5 m·s^{-1} compared to 165% in the heel-toe runners. However, Pose® runners increased their step frequency from 2.5-4.5 m·s^{-1} by 121% compared to 112% in the heel-toe runners. Similar step length increases took place despite different absolute lengths, but Pose® runners increased their frequency more over the speed range.

Vertical alignment of the shoulder, hip and ankle in the Pose® runners at impact, may suggest reaching or driving the swing leg forwards in front of the body, is absent in Pose® runners. Heel-toe running emphasises driving the swing leg forwards (Williams and Cavanagh, 1987). However, Williams and Cavanagh (1987) identified less knee drive in their most economical runners. Driving the swing leg will increase step length, and may possibly affect the timing of the braking ground reaction force (Pose® and heel-toe runners braking force was 10.6% and 24% of stance respectively). Support for driving the swing leg forwards in heel-toe runners is exhibited by lower differences for horizontal displacement during flight between the centre of mass and actual step length for the Pose® runners. For example, the differences in step length and centre of mass horizontal displacement during flight between the two techniques for the four test speeds beginning at 2.5 $m \cdot s^{-1}$ were 10.4 cm; 11.1 cm; 14.4 cm; 14.9 cm respectively. As the differences during flight for step length and centre of mass horizontal displacement were lower in the Pose® runners, it suggests the actual step length differences result from the heel-toe runners driving their swing leg forwards. In addition, the horizontal displacement of the centre of mass was lower in the Pose® runners for all test speeds, suggesting their swing leg returned to the ground earlier.

Kaneko *et al.* (1987) calculated optimal step frequency for 2.5 $m \cdot s^{-1}$, 3.5 $m \cdot s^{-1}$ and 4.5 $m \cdot s^{-1}$ using the work-energy relationship. Highest efficiency occurred at step frequencies between 2.8-3.0 Hz. The heel-toe runners fall below this range (2.5-2.8 Hz) while the Pose® runners are within or above this range (2.9-3.5 Hz). Kaneko *et al.* (1987) concluded that at lower frequencies, runners' muscles must develop relatively high external power (external work) to obtain longer strides, and at higher frequencies, the power to move limbs increases internal work. It is not certain yet, which is more beneficial for performance. Increasing stride frequency for a given speed consistently increases oxygen consumption and raises heart rate (Knuttgen, 1961; Cavanagh and Williams, 1982). Dallam *et al.* (2005) found a mean increase in sub-maximal absolute oxygen cost of 3.28 (±0.36) $L \cdot min^{-1}$ to 3.53 (±0.43) $L \cdot min^{-1}$, $P < 0.01$ in their Pose® trained group, whereas this thesis found no change (see chapter 6). This studies control group (see chapter 6) and Dallam *et al.*'s (2005) exhibited no significant changes in either running kinematics or oxygen cost. The Gravitational hierarchical model suggests step length and step frequency are a consequence of the forces involved in running. From the Pose® perspective, the body falls forwards creating step length without the need to drive the swing leg forwards. In support, Novacheck (1998) recorded the pelvis and trunk tilt further forwards as running speed increases, suggesting body position is creating the increased speed. Increased body tilt, increases the gravitational torque, which potentially results in faster running (changes in stride length and stride frequency) up to a point where the angle of inclination maximises. After this theoretical point, running speed could only increase via increased step frequency.

Muscle force

Reviewing electromyographical studies on running, each study consistently found that leg and hip extensor muscle activity ceased just after maximal vertical ground reaction force as leg extension begins supporting the 'extensor paradox' (Brandell, 1973; Mann and Hagy, 1980; Paré *et al.*, 1981; Schwab *et al.*, 1983; Nilsson and Thorstensson, 1985; Montgomery *et al.*, 1994; Heise *et al.*, 1996). Montgomery *et al.* (1994) recorded eleven-gait muscles for jogging, training and race pace. They found similar activity patterns at each speed with a general trend for increased activity as running speed increased. They determined the loading phase began at impact and continued until the centre of mass passed in front of the knee. The quadriceps muscle group were all maximally active up to this point to stabilise the knee. The biceps femoris muscle demonstrated an increase in activity as the centre of mass passed the knee, which they suggested initiated hip extension. Another possible explanation is the lower-limb extends because the body is moving forwards. Therefore, leg extension does not cause the centre of mass to pass forwards of the knee, rather the hip passively extends via inertia of the body activating the biceps femoris muscle (muscle lengthens via hip extension). Of the eleven gait muscles, only one muscle was significantly active after the centre of mass passed the knee until terminal stance: the iliacus muscle. Their conclusion was hip flexion during early and middle swing and knee extension during late swing provided forward propulsion, rather than knee or ankle extension at terminal stance. The Pose® technique, however, regards hip extension during stance's propulsive phase as a consequence of a gravitational torque, because the limbs during flight cannot horizontally (or vertically) displace the centre of mass. Montgomery *et al.* (1994) also noted eccentrically contracting muscles at impact (i.e. the rectus femoris, vastus intermedius and short and long head of biceps, semimembranosus) may have increased risk of injury at faster running paces. Pose® runners had lower knee eccentric work of 17 J/kg (0.08) than when they ran heel-toe 46 J/kg (0.15) (Arendse *et al.*, 2004), whereas they had an increase in eccentric ankle work 36 J/kg (0.9) and 43 J/kg (1.5) respectively.

Mero *et al.* (1992) recorded electromyography for the rear leg at the sprint start. The biceps femoris recorded peak activity at terminal stance while other muscles were virtually off, except for minimal activity from the rectus femoris. This potentially indicates that the rear leg is pulled-out (knee flexion) of the block because the leg extensors are not active and knee flexion is occurring via the hamstring group. It is plausible if a sprinter can pull his leg out of the blocks, then Pose® runners could be pulling their feet from the ground. In support of this concept, knee angular flexion velocity from terminal stance until maximum swing is 17% higher in Pose® runners for the mean across all test speeds. Further, leg extension angular velocity during stance is 13% lower in the Pose® runners. It appears the Pose® runners do not forcefully extend their legs, yet they powerfully flex their knees from terminal stance until maximum swing, which strongly suggests a pulling action.

The stretch-shortening cycle enhances muscle force output; however, muscle electromyography for leg extensors after maximum vertical ground reaction force reduces rapidly (Komi, 2000). A possible explanation for this dichotomy, is the muscles that extend on landing which enable a pre-stretch such as ankle and knee extensors, both interestingly have long tendons (Achilles and patella tendons) that are excellent storage sites for elastic strain energy (Alexander and Bennet-Clark, 1977). Efficiency of movement is possible because elastic mechanisms do not require adenosine triphosphate breakdown. During eccentric contraction, the cross-bridges forcibly detach and reattach without adenosine triphosphate splitting (Curtin and Davies, 1974). The stored elastic strain energy subsequently releases in the concentric muscle phase beginning at or just after maximum vertical ground reaction force (Farley and Ferris, 1998). The leg then acts as a spring allowing extension, but not from muscle contraction (owing to a lack of muscle activity reflected by electromyography at this time), although tension remains in the musculotendinous junctions (Edman, 1979). Further, vertical ground reaction force is decaying from its maximum point until terminal stance (body is rising off the ground), while elastic recoil acts in a predominantly vertical direction (angle of inclination at terminal stance is 70° to the horizontal), reducing work against gravity. Whether Pose® runners are more effective in utilising strain energy is unknown at this time. Muscle force and muscle elasticity are hierarchically above gravity in the Gravitational model, because gravity (body weight) causes the timing of their activity at impact as they absorb landing and as the gravitational torque accelerates the runner after mid-stance muscle activity ceases.

Ground reaction force

Mean braking ground reaction force was 0.23 body weights for Pose® and heel-toe runners across all four speeds. The mean time for the braking posterior ground reaction force across all speeds, as a percentage of stance was 10.6% for Pose® and 24% for heel-toe runners. Horizontal distance of the centre of mass from the support limb and running speed at impact affects impact force (Mero *et al.*, 1992; Hay, 1994). The time of braking force is earlier in Pose® runners, possibly reflecting the shorter distance the centre of mass was behind the support limb at impact via a more vertically aligned posture (Hamill *et al.*, 1983). Unshod Pose® runners had a lower braking force than their heel-toe running trials of 113.7 N (15% body weight) and 148.7 N (20% body weight) respectively (Arendse *et al.*, 2004). Munro (1984) recorded 25% body weight at a similar running speed of 3 $m \cdot s^{-1}$ in shod runners. Presently it is uncertain whether shoes or running technique, cause differences in the posterior ground reaction force.

Maximum vertical ground reaction also revealed almost similar bodyweights—2% difference—for both techniques across all test speeds. Frederick and Hagy (1986) found body mass accounted for 90% of maximum vertical ground reaction force. Chang *et al.* (2001) using reduced gravity with a specially designed harness for treadmill running reduced gravity to 0.5 g, 0.38 g and 0.25 g. Maximum vertical ground reaction force reduced from 1495 (100) N at Earth's gravity to 848 (58) N, 664 (40) N and 463 (39) N at the reduced gravity respectively. Clearly, gravity significantly affects maximum vertical ground reaction force. Chang and Kram (1999) applied a horizontal force of 10%, 15% and 20% of gravity specific body-weight to his runners. Interestingly, maximum vertical ground reaction force barely changed with the applied horizontal force, suggesting maximum vertical ground reaction force is weight related and thus caused by gravity.

Maximum vertical ground reaction force and vertical oscillation of the centre of mass were time-aligned (figures 5.4.50-57). In both techniques, maximum vertical ground reaction force aligns with the lowest point of the centre of mass (Cavanagh and LaFortune, 1980; Bobbert *et al.*, 1991; Derrick *et al.*, 2000). The ground reaction force curves decays from this point until terminal stance as the knee extends. The 'extensor paradox' (McClay *et al.*, 1990) identifies a lack of muscle activity as the knee extends from just after maximum vertical ground reaction force until terminal stance. If the lower-limb extensor muscles were active, a spike or plateau would be evident in the vertical ground reaction force curve (see Yeadon and Challis, 1994; figure 3.3.14, p. 84). However, ground reaction force curves for all techniques of running have a smooth decay rate. Similar to gravity's work on landing as weight is absorbed (force curve increases) until maximum vertical ground reaction force, the decay rate from this point until terminal stance reflects the body leaving the ground (centre of mass is rising).

Therefore, as the runner's body leaves the ground (rises by muscle elasticity/body geometry) the runner falls forwards via a gravitational torque, while ground reaction force reduces. In fact, at faster running speeds, the decay rate increases (Miller 1990), reflecting faster falling.

Propulsive ground reaction force may reflect the body pivoting around the foot as the runner leaves the ground without the foot actually pushing backwards (Mann *et al.*, 1986; Miller, 1990). If the foot pushed backwards, leg extension would begin at the ankle and not the hips (figures 5.4.50-57; Mann *et al.*, 1986; Montgomery *et al.*, 1994; Riley *et al.*, 2001; Belli *et al.*, 2002). The propulsive anterior ground reaction force occurred at 72% and 74% of stance in Pose® and heel-toe runners respectively, with a mean of 0.17 body weights recorded for both heel-toe and Pose® runners. The angle of inclination (producing the moment arm) for the centre of mass at terminal stance were also similar for both techniques possibly adding support that the gravitational torque is the motive force owing to the similar running speeds. Hunter *et al.* (2005) using 28 sprinters at 8 $m{\cdot}s^{-1}$ grouped them into high and low propulsion trials. They found the high propulsion trials increased propulsive impulse (0.37 $m{\cdot}s^{-1}$ to 0.33 $m{\cdot}s^{-1}$ for low propulsion), expressed relative to body mass, thus reflecting the change in velocity. It is possible that the faster running speeds produce increased friction from a faster body motion, rather than an increased pushing off the ground. Further, Hunter *et al.* (2005) using multiple linear regression to predict sprint velocity, found relative propulsive impulse explained 57% and relative braking impulse 7% of the variance in sprint velocity. Ground reaction force is a reflective (reactive) force with leg extensor muscles silent during the propulsive phase of stance; ground reaction force must be decreasing. This suggests a gravitational torque causes the ground reaction force trace, owing to a lack of any other force at this time (see chapter 3 for more a more detailed explanation).

Chang *et al.* (2000) reduced gravity by 0.75%, 0.50% and 0.25%, which reduced braking and propulsive ground reaction force as well as the horizontal impulse significantly. Conversely, when they increased gravity and inertia by 130% of body weight, propulsive ground reaction force increased and the horizontal impulse increased by 28%. However, increases in inertia only of 130% of body mass increased horizontal impulse by only 10%. This clearly suggests gravity (in relation to a gravitational torque) has a strong relationship to propulsive ground reaction force (18% change in horizontal impulse). This potentially explains the 'extensor paradox' (silent leg extensor muscles during the propulsive phase of stance) owing to gravity's strong relationship to propulsive ground reaction force rather than muscle activity. Further, Chang *et al.* (2000) used the same test speed for all gravitational conditions, and found the angle of inclination at impact and terminal stance were the same. This suggests the gravitational torque and the propulsive ground reaction force are related, because similar changes in gravity cause reciprocal reductions in the propulsive force. These reductions however, do not change the angle of inclination, because this appears directly related to maintaining their constant running test speed across all conditions of 3.0 $m \cdot s^{-1}$. Chang *et al.* (2000) concluded that gravity and not inertia has a major influence over both vertical and horizontal ground reaction force generation during running. In agreement with Chang *et al.* (2000), the Gravitational hierarchical model shows gravity affecting ground reaction force via body position.

Acceleration of the body

Maximum horizontal acceleration of the participant's centre of masses showed only one trial at 2.5 $m \cdot s^{-1}$ for the Pose® and heel-toe runners occurring after the propulsive horizontal ground reaction force. Despite difficulties in obtaining acceleration from position data, it appears that maximum horizontal acceleration does not occur at maximum horizontal ground reaction force or just after it, but rather before. Further research should verify these findings, because a large horizontal acceleration without a corresponding horizontal force is not possible. The Gravitational hierarchical model suggests the horizontal acceleration is caused via a gravitational torque and the ground reaction force reflects the work of gravity on the runner's body.

The heel-toe runners increased vertical oscillation of the centre of mass from maximum vertical ground reaction force until terminal stance increases work against gravity, which potentially reduces their gravitational torque. The Pose® runners consistently produced higher horizontal acceleration of the centre of mass coupled with less vertical oscillation. The Gravitational hierarchical model links gravity's work on the runner by identifying the centre of mass location in reference to the support limb. As the centre of mass moves anterior to the support limb a gravitational torque ensues. Pose® runners appear to utilise the gravitational torque more effectively through lower vertical oscillation and a faster leg recovery (less leg extension).

Centre of mass location to the support limb

At impact with the ground taken at 25 ms of stance to allow for potential differences in vertical impact (Arendse *et al.*, 2004), noticeable variations were found for the centre of mass position in relation to the point of support. Vertical alignment—centre of mass more vertically aligned to the support foot—in the Pose® runners was 7 cm less (more aligned) at 25 ms for the mean of four speeds compared with the heel-toe runners. In fact, as running speed increased this distance decreased in both Pose® runners and heel-toe runners possibly indicating it is beneficial to do so. Hunter *et al.* (2005) in support, found at impact the distance between support and the centre of mass was lower for runners with a reduced braking impulse.

Shoulder, hip and ankle vertical alignment at 25 ms after impact also showed more vertically aligned Pose® runners—8 cm less for the mean of four speeds—with this difference becoming more marked as running speed increased. Shoulder, hip and ankle vertical alignment resembles a coiled spring because of the body's 'S' like shape, which Pose® runners are trained to land in. Lee and Farley (1998) referred to the centre of mass progression in running as similar to a bouncing ball. Perhaps this landing body geometry aids in enhancing elastic mechanisms. Further, the body cannot move forward until the centre of mass passes over the support foot (ball of the foot). Therefore, a more aligned body position at impact enables the runner's centre of mass to pass more quickly over the support foot. This would suggest Pose® runners conserve momentum, because the centre of mass's difference between braking and propulsive horizontal velocity was positive in the Pose® runners (table 5.4.2).

The horizontal distance from the centre of mass to the toe-marker at terminal stance was less in Pose® runners for all speeds except 2.5 $m \cdot s^{-1}$. The angles of inclination of the centre of mass from the vertical axis at terminal stance were similar in Pose® and heel-toe runners (mean of four speeds 20.4°: 21.2° respectively). If the angle of inclination is similar and the horizontal distance less in Pose® runners, the heel-toe runners must have more extended legs at terminal stance, which is in fact the case. The maximum acceleration of the centre of mass was higher in the Pose® runners. This suggests that despite similar angles of inclination, the Pose® runners accelerate more from maximal vertical ground reaction force until terminal stance. Less knee extension in the Pose® runners, therefore, may facilitate increased horizontal acceleration via a gravitational torque. A clear link between the lower-limb's flexion and extension angular velocity and the centre of mass's displacement is therefore evident (Farley and Gonzalez, 1996).

Gravitational force

As an external force causes motion, the Gravitational hierarchical model identifies gravitational force as the leading cause of movement because the ground and muscle system do not cause propulsion (Zatsiorsky, 2002; p.51). Several body weights are recorded at impact with the ground after flight in running, reflecting gravity's work on a runner's body mass, with both techniques—heel-toe and Pose®—being equally affected (Bobbert *et al.*, 1991). Flight is predominately spent in descent, because maximum vertical oscillation occurs at or just after terminal stance (Fenn, 1930; Cavanagh *et al.*, 1977). There are, however, differences in landing posture between the two techniques, so the impact effects of gravity's work on the runners will vary. The body continues to lower after impact under gravity's work until maximum vertical ground reaction force as the centre of mass reaches its lowest position (Cavanagh and Lafortune, 1980; Bobbert *et al.*, 1991). Immediately after this as the centre of mass passes anterior to the support limb (ball of the foot), the two techniques again show significant variations (figures 5.4.50-57) in movement as a gravitational torque potentially accelerates the runner's body to terminal stance and into swing as the cycle is repeated again. Interestingly, the Pose® runners had lower propulsive velocity, which is more marked at the faster speeds. However, the Pose® runner's angle of inclination and horizontal velocity at terminal stance was similar to the heel-toe runners. A possible explanation for these apparently conflicting results is that Pose® runners have lower vertical oscillation coupled with less leg extension. Therefore, the Pose® runners do less work against gravity and hence are potentially more able to utilise the gravitational torque to their advantage (see chapter 3; figure 3.3.11) gaining an increased horizontal acceleration of their centre of mass. In support, Gracovetsky (1988) recorded legless participants walking on their ischiums by keeping normal spinal motion (spinal engine theory) and electromyography patterns for the trunk musculature. Spinal engine theory promotes the central role of gravity as the motive force for legless locomotion, illustrating gravity's potential for forward progression.

5.6 SUMMARY

Pose® and heel-toe runners had similar ground reaction forces. The time of braking and the vertical ground reaction force were earlier in the Pose® runners. Propulsive ground reaction force occurred at a similar percentage of stance time. Horizontal velocity of the centre of mass was lower in Pose® runners for braking and propulsion, while the angle of inclination of the centre of mass at terminal stance increased. Vertical displacement and horizontal displacement of the centre of mass were lower in Pose® runners. Their body was more aligned at impact; with knee flexion and extension during stance being lower in the Pose® runners. Knee angle at impact was the same but at maximum vertical ground reaction force it was lower in the Pose® runners. Stance time, flight time and step length were lower, while stride frequency was higher in Pose® runners. Mean knee flexion and extension angular velocity were lower during stance, whereas mean angular knee flexion velocity during swing was higher. Pose® runners therefore, exhibit very different gait characteristics to traditional heel-toe runners. It was argued, that leg extension did not propel the runner forwards, while using hip motion, it was implied that a gravitational torque creates forward progression. Support included silent leg and hip extensor muscle activity, decaying ground reaction force, an increased propulsive component of gravity in Pose® runners and the hip leading the lower-limb joints extension during the propulsive phase of stance. Joint moments were maximal at maximum vertical ground reaction force and therefore, not related with propulsion. Ground reaction force reflects gravity's work as the body leaves the ground because the lack of muscle activity during propulsion coupled with reducing ground reaction force suggests a gravitational torque is the motive force. Both heel-toe and Pose® runner's maximal horizontal acceleration occurred before their horizontal maximal ground reaction force, suggesting a gravitational torque by default is the motive force in running. It appears that both heel-toe and Pose® running techniques fall forwards via a gravitational torque, suggesting that these runners do not push off the ground. It was proposed that owing to lower vertical oscillation Pose® runners used the gravitational torque more effectively. The research variables were therefore, able to clearly explain the Pose® technique and the Gravitational hierarchical model. Whether Pose® running is effective at improving performance or reducing injury is discussed in the next chapter.

CHAPTER 6

POSE® METHOD TRAINING STUDY

6.1 INTRODUCTION

A review on the importance of improved running economy an optimal biomechanical profile and injury reduction is given. This study then seeks to apply the Pose® technique (Romanov, 2002) of running to eight male endurance runners and compare it with eight heel-toe runners using the primary and secondary research variables from chapter 3 and 5. The intervention of the Pose® method technique applied for 7-hours over seven days, will seek to improve performance. This chapter therefore, aims to review the biomechanical changes (optimal biomechanical profile) from a Pose® method intervention, and their affect upon performance, running economy and injury incidence.

6.2 THEORETCIAL BACKGROUND

Three parameters affect running performance: economy, an optimal biomechanical profile and sustaining an injury (Williams, 1985). Each parameter is reviewed in reference to how it may improve running performance.

Endurance runners are an array of shapes and sizes, which influences their running economy (Bergh *et al.,* 1991). From a survey of 1,468 male endurance runners, the mean stature was 176.5 cm and body mass was 65.8 kg, but stature ranged from 152-197 cm and body mass from 40-100 kg (Frederick and Clarke, 1981). In animals, size also has a dramatic affect on running economy; a mouse uses twenty times the energy of a pony to run a mile (Taylor, 1994). There has been substantial research on the energy cost of running and differing body mass (for example, Oyster and Wooten, 1971; Bale *et al.,* 1986). Their conclusions on endurance running attribute running economy to the effects of stature and body mass. Running economy's relationship with stature and body mass relates to the Froude number. The Froude number links running speed to gravity (body mass) and leg length (stature), suggesting gravity as an external force plays a significant role in running performance. If speed of locomotion increases and leg extension at terminal stance remains the same as speed increases (Hunter *et al.*, 2005), then gravity is the only mechanism that can increase running speed. However, gravity is a constant force. In order for gravity to increase running speed, gravity must be able to work in such a way as to increase its affect on the runner. Gravity's increased affect on running speed must be the result of the angle of inclination of the body (creating a gravitational torque) during the propulsive phase of stance (see chapter 3, 5).

Williams and Cavanagh (1987) identified that 54% of the variance in running economy was attributed to biomechanical variables. Examining the affects of technique on running economy identified several related biomechanical factors (Williams and Cavanagh, 1987). For example, running economy has been associated with a freely chosen stride frequency and length (Cavanagh and Williams, 1982). It has also been related with lower vertical oscillation (Cavanagh *et al.*, 1977), earlier co-activation of hamstring and gastrocnemius muscles during the support phase (Heise *et al.*, 1996), and reduced plantar flexion occurring at higher speeds during foot removal (Williams and Cavanagh, 1987). Lower vertical oscillation and less plantar flexion would reduce work against gravity and therefore, enhance the effects of the gravitational torque on the runner.

Miura *et al.* (1973) suggested, technique attributed to the differences in running speed—5.6 $m \cdot s^{-1}$ to 5.2 $m \cdot s^{-1}$—for their participants running with the same maximum oxygen uptake of 70 ml/kg·min. Their faster runners all had a greater angle of inclination (34°) of the body at terminal stance compared with their poor runners (31.8°). An increased angle of inclination produces an increased moment arm for gravity from the centre of mass to the support foot, which increases the gravitational torque potentially increasing running speed.

Several studies attempted to modify running economy by manipulating running technique directly via stride length (Cavanagh and Williams, 1982, Petray and Krahenbuhl, 1985; Kaneko, 1987, Morgan *et al.*, 1994). However, these studies failed to achieve a significant change in either running technique or economy. In contrast, Dallam *et al.* (2005) was successful in producing significant changes in triathletes' biomechanical profiles by employing the Pose® technique using twelve hours of instruction. Elite triathletes in the British Olympic squad via anecdotal reporting (Chris Jones: head coach) were able to improve their running times by employing the Pose® technique. The mean improvement in their 10-km personal best times for two males and two females during the 2003/04 season was 108.5 s, although the mechanisms for this improvement remain unclear. This present study will aim to identify the potential biomechanical changes and their effects on performance.

Cavanagh and LaFortune (1980) found a mean decrease in the horizontal velocity of the centre of mass of 0.18 $m{\cdot}s^{-1}$ during the braking phase for seventeen participants running at 4.47 $m{\cdot}s^{-1}$. If the foot lands further ahead of the centre of mass at impact, an increased braking effect can occur (Fenn, 1930; Deshon and Nelson, 1964; Cavanagh *et al.*, 1977; Bates *et al.*, 1979; Kunz and Kaufman, 1981; Girardin and Roy, 1984; Hinrichs, 1990). Impact patterns also affect stance-limb impact angles at the hip, knee and ankle, via the kinetic chain (Bartlett, 2000), which subsequently alter the centre of mass vertical displacement (Lee and Farley, 1998). Lower-limb angles, vertical oscillation of the centre of mass and foot position at impact, therefore, have an important relationship to reductions in horizontal velocity of the runner and consequently performance.

Miura *et al.*'s (1973) good runners exhibited a longer stride length of 1.77 m compared to their poor runners of 1.60 m over a 5-km race, while stride-time was similar. In contrast, Cavanagh *et al.* (1977) found their good runners took shorter strides with a higher frequency in comparison to poorer runners. Possible differences may reflect the fact that Cavanagh *et al.*'s (1977) study was conducted on a treadmill where ten strides were filmed after ten minutes of running at 4.47 $m{\cdot}s^{-1}$, whereas Miura *et al.*'s (1973) runners ran 5-km on a track at 5.2-5.6 $m{\cdot}s^{-1}$. It is currently not lucid whether runners should have longer strides or higher frequency.

Dallem *et al.* (2005) found a significant reduction in their Pose® group in vertical oscillation in comparison to the control group at a given treadmill velocity following the Pose® method intervention. Although not statistically significant, the Pose® group recorded reductions in mean hip to ankle distance at foot strike (more vertically aligned body position) and lower support time. However, the modifications in running biomechanics elicited by the Pose® method intervention were also associated with a significantly increased submaximal oxygen cost (a 4.2 ml/kg/min increase in steady state oxygen cost at 215 m·min following the instructional period). This may be owing to the fact that the majority of the participants were experienced enough to have already developed their most economical self-selected stride rate. Notably one of the eight Pose® group participants did demonstrate an improvement in economy following the instructional period. He was the least experienced triathlete/runner in the group with a two year training history in running and triathlon, as well as having the lowest initial stride rates (2.6 steps·s^{-1} at 215 m·min and 2.8 steps·s^{-1} at 250 m·min). This participant may not have been experienced enough to have developed his most economical freely chosen stride length before the study allowing him to possibly respond more favorably to the instruction. The mean increase in running economy of approximately 8%, should substantially affect running performance in their Pose® group. However, the Pose® group in Dallem *et al.* (2005) also demonstrated a similar perceived exertion during the pre and post steady state trial speeds (RPE = 11.3 $\pm$ 2.1 versus 11.0 $\pm$ 1.8 and 14.5 $\pm$ 1.6 versus 14.7 $\pm$ 3.1). They suggested the increase in steady state oxygen cost on the participant's steady state rate of perceived exertion may have been negated by a reduction in the muscular activation associated with each individual step (reduced stride length and increased stride frequency).

Dallam *et al.*'s methodological design may have also attributed to the increase in running economy. The running economy data was collected after the lactate threshold and maximum oxygen consumption tests. Further, biomechanical data was acquired after the physiological tests when all the participants were in an extremely fatigued state. The data were also collected on a treadmill, which pulls the foot backwards. The pulling back of the foot significantly affects Pose® running technique because the foot should be pulled directly upwards in Pose® running not backwards. It is unlikely the Pose® group were able to maintain their new technique when fatigued while on a treadmill, which could have affected the results. Therefore, this study aims to collect oxygen consumption in a non-fatigued state during over-ground running, to determine, if the Pose® technique does in fact improve running economy. Dallam *et al.*'s (2005) study did not include a performance test. This present study will include a 2400 m time trial to determine if Pose® running improves performance from the potential biomechanical changes.

The Pose® technique has also made claims that it reduces running injuries (Romanov, 2002). Pose® runners land on the forefoot, however, forefoot running is not associated with a lower risk of injury (Cavanagh and LaFortune, 1980). Arendse *et al.* (2004) trained twenty heel-runners in Pose® running. They found Pose® running was characterised by a shorter stride length, lower vertical impact force, a greater knee flexion in preparation for and at initial contact, less eccentric work at the knee and more eccentric work at the ankle compared with heel-toe and forefoot running. They proposed the position of the torso during the gait cycle may explain the reduced knee eccentric work and increased ankle eccentric work in Pose® running compared with the heel-toe running technique. They suggested that the position of the torso and the centre of mass should be included in future studies of running technique modification. This present study will measure the centre of mass position and velocity including torso position during the gait cycle.

Arendse *et al.* (2004) evaluated their runners in the barefoot condition, to which they were not habituated. Although standard to all test conditions, the barefoot condition may prevent the adoption of a conventional heel-toe running technique. Runners protect the heel during barefoot running and reduce distortion of the heel fat pad (De Wit and De Clercq, 2000). Subsequently, initial contact occurs predominantly with the anterior portion of the foot. Their horizontal braking and propulsive ground reaction forces differed between Pose® and heel-toe running in contrast to this thesis (chapter 5). Pose® running also produced significantly smaller vertical displacement of the body, the feet were kept close to the supporting surface with a shorter stride length compared with heel-toe running. However, Arendse *et al.* (2004) collected no injury data post intervention to determine if these Pose® running changes reduced injuries.

The aim of this present study is to measure via an economy and time trial run the participant's pre-test baseline physiological measures while the primary research variables will provide a biomechanical profile. The post-test will determine whether there is an improved performance on the economy and 2400 time trial run resulting from the potential biomechanical changes in the Pose® group from a 7-hour Pose® training intervention. A 3-month post intervention survey for any injury incidence will follow for all participants.

6.3 METHODS

Participants

Sixteen recreational male heel-toe runners and triathletes were recruited for this study. The heel-toe group (n = 8) and the Pose® group's (n = 8) personal information are recorded in table 6.3.1. Written informed consent and ethical approval from Sheffield Hallam University were obtained before testing. All participants had no history of surgical intervention, chronic pain, orthotic use or current pathology of the lower extremity, except one participant from the heel-toe group post-test who had sore ankle musculature. Each participant wore his normal running shoes. All shoes were qualitatively assessed for rigidity of the heel counter and compliance of the cushioning element of the rear section of the shoe.

Table 6.3.1 Participant's personal data (N = 16)

Group	Age (yrs)	Stature (cm)	Mass (kg) Pre	Mass (kg) Post	10-km P.B. time (min)
Heel-toe Group					
Range	18-27	174-193.5	65.3-100.5	65.3-100.5	38-45
Mean	20.8	180.2	82.3	82.0	41
S.D.	3.6	6.2	11	10.9	2.1
Pose® Treatment Group					
Range	19-24	173-189	71.4-85.7	69.4-85.7	38-45
Mean	21.1	180.9	76.9	76.5	40.6
S.D.	1.7	5.2	5.4	6.7	2.8

Experimental protocol (see appendix 1 for participant recruitment)

All participants were pre-selected before testing via personal contact. All respondents were selected based on the following criteria: 1) they had been without injury in the past 3-months. 2) They had been running for at least 2-years. 3) No-one in the study had read or heard anything about the Pose® method of running. 4) They were heel strikers, 5) sub-elite runners (37-45 minute 10-km P.B.), 6) male, 7) and aged between 18-30 years old. 8) The pre-selection meeting finalised whether a participant was accepted into the study. Two participants were rejected from the study based on the study criteria. Sixteen participants were available for the study dates and divided into two groups of heel-toe and Pose® treatment runners. The participants were randomly distributed through an equal bias towards running technique from the pre-test questionnaire scores (table 6.4.4). All participants were tested on two separate occasions in a pre-post test design.

Track test (see appendix 2 for track data collection sheets)

The track pre-tests were held between May 24th and 25th, 2003 where all the participants ran a 2400 m economy run followed immediately by a 2400 m time trial on a running track at Loughborough University. The post-test track tests took place on June 6th 2003. After a self-selected warm-up a 2400 m economy run was collected at 8 min per mile pace. Mean heart rate, oxygen consumption via a Cosmed/K4b2, stride rate, and time were recorded. The Cosmed/K4b2 was found to have a 2% measurement error, and, Kawakami *et al.* (1992) recommended it as a powerful measurement tool for the field with strong correlation to values obtained from a metabolic cart (McLaughlin, *et al.*, 2001; Pinnington *et al.*, 2001). To ensure participants ran constantly at 8 min per mile orange pace cones were placed at each 100 m segment of the track. Each 100 m section took them 30 s, which the participants checked using a hand-held stopwatch. Stride rates were determined from a digital video recorder (DCR-TRV, Sony Corporation, Japan) which filmed at 25 frames$\cdot s^{-1}$ 20 m of the home straight for each lap of their economy and time trial run. For the 2400 m time trial that followed immediately after the economy run, mean and maximum heart rate, stride rate, Borg (Borg, 1970) scores and time were collected. No verbal encouragement was given during the time trial. In trained, non-elite runners, the coefficient of variation for economy ranges from ±2.64% in 95% of all trials for field tests of 1600 to 2400 m (Morgan *et al.*, 1991). They concluded a stable measure of running economy can be obtained in a single data collection session involving trained non-elite male runners if the testing environment is controlled to minimise non-biological variability.

The laboratory tests (see appendix 3 for laboratory data collection sheets)

A printed itinerary was given to each participant before their test date covering procedures and test times. Before the start of the test, each participant was given a verbal explanation of the test procedures. Every participant warmed up for as long as needed. All participants wore their own running flats for both pre and post-tests. Participants were asked to maintain normal weekly training activities. The laboratory pre-tests were held between May 26th-29th, 2003 and required each participant to run across a force plate at 3.35 $m\cdot s^{-1}$ (8 min per mile pace) while simultaneously recording kinematic data. The post-tests were held between June 9th–11th, 2003.

The intervention (see appendix 4 for intervention sheets)

Both interventions were held between May 30th and June 5th. The Pose® group received seven one-hour daily intervention sessions in the Pose® method of running technique by a trained and experienced Pose® instructor. The heel-toe group were to complete seven intervention sessions of traditional running drills and interval repeats on their own. Both interventions required the participants to complete a series of specific drills each day. The heel-toe group were trained to drive the leg forwards and to push-off the ground in bounding movements using traditional running drills such as butt kicks, high knee lifts and kick outs. The Pose® group using many specific drills were taught to use their body weight to create speed through falling forwards while pulling their foot from the ground using their hamstring muscles.

Collection and processing of ground reaction force data

Biomechanical data were collected using a piezoelectric transducer force plate with eight output signals, which were sampled at 1200 Hz (9281-CA Kistler Instruments Corporation, Winterthur, Switzerland). The force plate was mounted flush with the running surface on a 15.66 m runway. The force plate was 8.66 m from the start position and measured 40 by 60 cm (figure 6.3.1). Participants were instructed to run normally while aligning their run-up to land with their right foot on the force plate. Each participant was allowed as many practice trials as needed to achieve 'normal' foot contact with the plate in their regular running shoes, with five trials collected. After each trial, the data was visually inspected to ensure that the footfall was 'normal' and centred on the force plate. After data collection, the ground reaction force analogue data was processed through Matlab 6 software to convert volts into newtons. In accordance with Munro *et al.* (1987), ground reaction force data were normalised to the participant's body weight. Initial contact of the foot with the ground was identified from the ground reaction force data. Foot contact began once the vertical ground reaction force data exceeded 20 N and ended as it went below 20 N (Bobbert *et al.*, 1991; Wright *et al.*, 1998; Tirosh and Sparrow, 2003).

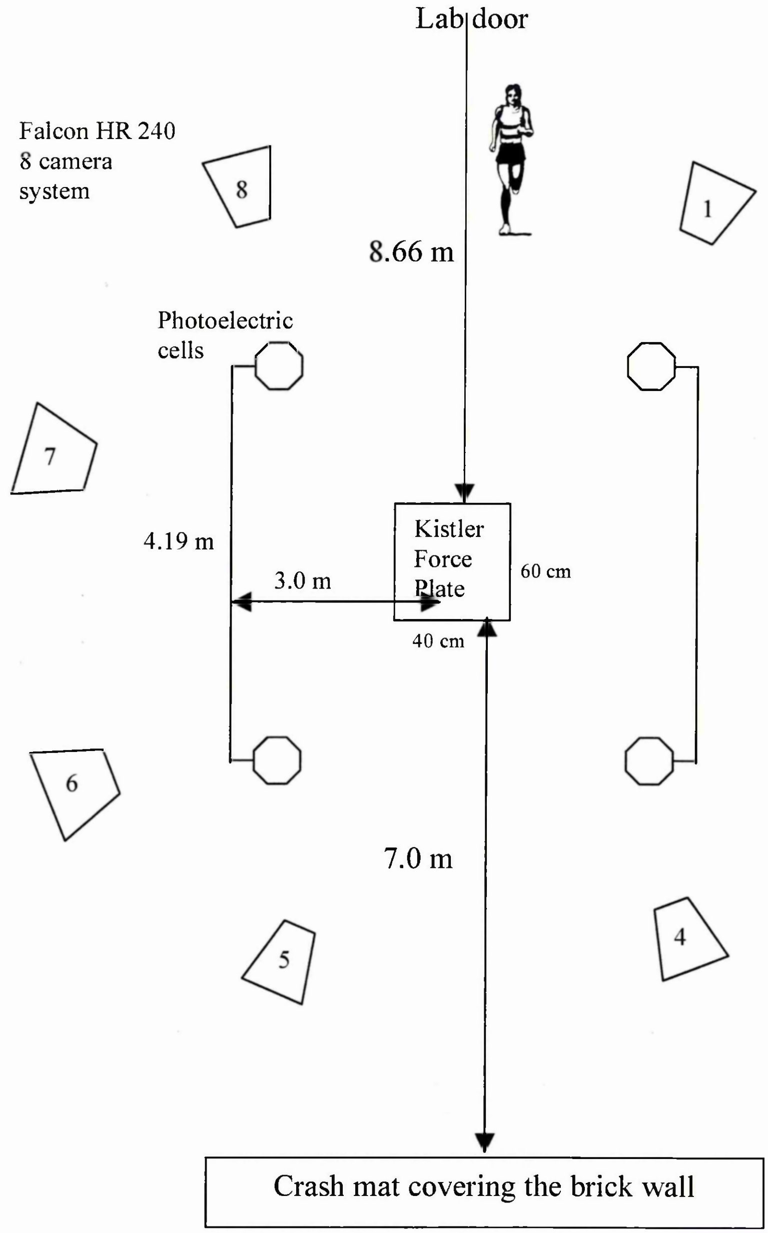


Figure 6.3.1 Measurement set-up for laboratory data collection

Collection and processing of kinematic data (see appendix 5 for raw data)

A modified Helen Hayes marker set (22-markers) was used to collect their three-dimensional trajectories for computing kinematic data. Retroflective spheres of a diameter of 2 cm (4.4 g) were applied to their bodies in order to define a model comprised of twelve body segments: two segments for feet, lower legs, upper legs, forearm, upper arm and two single segments comprising the head/neck and trunk. These markers were applied directly onto the skin using athletic tape on the acromion processes, elbow and radiocarpal joints, sacrum, anterior superior iliac spines, lateral femoral condyles, lateral malleolus, and the dorsim of the feet between the second and third metatarsals. Two lateral wands were used to calculate the medial knee and ankle markers during the dynamic trials. The two lateral wands were 10 cm long and attached using athletic tape to the thigh, midway between the hip and knee joints, and for the shank, midway between the knee and ankle joints. Both wands were vertically aligned with the relevant joints. The attachment and length of the wands were such that oscillations of the marker at the tip of the wands were insignificant. An off-set marker placed on the right scapula precipitated software marker recognition through body asymmetry. Video data were collected using a VPAT 310 video recorder and an eight-camera (Falcon HR 240) motion analysis system recording at 120 Hz (Motion Analysis Corporation, Santa Rosa, California) which collected data for one step of the right leg while running in the positive *X* direction. The cameras were zoomed in as far as possible to a volume of 3.6 m in *x* (fore-aft axis) by 1.4 m in *y* (medio-lateral axis) and 2 m in *z* (vertical axis) with the centre of the base corresponding to the centre of the force plate. The laboratory (global) orthogonal coordinate system followed the right hand rule and had the positive *x*-direction orientated in the direction of forward progression, the positive *y*-direction orientated to the left and the positive *z*-direction orientated vertically upward. The volume was calibrated before data collection using a cube and a 500 mm wand associated with EvaRT 3.2 data collection software (Motion Analysis Corporation, Santa Rosa, California). All participants ran a pre-post test at 3.35 $m \cdot s^{-1}$ in two separate laboratory sessions eleven-days apart. Running speeds were measured by two photoelectric cells 4.19 m apart and 3 m from the centre of the force plate, and mounted so the participant's waist triggered the photoelectric cells. Up to five trials were recorded, and only trials in which 'good' foot contact with a steady stride and speeds within 5% of the measured speed were analysed. The three dimensional coordinate data were filtered using a 2nd order low-pass Butterworth filter (commonly known as the Butterworth fourth order); a cut-off frequency of 6-8 Hz was used and was selected through visual inspection of the fit (Winter, 1987). Video and analogue data were time synchronised using impact recorded when vertical ground reaction force exceeded 20 N. Following the filtering process in EvaRT 3.2, the filtered video data were extracted using OrthoTrak 5 software. Coordinate and angular data were calculated according to the method used by Winter (1990) from the filtered raw data.

Statistical analysis

Assumptions of normality were satisfied for the inferential statistical analysis using the Ryan-Joiner's normality test. Homogeneity of variance were satisfied using Levene's test. Individual means and standard deviations were calculated for a variety of secondary research variables both before and after the instructional period. Sixteen 2 x 2 mixed factorial ANOVAs assessed the primary research variables for the main effects of group (control vs. treatment), and treatment (pre to post changes). Tukey's tests of honestly significant differences were used to assess individual cell differences *post hoc*. Data analysis was conducted using Minitab (version 14) statistical analysis software. Statistical significance for the inferential statistical procedures was established at P = 0.05.

6.4 RESULTS

The seven-hour intervention in Pose® running aimed to make consistent biomechanical changes to eight of the heel-toe participants while the other eight participants (control group) practiced traditional running drills. Figures 6.4.1-6.4.6 allow visual inspection of the biomechanical changes for the Pose® and heel-toe group. Heel-toe runners (control group) pre and post-test illustrate a lack of any biomechanical changes. Pose® runners show distinct biomechanical changes pre and post-test.

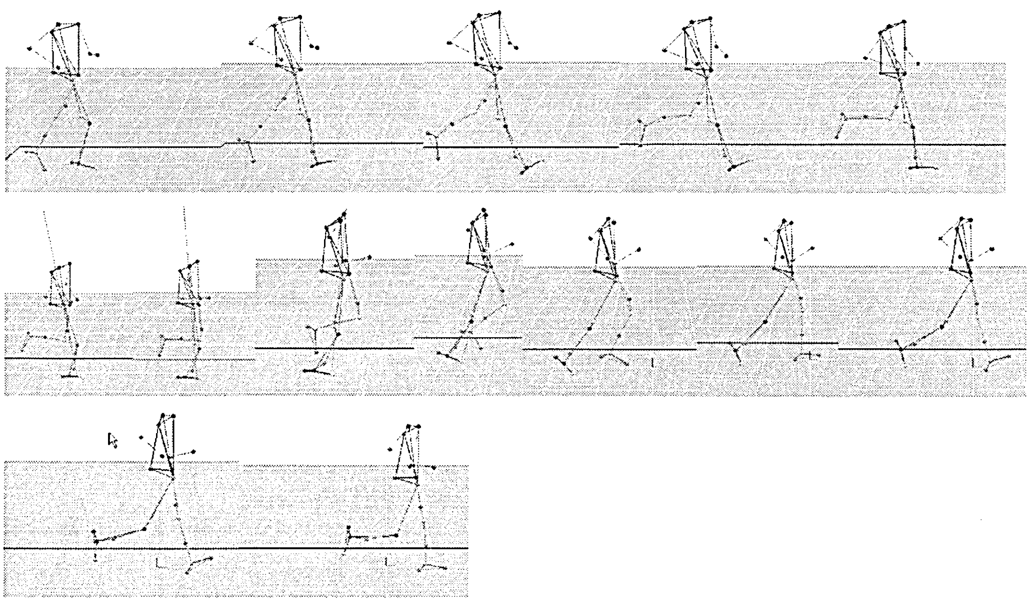


Figure 6.4.1 Pre-test heel–toe runner 1 at 3.35 ms^{-1} taken every 5 frames at 120 $frames.s^{-1}$.

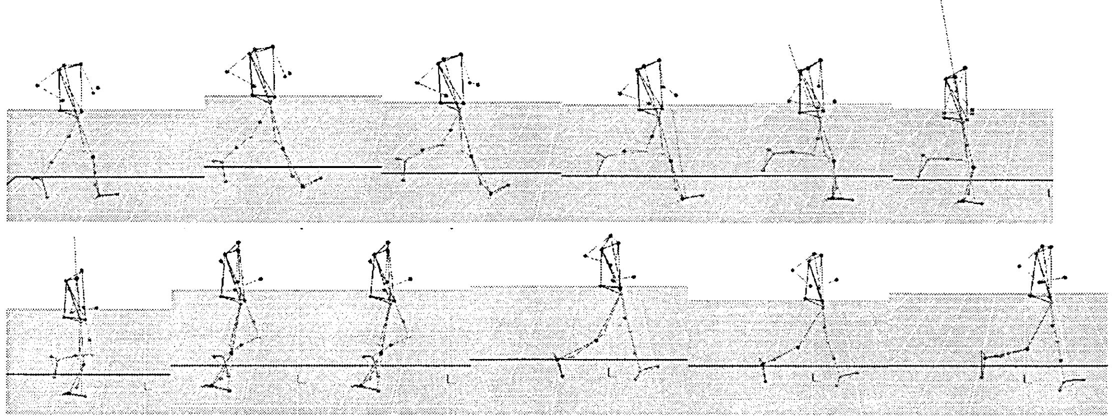


Figure 6.4.2 Post-test heel–toe 1 runner at 3.35 ms^{-1} taken every 5 frames at 120 $frames.s^{-1}$.

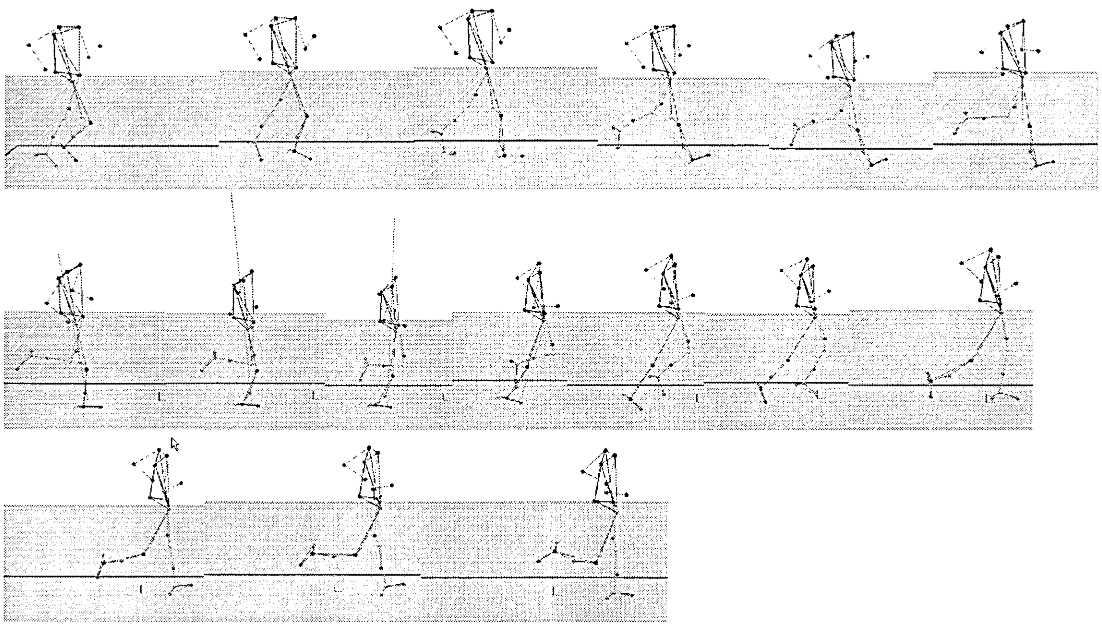


Figure 6.4.3 Pre-test Pose® runner 1 at 3.35 ms^{-1} taken every 5 frames at 120 $frames.s^{-1}$.

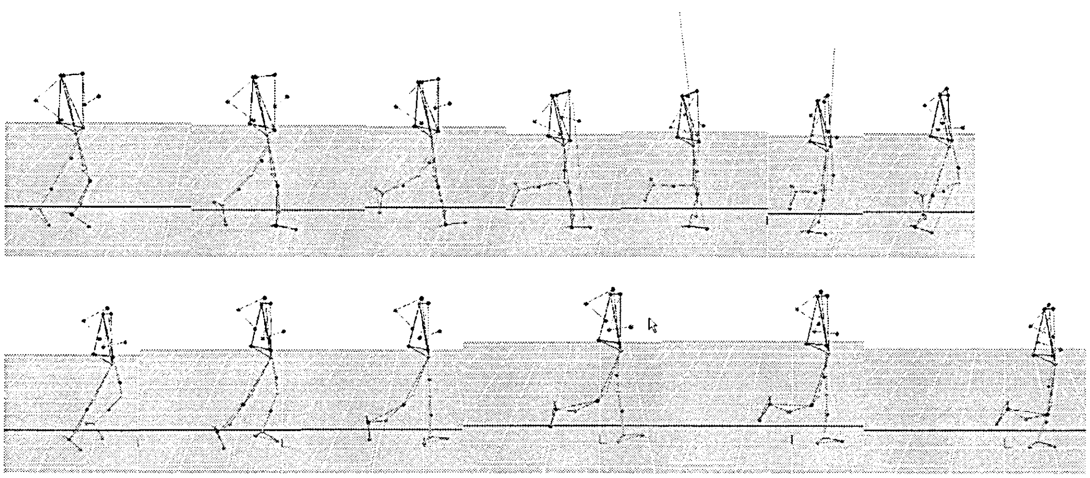


Figure 6.4.4 Post-test Pose® runner 1 at 3.35 ms^{-1} taken every 5 frames at 120 $frames.s^{-1}$.

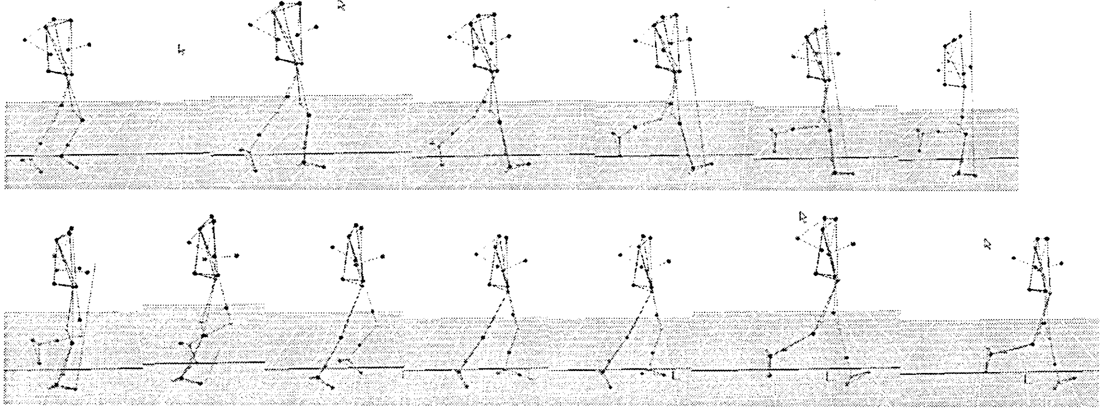


Figure 6.4.5 Pre-test Pose® runner 2 at 3.35 ms^{-1} taken every 5 frames at 120 $frames.s^{-1}$.

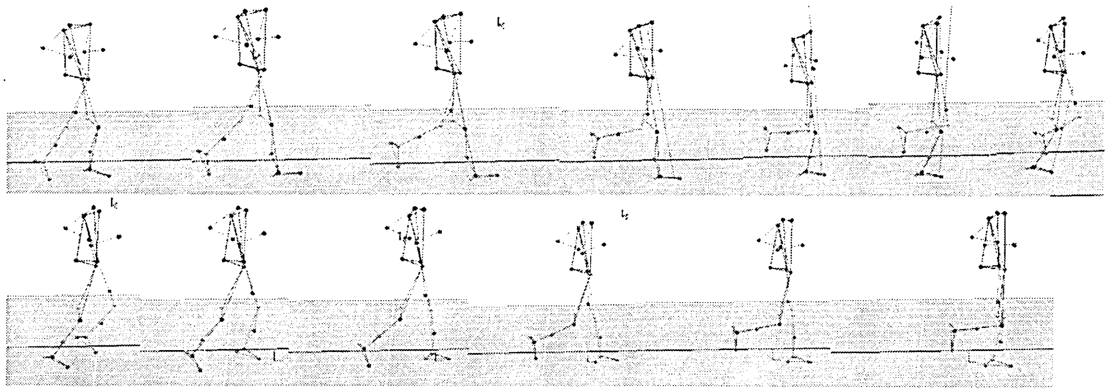


Figure 6.4.6 Post-test Pose® runner 2 at 3.35 ms^{-1} taken every 5 frames at 120 $frames.s^{-1}$.

The primary and secondary variables in Table 6.4.1 give the pre and post-test scores for the heel-toe and Pose® runners. Mean scores for comparison are given in bold from the experienced Pose® and heel-toe runners from chapter 5 at the same running speed of 3.35 ms^{-1}.

Table 6.4.1 Heel-toe and Pose® group's (*N*=16) primary (in bold) and secondary mean scores and standard deviations plus for comparison the experienced Pose® and heel-toe technique runners at 3.35 m·s⁻¹ in bold.

	Pose®			Heel-Toe		
Variables	**Pre**	**Post**	**Pose®**	**Pre**	**Post**	**Heel-Toe**
ST (ms)	245 (3)	210 (1)*	**220**	250 (2)	250 (1)	**260**
MA-P GRF (BW)	-0.18 (0.03)	-0.18 (0.03)	**-0.23**	-0.21 (0.03)	-0.22 (0.04)	**-0.20**
M V GRF (BW)	2.63 (0.4)	2.69 (0.24)	**2.63**	2.59 (0.22)	2.57 (0.16)	**2.58**
MA-PGRF(p)(BW)	0.16 (0.03)	0.16 (0.02)	**0.16**	0.17 (0.03)	0.16 (0.01)	**0.15**
CM (brak) (cm·s⁻¹)	-21.3 (8.4)	-16.2 (11.6)	**-15.3**	-19.7 (7.6)	-20.0 (6.5)	**-22.6**
CM (prop) (cm·s⁻¹)	17.1 (5.9)	14.1 (6.7)	**17.7**	17.4 (7.3)	15.7 (8.1)	**20.4**
CM 25 (cm)	32.7 (6.3)	24.9 (5.8)**	**24.9**	31.2 (3.1)	32.1 (2.3)	**31.9**
VO (cm)	11.5 (2.3)	9.7 (2.1)	**9.3**	11.4 (1.5)	11.3 (1.6)	**11.9**
KFV (rad·s⁻¹)	6.1 (1.56)	5.27 (1.48)*	**5.25**	7.52 (0.71)	6.94 (1.37)	**5.41**
KEV (rad·s⁻¹)	4.22 (0.71)	3.72 (1.47)	**3.48**	4.16 (0.49)	4.11 (0.41)	**4.1**
KFVS (rad·s⁻¹)	6.89 (0.85)	7.91 (1.14)**	**7.65**	6.29 (0.97)	6.14 (0.85)	**6.42**
SL (cm)	103.5 (9.4)	89.1 (9.3)**	**89.9**	106.4 (10.6)	100.7 (7.96)	**98.4**
CM Dis (cm)	87.3 (10.4)	72.7 (5.4)*	**75.6**	89.8 (5.8)	87.4 (6.4)	**89.3**
SF (Hz)	2.6 (0.09)	3.0 (0.25)*	**3.04**	2.6 (0.17)	2.57 (0.18)	**2.65**
Time trial (s)	568.1 (10.6)	543.4 (7.1)		570 (63.5)	573.3 (62.2)	
O2 Con (ml)	2936.9 (252.6)	2918.1 (174.8)		3168.9 (399.9)	3018.5 (444.3)	
TA-PGRF (b) (% of stance)	26.2 (2.2)	17.2 (8.55)	**8.4**	23.8 (2.3)	23.8 (1.85)	**23.8**
T V GRF (% of stance)	44.8 (3.98)	44.0 (3.84)	**37.9**	44.1 (2.45)	44.2 (1.73)	**44.1**
TA-PGRF(p) (% of stance)	75.8 (1.99)	74.9 (2.28)	**71.2**	76.1 (2.15)	74.8 (1.88)	**73.3**
CM S (cm·s⁻¹)	-22.0 (0.7)	-15.2 (0.5)	**-27.3**	-28.7 (6.4)	-31.7 (6.4)	**-18.9**
CM TO (cm)	37.0 (5.4)	34.1 (4.6)	**36.8**	42.8 (4.3)	40.7 (3.9)	**40.5**
CM θ (rad)	0.33 (0.05)	0.3 (0.03)	**0.34**	0.38 (0.02)	0.37 (0.03)	**0.35**
SHA (cm)	13.8 (7.7)	8.7 (4.7)	**8.0**	12.6 (3.03)	13.5 (2.4)	**16.1**
KF (rad)	0.54 (0.07)	0.43 (0.11)	**0.44**	0.58 (0.03)	0.58 (0.04)	**0.55**
KE (rad)	0.59 (0.08)	0.46 (0.19)	**0.48**	0.66 (0.05)	0.63 (0.09)	**0.64**
KSW (rad)	1.54 (0.25)	1.6 (0.24)	**1.57**	1.42 (0.18)	1.36 (0.22)	**1.49**
KTD (rad)	0.22 (0.09)	0.28 (0.09)	**0.32**	0.23 (0.07)	0.24 (0.07)	**0.34**
KVGRF (rad)	0.71 (0.12)	0.68 (0.11)	**0.74**	0.77 (0.06)	0.78 (0.08)	**0.87**
FT (ms)	136 (4)	126 (3)	**120.0**	134 (3)	130 (2)	**120.0**

Significant difference ($P = 0.01$) from * Pose® pre to post-test. Significant difference ($P = 0.05$) from ** Pose® pre to post-test. No significance was found pre-post test for the control group or between pre-tests for the Pose® and control groups.

Experienced Pose® and heel-toe runner's scores are in bold as well as the training study's primary research variables. Standard deviations are in parenthesis. ST = stance time (ms) right foot, M A-P GRF (brak) = maximum posterior ground reaction force (braking) (BW), M V GRF = maximum vertical ground reaction force (BW), M A-P GRF (prop) = maximum anterior ground reaction force (propulsive) (BW), CM (brak) = centre of mass horizontal velocity largest decrease after impact until maximum vertical ground reaction force ($cm \cdot s^{-1}$), CM (prop) = centre of mass horizontal velocity largest increase from maximum vertical ground reaction force until terminal stance ($cm \cdot s^{-1}$), CM 25 = centre of mass behind the toe-marker (horizontal difference at 25 ms), VO = vertical oscillation of the centre of mass (cm), KFV = mean knee flexion angular velocity for stance ($rad \cdot s^{-1}$), KEV = mean knee extension angular velocity for stance ($rad \cdot s^{-1}$), KFVS = mean knee flexion angular velocity from terminal stance to maximum swing angle ($rad.s^{-1}$), SL = step length for right foot (cm), CM dis = centre of mass displacement during stance (cm), SF= step frequency (Hz), Time trial (s), O2 con = oxygen consumption (ml), T A-P GRF (brak) = time of posterior ground reaction force (braking) (% of stance), T V GRF = time of maximum vertical ground reaction force (% of stance), T A-P GRF (prop) = time of anterior ground reaction force (propulsion) (% of stance), CM diff = horizontal velocity of the centre of mass from maximum vertical ground reaction force until terminal stance minus horizontal velocity of the centre of mass from impact until maximum vertical ground reaction ($cm \cdot s^{-1}$), CM S = centre of mass horizontal velocity decrease between terminal stance and maximum swing (flexion) for the right leg during flight ($cm \cdot s^{-1}$), CM TO = centre of mass forward of the toe-marker (horizontal difference at terminal stance) (cm), CM θ = centre of mass and toe-marker angle at terminal stance from the vertical axis going clockwise (rad), SHA = shoulder, hip, and ankle marker difference in vertical alignment at 25 ms (cm), KF = knee flexion range during stance (rad), KE = knee extension during stance (rad), KSW = knee flexion from terminal stance to maximum swing (rad), KTD = knee angle at impact (rad), KV GRF = knee angle at maximum vertical ground reaction force (rad), FT = flight time (ms).

Figures 6.4.7-8 give pre and post-test mean scores for the Pose® and heel-toe groups for time-aligned hip, knee and ankle joint displacements with maximum vertical ground reaction force and vertical oscillation of the centre of mass. Note, the horizontal displacement of the centre of mass during flight for the Pose® group post-test is 44.9 cm and the heel-toe group is 46.2 cm, whereas step length decreased in the Pose® group post-test.

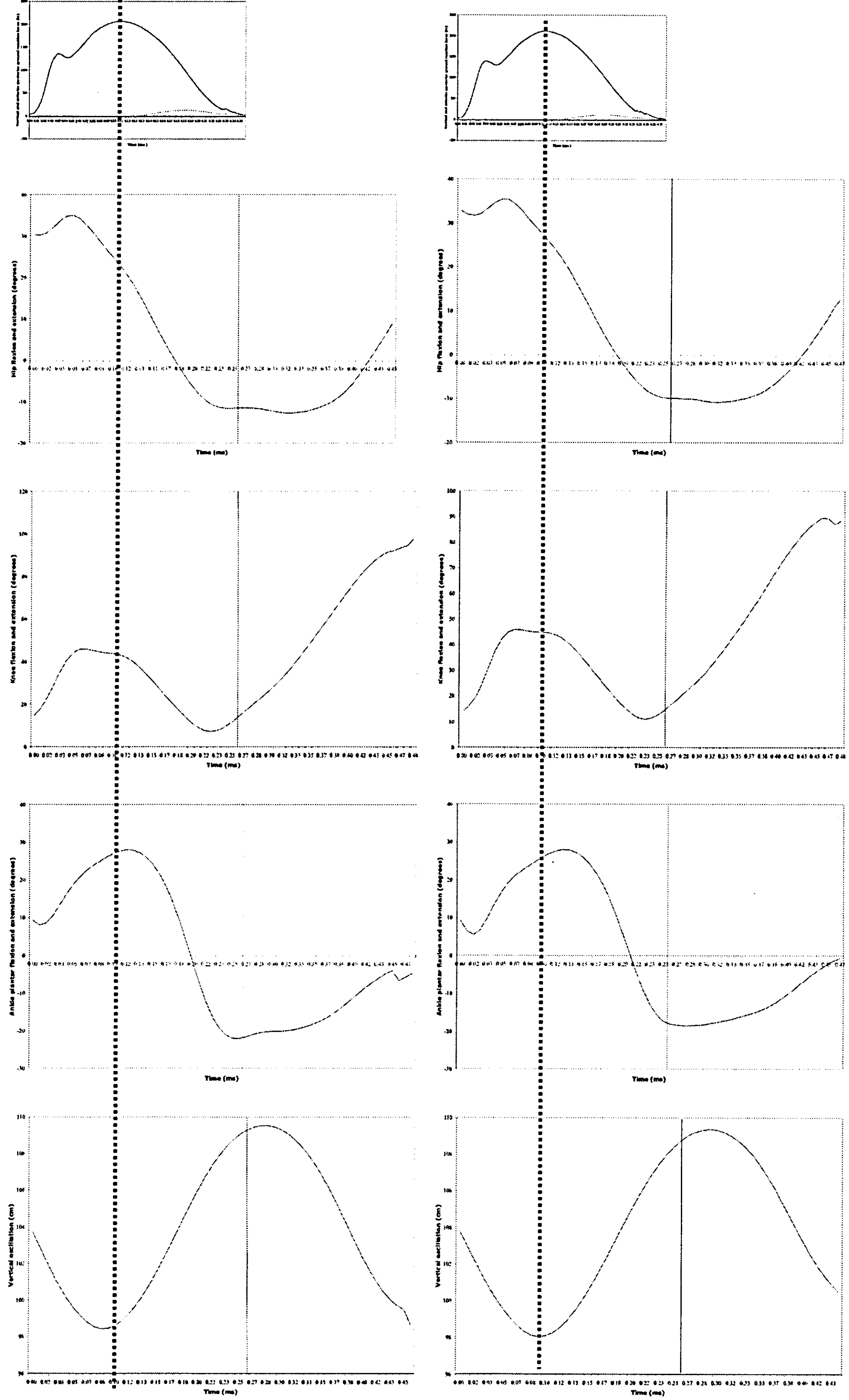


Figure 6.4.7 Pre (left) and post-test (right) control group (heel-toe) mean scores for ground reaction force, hip, knee, ankle and vertical oscillation of the centre of mass.

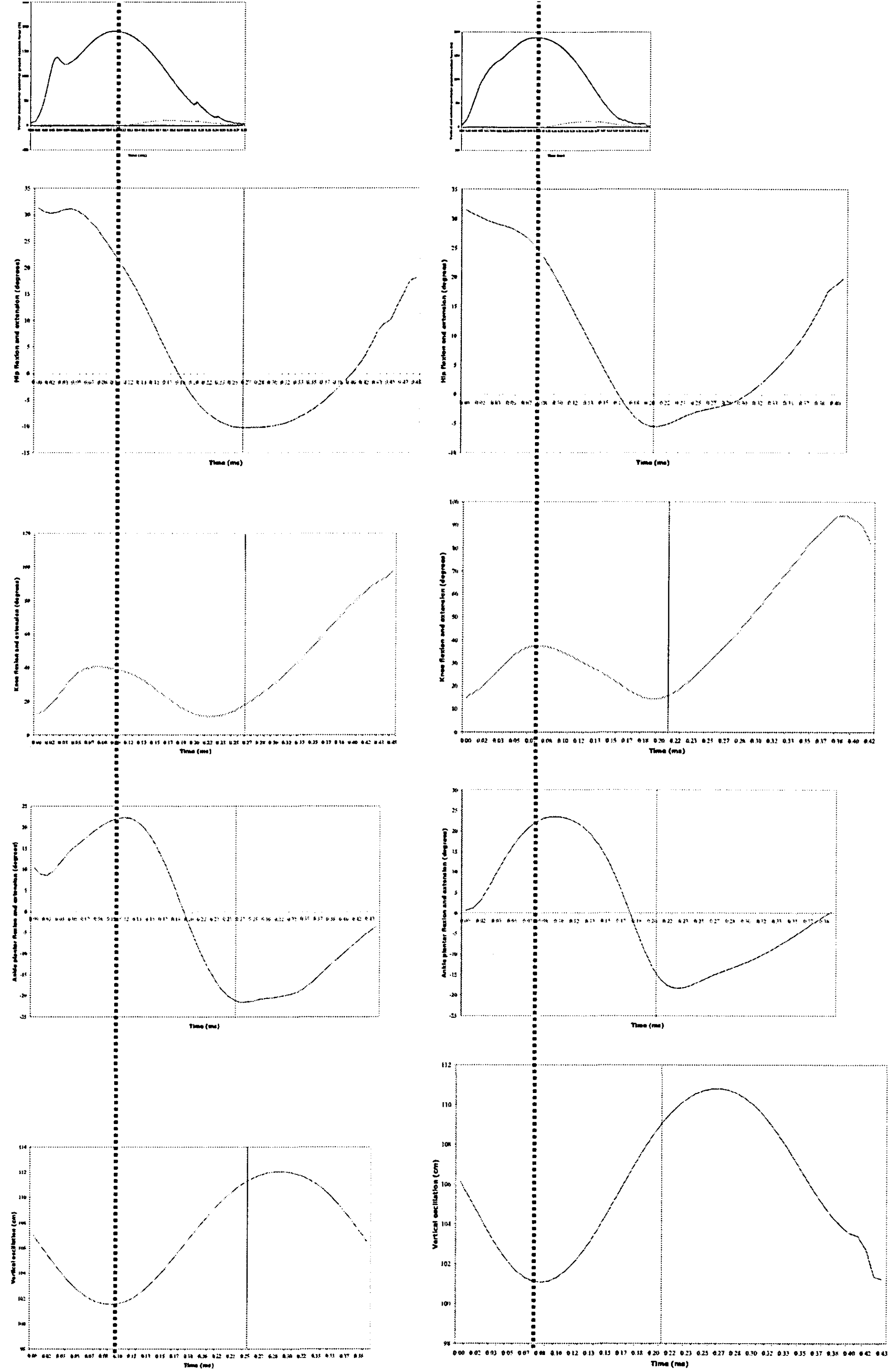


Figure 6.4.8 Pre (left) and post-test (right) Pose® group mean scores for ground reaction force, hip, knee, ankle and vertical oscillation of the centre of mass.

The following tables (tables 6.4.2-6.4.6) cover the economy run and the time trial. The London Met. office had no weather stations at Loughborough University so the two nearest stations were used to record the weather for the economy run and the time trial.

Table 6.4.2 Economy run (2400 m) ($N = 16$)

	Pose®		Heel-toe	
Variables	**Pre-test**	**Post-test**	**Pre-test**	**Post-test**
AV HR	169.9 (10.5)	166.9 (7.1)	170.0 (22.0)	167.6 (20.5)
SF	15.7 (0.59)	16.6 (1.5)	15.4 (0.74)	15.6 (0.92)
O_2	2936.9 (252.6)	2918.1 (174.8)	3168.9 (399.9)	3018.5 (444.3)

AV HR = mean heart rate (bpm), SF = Step frequency (mean for the 6 laps for the steps taken from a 20 m stretch in the home straight), 0_2 = Economy run (oxygen consumption) (ml)

Table 6.4.3 Time trial run (2400 m) ($N = 16$)

	Pose®		Heel-toe	
Variables	**Pre-test**	**Post-test**	**Pre-test**	**Post-test**
T	568.1 (10.6)	543.4 (7.1)	570.0 (63.5)	573.3 (62.2)
M HR	194.0 (9.9)	194.6 (6.9)	195.9 (13.6)	193.1 (11.3)
AV HR	184.9 (9.58)	185.6 (7.2)	183.1 (15.4)	181.0 (13.3)
Borg	17.5 (0.53)	18.1 (0.99)	16.8 (0.71)	17.0 (1.41)
SF	12.7 (1.1)	13.4 (1.5)	13.0 (1.34)	13.8 (1.51)

T = Time (s), M HR = Maximum heart rate (bpm), AV HR = mean heart rate (bpm), Borg = Borg Scale (6-20), SF = Step frequency (mean for the 6 laps from the steps taken from a 20 m stretch in the home straight).

Table 6.4.4 Questionnaire (scale 1-5) How important do you believe running technique is to overall performance? ($N = 16$)

	Pose®		Heel-toe	
	pre-test	**post-test**	**pre-test**	**post-test**
	5	5	4	4
	3	4	5	5
	4	4	5	5
	4	5	5	4
	5	5	5	4
	4	5	4	3
	5	5	4	4
	5	4	4	4
Mean	4.4	4.6	4.5	4.1
S.D.	0.74	0.52	0.53	0.64

1 = not important at all; 2 = fairly unimportant; 3 = in between; 4 fairly important; 5 = extremely important

Table 6.4.5 Weather on time trial and economy run days from Sutton Bonnington.

Date	W N	W S	W Gust (N)	W Gust	Temp	Hum	Rain
May-24	268	7	266	14	13.7	82.8	0.0
May-25	294	8	295	16	14.7	78.6	0.0
Jun-06	209	9	207	17	16.8	85.3	0.1

NGR = 4507E 3259N, Altitude = 48 metres, Latitude = 52:83 N Longitude = 01:25 W (London Met. office ©, 2003) W N = Wind - Mean Direction Degrees True Clockwise from North, W S= Wind - Mean Speed (kn), W Gust (N) = Wind - Max Gust Direction Degrees True Clockwise from North, W Gust = Wind - Max Gust Speed (kn), Temp = Temperature - Dry Bulb (°C), Hum = Relative Humidity %, Rain = Rain - Amount (mm).

Table 6.4.6 Weather on time trial and economy run days from Leicester University.

Date	W N	W S	W Gust (N)	W Gust	Temp	Hum	Rain
May-24 pre-test	245	5	265	12	14.2	80.4	0.0
May-25 pre-test	305	7	295	15	14.9	76.7	0.0
Jun-06 post-test	192	6	195	14	16.4	88.3	0.1

NGR = 4595E 3032N, Altitude = 80 metres, Latitude = 52:62 N Longitude = 01:12 W (London Met office ©, 2003) W N = Wind - Mean Direction Degrees True Clockwise from North, W S= Wind - Mean Speed (kn), W Gust (N) = Wind - Max Gust Direction Degrees True Clockwise from North, W Gust = Wind - Max Gust Speed (kn), Temp = Temperature - Dry Bulb (°C), Hum = Relative Humidity %, Rain = Rain - Amount (mm).

Statistical Analysis

Statistical tests were performed with a commercial statistical programme Minitab (version 14). Significant differences between the means of the primary research variables were found using a 2 * 2 mixed factorial ANOVA, with the level of significance posted at $P < 0.05$. Significant differences between the means as indicated by significant F-ratios were explored with the Tukey *post hoc* analysis test. Significant interaction effects were found for stance time ($P = 0.012$), centre of mass to support limb at 25 ms ($P = 0.014$), centre of mass displacement during stance ($P = 0.030$) and step frequency ($P = 0.005$). Tukey *post hoc* tests revealed significant differences between the Pose® group pre and post-test for stance time ($P = 0.001$), centre of mass to support limb at 25 ms ($P = 0.042$), centre of mass displacement during stance ($P = 0.001$), knee flexion angular velocity during stance ($P = 0.005$) plus swing ($P = 0.043$) and step frequency ($P = 0.002$).

A three-month prospective injury report was undertaken post intervention for the sixteen participants. Their self-report data is summarised. It was not possible to control the participants running training owing to an inability to maintain personal contact (the researcher lived 6000 miles away). Each participant was asked to keep a diary of training mileage and injury incidence. All the participants (except two who ceased running) maintained their normal weekly mileage (mean 25-km).

Table 6.4.7 All but two participants continued running their normal weekly schedules. A self-report injury study was conducted for three-months post-test ($N = 16$)

Pose® group	**Heel-toe group**
No injuries in the six runners who continued to run Pose®.	Four developed patellofemoral pain syndrome.
Two runners (who least learned Pose® running) reverted back to their former heel-toe technique and developed iliotibial band friction syndrome.	One developed subcalcaneal pain syndrome.
	One developed chronic compartment syndrome in their legs.
	Two ceased running but were not injured.

6.5 DISCUSSION

The major findings of this present study on Pose® running were as follows: 1) There were no significant differences in ground reaction forces in the Pose® group between pre and post-test. 2) There were significant differences in body and limb activity in the Pose® group between pre and post-test. 3) There was no significant change in economy in the Pose® group's economy run, yet they ran faster in the 2400 m time trial. 4) No injuries occurred in the Pose® group who continued to run the Pose® technique, whereas all of the heel-toe technique that continued to run developed injuries. However, owing to the small sample size conclusive comment about injury incidence is not possible at this time.

Arendse *et al.* (2004) administered a Pose® method intervention to twenty male and female endurance runners using a repeated measures experimental design (within-subjects). Biomechanical data were collected for their natural heel-toe running style. During the same data collection, they ran on their forefoot while the same biomechanical data was collected. Pose® running instruction was then administered, which consisted of a maximum of seven and half hours and comprised of one and half-hour sessions daily for five consecutive days. Seven and half hours of Pose® instruction from a trained Pose®

method teacher was adequate to change their heel-toe runners into Pose® runners. This study therefore employed a similar seven-hour Pose® instruction over seven-days.

Previous attempts to modify running technique have focused on one or two (stride length/frequency) modifications (for example, Petray and Krahenbuhl, 1985; Messier and Cirillo, 1989; Williams and Ziff, 1991). Although these studies recorded individual kinematic variables—stride length, vertical oscillation, trunk inclination and arm swing—their results were inconsistent across their sample groups, showing a resistance to change from their individual running technique. In contrast, Pose® running produced consistent biomechanical changes (see table 6.4.1; Arendse *et al.*, 2004; Dallam *et al.*, 2005). This study seeks to evaluate these biomechanical changes in the Pose® group (no changes were found in the heel-toe group) in relation to a performance test, economy run and injury incidence.

Kinetic and kinematic (primary and secondary) variables

The 2 x 2 mixed factorial ANOVA found all the ground reaction force variables non-significant. Lack of change in the ground reaction force makes sense. Chang *et al.* (2000) increased and decreased gravity on eight male endurance runners. They also increased inertia without changing gravity. Horizontal impulses, maximum braking and propulsive ground reaction force changed substantially with increased gravity compared to inertia. With increased gravity, the braking and propulsive impulses increased proportionally, whereas with inertia they did not. The vertical ground reaction force did not change with increased inertia, but when gravity reduced, the vertical ground reaction force reduced proportionally. This confirms gravity and maximum vertical ground reaction force (the runner's weight) strongly relates with impact and is not propulsive (discussed in detail in chapter 5; Biewener *et al.*, 2004).

Propulsive (horizontal) ground reaction force did not change in the Pose® runners, while muscle activity is absent in all runners during the propulsive phase of stance (Montgomery *et al.*, 1994), indicating the runner is not pushing off the ground with their muscle system (McClay *et al.*, 1990). The lack of muscle activity, maximum horizontal acceleration occurring before maximum horizontal ground reaction force (see chapter 5 table 5.4.1), and changes in ground reaction force that are proportional with changes in gravity (Chang *et al.*, 2000) lead to the deduction that a gravitational torque creates propulsion (see chapter 3, 5) rather than the ground and the muscle system.

However, propulsive impulse increases with running speed (Hunter *et al.*, 2005). Using multiple linear regression to predict sprint velocity, relative propulsive impulse explained 57% of their variance in sprint velocity. The impulse-momentum relationship correctly explains motion changes in runners, but as running speed rises, the propulsive impulse increases do not have to come from more muscle activity, because the leg and hip extensors are silent during propulsion (McClay *et al.*, 1990; Montgomery *et al.*, 1994). Rather an increase in the propulsive impulse may occur via a gravitational torque increasing the acceleration of the runner's centre of mass. At faster running speeds, the increase in trunk inclination will subsequently increase the gravitational torque via an increased moment arm. The propulsive impulse may simply be reflecting the increased acceleration of the centre of mass via the increased gravitational torque at higher running speeds.

The timing of the ground reaction forces only differed in the braking condition for the Pose® runners. This may reflect their more aligned shoulder, hip and ankle at impact after the intervention (5.1 cm) and the significant difference found in their centre of mass being more vertically aligned (7.8 cm) with the support foot at impact. Although not significantly different, the Pose® group had a lower braking effect (0.051 $m \cdot s^{-1}$) for the horizontal velocity of their centre of mass during this time possibly reflecting a more aligned body position. As the Pose® group were faster post-test for the time trial this more aligned body position may reflect the cause of improved performance, because faster runners brake less (Bates *et al.*, 1979; Girardin and Roy, 1984; Hinrichs, 1990).

Horizontal velocity of the centre of mass during the propulsive phase of stance was also not significantly different in the Pose® group although it did decrease. It is possible that the Pose® group did not need to accelerate as much during this phase to maintain a constant running speed because they braked less. Another possible explanation is the ipsilateral leg is driven forwards during this part of stance in heel-toe runners, which would increase the horizontal velocity of the centre of mass. Pose® runners are trained not to drive the swing leg forwards. Finally, calculation of the change in horizontal velocity of the centre of mass (difference between maximum vertical ground reaction force and terminal stance), may have masked increased acceleration in the Pose® group, because the experienced Pose® runners in chapter 5 had higher horizontal acceleration of their centre of mass (chapter 5; figures 5.4.58-61).

The Pose® group reduced their vertical oscillation in-line with other Pose® studies (Arendse *et al.*, 2004; Dallam *et al.*, 2005). Reduced vertical oscillation appears to be a distinguishable characteristic of Pose® running. Less knee extension correlates with lower vertical oscillation (Wank *et al.*, 1998). The Pose® group reduced knee extension (0.13 rad) and vertical oscillation (1.8 cm). Stance time also significantly decreased in Pose® runners, suggesting having the support foot remain longer on the ground (increased stance time) via increased leg extension potentially increases vertical oscillation. Increased stance time correlated positively ($r = 0.49$) with poorer economy reflecting decreased performance (Williams and Cavanagh, 1986; Williams and Cavanagh, 1987). In addition, as endurance runners fatigue, stance time increases (Nicol *et al.*, 1991). Directly the body begins to fall forwards (after mid-stance), Pose® runners are taught to pull their foot from the ground, which potentially decreases the knee passively extending, thus reducing vertical oscillation. Pose® running is characterised by decreased vertical oscillation, which may correlate with reduced stance time and lower knee extension possibly affecting performance. Enomoto *et al.* (1999) using thirty-two participants found their fastest runners produced lower vertical oscillation and less braking of the centre of mass's horizontal velocity. This study's Pose® runners improved their time trial performance eliciting these same traits.

The Pose® group significantly reduced knee flexion angular velocity at impact to maximum vertical ground reaction force. This possibly reflects their more aligned body at impact, because their knees flex less from impact to maximum vertical ground reaction force (0.08 rad). Knee extension angular velocity from maximum vertical ground reaction force until terminal stance decreased. The Pose® group flex and extend the knee less during stance, which potentially translates into less work and improved performance (Arendse *et al.*, 2004). The knee flexion angular velocity for swing in the Pose® group post-test significantly increased, whereas knee range of motion barely changed (0.06 rad). The reduced moment of inertia at the knee (less extension) during stance and the significantly increased knee flexion angular velocity during swing may enhance performance based on lower energy cost (Enomoto *et al.*, 1999).

The Pose® group reduced step length and significantly increased step frequency creating another recognisable characteristic of Pose® running (Arendse *et al.*, 2004; Dallam *et al.*, 2005). Increased vertical alignment of the shoulder, hip and ankle in the Pose® group at impact, may suggest reaching or driving the swing leg forwards in front of the body, is absent in Pose® runners. Driving the swing leg will increase step length, and may possibly affect the timing of the braking ground reaction force. Support for driving the swing leg forwards in heel-toe runners is exhibited by lower differences for horizontal displacement during flight between the centre of mass and actual step length for the Pose® runners.

Economy and time-trial runs

Dallam *et al.* (2005) found a mean increase in sub-maximal absolute oxygen cost of 3.28 (±0.36) $L{\bullet}min^{-1}$ to 3.53 (±0.43) $L{\bullet}min^{-1}$, $P < 0.01$ in their Pose® trained group. However, this study found no significant change in economy. Differences between the two studies methodologies may explain the conflicting results. In contrast, to Dallam *et al.* (2005) this study employed an over-ground economy run test of 2400 m at 3.35 $m{\cdot}s^{-1}$ when the participants were in a non-fatigued state. Dallam *et al.* (2005) tested economy immediately after a maximal oxygen consumption test on a treadmill, leaving the Pose® runners in a very fatigued state. Use of a treadmill may also affect Pose® running.

Consistent increases in submaximal oxygen cost occur with short term attempts to manipulate running economy by altering the self-selected stride rate or length (Cavanagh and Williams, 1982; Kaneko *et al.*, 1987; Messier and Cirillo, 1989; Cavagna *et al.*, 1991). This is the first study in running to alter self-selected stride rate and length and not subsequently increase oxygen consumption. A possible reason for the difference is the Pose® method produces other biomechanical changes as well as changes in stride length and frequency (Table 6.4.1). Previous studies do not address how stride length and stride frequency occur, because they require participants to manipulate their own changes. The Pose® method instruction attempts to teach runners that stride length is a consequence of the body's displacement (via a gravitational torque) not a cause of it. Stride frequency results from the need to pull the foot from the ground to keep up with the moving body while the swing leg is not driven forwards. Finally, the swing foot in the Pose® runners lands under the body identified by a significant change in the vertical alignment of the centre of mass over the support foot at impact.

In one exception to the above, Morgan *et al.* (1994) found that step length optimization training among runners who had self selected a stride length that was longer than that predicted as most economical resulted in improved economy. By testing these runners at multiple stride lengths, they determined which was most economical. Approximately 20% of the runners tested demonstrated a self-selected stride length that was not the same as their most ideal economical stride length. Consequently, the runners improved their economy by training for three weeks (Monday-Friday for 30 min) with audiovisual feedback that allowed them to reproduce the reduced stride length determined to be their most economical. Morgan *et al.* (1994) suggested the longer stride lengths were less economical owing to reduced elastic mechanisms and an increase in postural maintenance. In contrast, Williams *et al.* (1991) reported lowered predicted economy across a series of relative stride lengths (± 20% of leg-length) after 3-weeks of training at a non-optimal stride length condition (+10% of leg-length from their freely chosen stride length). They suggested improved economy results from favourable biomechanical changes that were not quantified. This study quantified biomechanical changes in the Pose® group and in agreement with Morgan *et al.* (1994) posture significantly altered. For example, at impact the Pose® group became more vertically aligned at the ankle, hip and shoulder, their centre of mass displaced less during stance and they had lower vertical oscillation. They left the ground with a less extended knee and were faster to flex the knee during early swing.

Evidence of a similar response may be found in cycling studies that examined pedalling rate, oxygen cost and cycling efficiency. Chavarren and Calbet (1999) demonstrated the most economical cycling cadences in experienced road cyclists (60 rpm) are lower than cyclists commonly self-select for training and racing (90-105 rpm). They attributed this phenomenon to a small but significant increase in delta efficiency with increased cadence. The change in muscular activation patterns resulting from movements at a higher frequency at the same power output, while cycling or running, may contribute positively to reducing peripheral fatigue mechanisms by reducing local leg fatigue later in the race. The participant feedback (Appendix 4) in this study indicated the Pose® runners felt reduced fatigue in their legs, which they concluded was significant in improving their performance.

Curvilinear increases in aerobic demand occur when stride length increases or decreases at any given speed from one self-selected by the runner (Hogberg, 1952; Knuttgen, 1961; Morgan *et al.*, 1989; Kyrolainen *et al.*, 2000a). The optimal economical solution identified was a combination of self-selected stride lengths and stride frequencies. The Pose® group self-selected their stride lengths and stride frequencies, which were significantly altered from their original running technique. Pose® training does not teach or emphasise changing stride lengths and stride frequencies. The Pose® technique teaches the runner to fall forwards from mid-stance and pull the support foot from the ground without regard for changing stride length and stride frequency. As the runner follows these commands their stride length and stride frequency are a consequence not the cause of running gait. That is, the speed the body leaves the ground from falling determines stride length. Stride frequency results from pulling the support foot faster from the ground to keep up with a faster moving body as running speed increases. The Pose® method's novel focus on body posture (running Pose®) and a precise action of pulling the support foot from the ground may explain economy differences between this study and all other studies.

Other variables identified with economical running such as maximum thigh extension at terminal stance had a positive correlation ($r = 0.53$) with increased economy (Williams and Cavanagh, 1986) although this is not a consistent finding (Williams and Cavanagh, 1987). Miura *et al.* (1973) associated thigh extension with increased push-off at terminal stance, identifying this as 'good' and associated with their elite runners, however, this increases the moment of inertia at terminal stance, which increases work (Fenn, 1930). Cavanagh *et al.* (1977) found more acute knee angles during the swing phase enhanced economy suggesting a reduced moment of inertia is beneficial (Bailey and Pate, 1991). The Pose® group reduced knee extension at terminal stance and increased significantly their knee flexion angular velocity from terminal stance to maximum swing. There is general support for improved running economy with lower vertical oscillation (Slocum and James, 1968; Cavanagh, *et al.*, 1977; Williams and Cavanagh (1987). The Pose® group reduced vertical oscillation, which correlates with reduced knee extension (Wank *et al.*, 1998), possibly suggesting driving off the ground is not economical. Finally, Nilsson and Thorstensson (1987) reported no significant difference in running economy between a group of six forefoot and six rear foot strikers potentially negating changes in foot contact in the Pose® group had any affects on economy.

Increased heart rate and ventilation correlated strongly with inter-individual variation in running economy (Pate *et al.*, 1989), indicating lower heart rate and ventilation correlated with improved economy. Increased ventilation and heart rate are associated with stress, often caused by change (Hahn and Payne, 1999). Despite the Pose® group changing their biomechanical profiles they did not worsen economy, in fact, mean heart rate reduced by three beats post-test. In Dallam *et al.* (2005), fatigue and running on a treadmill, which they had not trained for in their Pose® intervention, increased minute ventilation and heart rate and thus worsened economy.

Despite not improving running economy all the Pose® group ran faster in the time trial with a mean improvement of 24.7 s for the post-test, with the heel-toe group differing by 3 s. Interestingly, maximum and mean heart rate were almost identical in the Pose® and heel-toe groups pre and post-test. One Pose® runner was 56 s quicker for his post-test run with a mean heart rate 3 bpm lower than his pre-test score while having the same maximum heart rate. His Borg scale scores were 16 post-test and 17 pre-test. Borg scale scores did not change in the Pose® and heel-toe groups, pre and post-test. It is evident that improvements over one-week were not owing to physiological adaptation, but reflect the significant biomechanical changes post-test in the Pose® group.

The prospective injury study

The questionnaire asked, "How important do you believe running technique is to overall performance?" The Pose® group increased by 4% their belief that technique was important, whereas the heel-toe group reduced their belief by 8%. These shifts are small and probably insignificant because both groups still regarded technique as fairly too extremely important. Regarding technique as important does not necessarily predispose a runner to less injury. Interestingly, reviews on running injuries consistently neglect to mention technique (and changes) as a possible method of injury reduction or even as a cause (for example, Yzerman and Van Galen, 1987; van Mechelen, 1995; Taunton *et al.*, 2002). All participants recorded their running training plus injuries sustained over a three-month period post intervention, while maintaining their normal running routine. The prospective injury study revealed that those runners who continued to run Pose® did not injure in the proceeding three-months after the intervention. However, the two Pose® runners who returned to heel-toe running possibly because they found it hard to maintain Pose® running through practice drills, both developed iliotibial band friction syndrome. Six of the heel-toe runners developed injuries while the two without injuries had ceased running altogether (Table 6.4.7). Therefore, the self-report data collected from the post-test three-month injury study identified six overuse injuries in the heel-toe group and two overuse injuries in the Pose® group. Renstrom (1994) states overuse symptoms usually occur over time, making it difficult to determine the onset and specific cause. If incidence is calculated in relation to time, it varies from 2.5 to 12.1 injuries per 1000 hours of running (Lysholm and Wiklander, 1987; van Mechelen, 1992). This studies injury rate was 12.5 injuries per 1000 hours for the heel toe group and 4.2 injuries per 1000 hours for the Pose® group. However, the two injured runners in the Pose® group reported they reverted to heel-toe running owing to difficulties in maintaining the Pose® technique, essentially leaving no injuries in those that remained running Pose®.

Most running injuries are lower extremity injuries, with the knee joint being the main site of injury (van Mechelen, 1992; Stanish and Wood, 1994). In support of this finding, four heel-toe and two Pose® runners who reverted to their heel-toe running had knee injuries. Therefore, the knee joint was the main site of injury in this study. Eccentric and concentric muscle contractions in a stretch-shortening cycle are potential components for overuse injury at the knee (Johansson, 1992). He suggested knee extensor muscle loading result from variations in running technique. Arendse *et al.* (2004) found knee power absorption and knee eccentric work were significantly less in Pose® runners compared to running heel-toe. Muscle strains usually occur during eccentric contractions (Glick, 1980). Ankle power absorption and eccentric work were greater in Arendse *et al.*'s Pose® runners compared with their heel-toe running. Their knee power generation and concentric work were less in Pose® running compared to their heel-toe running, however, there were no differences in ankle power generation and concentric work between the running techniques. In-line with Arendse *et al.* (2005), this study's Pose® runners may have had less eccentric work and power absorption at the knee, however larger injury studies will confirm whether the Pose® technique significantly reduces knee injuries or possibly increases ankle injuries.

Vertical impact force has been strongly associated with the transmission of shock waves upward through the musculoskeletal system (Radin and Paul, 1971; Verbitsky *et al.*, 1998). Several investigators identified a positive relationship between the magnitude of impact force and the numbers of overuse injuries in runners (Voloshin and Wosk, 1982; Wosk and Voloshin, 1982; Cavanagh, 1990). Vertical impact force was similar between the two techniques in this thesis. However, the time of the maximum horizontal braking force was earlier in the Pose® runners coupled with a more vertically aligned body position (shoulder, hip and ankle joints). Pose® runners are trained to land in this body position because the 'S' like position is meant to reduce the effects of impact forces. The 'S' like position did not reduce maximum vertical impact force but maximum horizontal braking force occurs earlier suggesting a change in the ground reaction force vector.

Stergiou *et al.* (1999) support this study, in that they identified coordination patterns between the ankle and knee joints change the ground reaction force vector. Overall, these studies suggest lower-limb activity at impact affects the loading of the body.

Running volume is an important risk factor for increased injury incidence, whereas, running velocity is not associated with injury risk (Yzerman and Van Galen, 1987). The mean weekly mileage was 25-km for both groups (before and after the intervention), however, running intensity was not recorded. During a 10-km race, eight elite runners were filmed at different stages of the race (Elliot and Ackland, 1981). Fatigue produced a more extended lower-limb throughout the gait cycle (negative impact on performance) during the later stages of the race. Therefore, differences in landing posture between the two techniques in this study may vary gravity's work on the runners. For example, centre of mass location to the support limb at impact may influence the impact force, owing to Arendse *et al.* (2004) finding Pose® running reduced eccentric work at the knee, while increasing eccentric work at the ankle. Hunter *et al.* (2005) found at impact that the distance between the support foot and the centre of mass was lower for runners with a reduced braking impulse. Impact force did not change in this study but the time it occurred did for the Pose® group, while impact distance of the support limb to the centre of mass reduced significantly after the Pose® intervention. The timing of braking force was earlier in the Pose® group post intervention possibly reflecting the more aligned body position at impact, which would affect the braking impulse and may be related to reduced injury incidence.

Using a 1-metre depth jumping exercise as an exaggerated motion for landing while running, ten healthy males landed on their heels or forefeet (Kovacs *et al.*, 1999). Total torque contributions were highest for heel-toe landing (during the extension phase) with 41% and 45% attributed to the knee and ankle joints and 34% and 55% with the forefoot. Electromyography for vastus lateralis muscle activity differed during re-contact for the heel-toe landing, whereas gastrocnemius muscle activity in the forefoot group increased. Exaggerated motion (depth jumps) highlights greater loading characteristics between heel and forefoot contact, which in light of previous comments, suggests limb and body positions relationships play important roles in force attenuation and injury incidence.
This study's sample is obviously too small to draw any conclusions about Pose® running reducing injury, except to mention the results are encouraging in that Pose® technique

changes may reduce injuries. Therefore, large retrospective and prospective injury studies should be conducted.

6.6 SUMMARY

A 2 x 2 mixed factorial ANOVA *post hoc* found significant differences between the Pose® group pre and post-test for stance time ($P = 0.001$), centre of mass to support limb at 25 ms ($P = 0.042$), centre of mass displacement during stance ($P = 0.001$), knee flexion angular velocity during stance ($P = 0.005$) plus swing ($P = 0.043$) and stride frequency ($P = 0.002$). It was suggested, posterior and anterior ground reaction force did not change because of its strong correlation with gravity, a constant force. It appears seven-hours of instruction in Pose® running is an adequate time to significantly make consistent biomechanical changes in male recreational endurance heel-toe runners, which matched other Pose® runners. Pose® runners ran faster after the intervention for a 2400 m time trial, while heart rate, and perceived exertion did not change. In addition, economy did not change for the Pose® group post-test in the 2400 m economy run. The improved running speed for the Pose® group in the time trial was attributed to the significant biomechanical changes in the Pose® technique rather than any physiological adaptations, owing to the short intervention time. It was suggested that the running Pose® (vertical alignment of the shoulder, hip and ankle at impact) improved performance via reduced braking of the horizontal velocity of the centre of mass. Potentially, after mid-stance, as the Pose® runners fell forwards they made better use of the gravitational torque through lower leg extension and vertical oscillation. A faster leg recovery during swing enabled the leg to keep up with the body but without the need to drive the swing leg forwards of it, which decreases horizontal velocity of the centre of mass at impact. Stride length and stride frequency therefore, were a consequence of running Pose®, not the cause. A preliminary prospective three-month injury report revealed lower injury incidence in the Pose® runners as opposed to the heel-toe group.

CHAPTER 7

CONCLUSIONS

Research into endurance running performance has focused on three main areas: economy, optimal running biomechanics, and injury mechanisms. However, this research has not provided a universal running technique, except to identify 80% of endurance runners land on their heels. Hay and Reid's (1988) hierarchical model on running reflects propulsion in running occurs via pushing off the ground through leg extension. Alternatively, Pose® running claimed to be a universal technique that was economical, having an optimal biomechanical profile while reducing injuries. Therefore a new Gravitational hierarchical model of running based upon the Pose® technique was developed, which clarified the interaction of the forces involved in running by establishing gravity as the motive and hierarchically leading force in running. Experienced Pose® runners were then compared with experienced heel-toe runners (chapter 5; study 1). The study confirmed the Gravitational hierarchical model explains the interactions of the forces involved in running while clearly distinguishing heel-toe and Pose® running. The Pose® method study (chapter 6; study 2) replicated the same biomechanical profile as the experienced Pose® runners by training eight heel-toe recreational endurance runners in Pose®. The Pose® group improved performance without changes in economy while reporting no injuries in those who continued running Pose®.

7.1 THEORETCIAL MODELS

There are three known forces (neglecting air resistance) involved in running (gravity, ground reaction force, and muscle force) plus potential strain energy. Theoretical support for the Pose® method and the new Gravitational hierarchical model were identified from the literature.

- Ground reaction force is not a motive force but operates according to Newton's third law (Zatsiorsky, 2002; p.51).
- The ground can only propel a runner's centre of mass forward in combination with muscle activity (Zatsiorsky, 2002; p.51). Leg and hip extensor muscles have consistently proven to be silent after knee extension begins (Brandell, 1973; Mann and Hagy, 1980; Paré *et al.*, 1981; Schwab *et al.*, 1983; Nilsson and Thorstensson, 1985; MacIntyre and Robertson, 1987; Montgomery *et al.*, 1994; Kyrolainen *et al.*, 2003) suggesting the ground in combination with the muscle system are not propulsive.
- High muscle-tendon forces at terminal stance suggest elastic recoil is doing work against gravity rather than muscle force during leg extension (Cavagna *et al.*, 1964; Cavagna and Kaneko, 1977; Hinrichs, 1987; Alexander, 1992; Taylor, 1994; Jung, 2003).
- Elastic recoil is predominantly in the vertical direction (Farley and Ferris, 1998).
- A flic-flac movement shows a spike at terminal stance in the ground reaction force from a push-off action reflecting leg extensor activity, which is completely absent in runners (Yeadon and Challis, 1994). In fact, the ground reaction force decay rate increases as running speed increases, owing to the higher acceleration of the centre of mass as it leaves support (Miller, 1990). Therefore, the decay rate is reflecting the body rising from the ground and does not support a pushing off from the lower-limb musculature.
- Gravity (via a gravitational torque) is the only external force that can horizontally displace the centre of mass if muscle activity is silent during leg extension.
- Gravity causes a torque around the support foot as the centre of mass passes maximal vertical ground reaction force until terminal stance, creating a horizontal displacement of the centre of mass as the body falls forwards (Gracovetsky, 1988).
- The horizontal 'propulsive' ground reaction force may reflect the gravitational torque's propulsive component, because in reduced (or increased) gravity, horizontal propulsive ground reaction force changed proportionally (Chang *et al.*, 2000).
- The hip's extension coincided with reducing vertical ground reaction force (Payne, 1983). The hip passively extends via a gravitational torque as the body moves past the stationary foot, because hip extensors are only active at mid-stance and late swing while hip flexors are mainly active in early swing

(Montgomery *et al.*, 1994). This again suggests the body is moving forward of the support limb (via a gravitational torque) and not being pushed forwards from the foot/ground via the ankle and knee joints (Fenn, 1930; McClay *et al.*, 1990; Montgomery *et al.*, 1994; Pink *et al.*, 1994; Belli *et al.*, 2002; Hunter *et al.*, 2005). This is in direct contrast to Hay and Reid (1988; pp. 264 and 287-288) who suggest leg extension via ankle, knee and hip musculature is the motive force in running.

- Driving the swing leg forwards causes the foot to land ahead of the body. This potentially reduces horizontal velocity of the centre of mass by increasing the horizontal distance of the centre of mass from the support foot at impact (Fenn, 1930; Deshon and Nelson, 1964; Cavanagh *et al.*, 1977; Bates *et al.*, 1979; Kunz and Kaufman, 1981; Girardin and Roy, 1984; Hinrichs, 1987).

7.2 EXPERIENCED POSE® AND HEEL-TOE RUNNER'S STUDY

Two experienced male heel-toe and Pose® runners were matched for age, mass, stature and experience. Comparison of these two running techniques was conducted using the research variables (primary and secondary), identified from the Gravitational hierarchical model. All data used here are the mean of the four test running speeds (2.5 $m \cdot s^{-1}$, 3.35 $m \cdot s^{-1}$, 4.0 $m \cdot s^{-1}$ and 4.5 $m \cdot s^{-1}$). The research variables distinguished the two techniques of running, while giving strong support for the Gravitational hierarchical model.

- Pose® and heel-toe runners had similar ground reaction forces, possibly reflecting their similar body mass and running speed. It was suggested gravity causes maximum vertical and anterior-posterior ground reaction force (Chang *et al.*, 2001). Running speed was associated with the angle of inclination of the centre of mass at terminal stance and the subsequent gravitational torque (Chang *et al.*, 2001).
- Each running speed (2.5 $m \cdot s^{-1}$, 3.35 $m \cdot s^{-1}$, 4.0 $m \cdot s^{-1}$ and 4.5 $m \cdot s^{-1}$) produced increasing angles of inclination and ground reaction forces for the two techniques. It was suggested, increased angles of inclination (increased moment arm) increase the gravitational torque producing increased horizontal acceleration of the centre of mass. Increased horizontal acceleration of the centre of mass will

subsequently increase ground reaction force. Further, maximal horizontal acceleration of the centre of mass increased with running speed.

- The time of braking ground reaction force was earlier as a percentage of stance for the Pose® runners by 13.5% of stance time. Different body geometry at impact explained the braking ground reaction force differences (Deshon and Nelson, 1964; Bates *et al.*, 1979). Propulsive and vertical ground reaction force occurred at a similar percentage of stance time for both techniques. Similar angles of inclination for each running speed explained the similar timing of propulsive ground reaction force, owing to their potential relationship to the gravitational torque (Chang *et al.*, 2001).
- Both heel-toe and Pose® runner's maximal horizontal acceleration of the centre of mass occurred before their horizontal maximal ground reaction force, suggesting by default that a gravitational torque is the motive force in running.
- The propulsive component of gravity caused increased horizontal velocity for the Pose® runners. The increase was observed by graphing the vertical oscillation of one Pose® and heel-toe runner's centre of mass. This clearly illustrated gravity's increased propulsive component in the Pose® runner.
- In addition, the Pose® runners had consistently higher horizontal acceleration of their centre of mass at all test speeds supporting the larger observed propulsive component of gravity in figure 5.5.2.
- Lack of muscle activity during the propulsive phase of stance and maximum horizontal acceleration occurring before the maximum horizontal ground reaction force, suggest that both running techniques do not push off the ground but fall forwards via a gravitational torque.
- Horizontal velocity of the centre of mass was lower in Pose® runners for braking and propulsion by -11 $cm \cdot s^{-1}$ and 6.2 $cm \cdot s^{-1}$ respectively. The angle of inclination of the centre of mass at terminal stance and the horizontal velocity were similar, suggesting the greatest change in the propulsive horizontal velocity masks a rapid acceleration via the gravitational torque in the Pose® runners.
- Lower vertical oscillation was associated with less work against gravity in the Pose® runners. Vertical displacement and horizontal displacement during stance for the centre of mass were lower in Pose® runners by 3.4 cm and 12.3 cm respectively. The Pose® runners utilise the gravitational torque more effectively via lower vertical oscillation, while lower vertical oscillation is associated with faster running (Miura *et al.*, 1973).

- Less horizontal displacement during stance was associated with a more vertically aligned body at impact. Pose® runners were more vertically aligned at impact, for shoulder, hip and ankle (8 cm), and the centre of mass more vertically above the support foot (7 cm). This is associated with less braking of the horizontal velocity of the centre of mass (Hunter *et al.*, 2005).
- Knee flexion and extension during stance was lower in the Pose® runners by 0.12 rad and 0.2 rad respectively. Less knee extension was associated with lower vertical oscillation (Wank *et al.*, 1998).
- Knee angle at impact was similar in both techniques but at maximum vertical ground reaction force, it was lower by 0.11 rad in the Pose® runners. Less knee flexion was associated with increased leg-spring and possibly increased elastic recoil during stance (McMahon and Cheng, 1990).
- Stance time, flight time and step length were lower by 31 ms, 23 ms, and 20.2 cm respectively for the Pose® runners. While step frequency was higher in Pose® runners by 0.5 Hz. Conflicting research on whether shorter steps and increased frequency is more efficient make conclusive comment untenable at this time.
- Knee flexion and extension angular velocity were lower in the Pose® runners during stance by 0.5 $rad{\cdot}s^{-1}$ and 0.6 $rad{\cdot}s^{-1}$ respectively, whereas angular knee flexion velocity during swing was higher in the Pose® runners by 1.5 $rad{\cdot}s^{-1}$. Less knee angular flexion during stance may again be associated with a more aligned body geometry. Less knee extension angular velocity was associated with Pose® runners passively extending their legs. The higher knee flexion angular velocity from terminal stance until maximum swing was associated with the Pose® runners pulling their foot from the ground, in order to catch up with their body, potentially reducing rotational inertia of the lower-limb via less leg extension (Bailey and Pate, 1991).
- It was suggested in Pose® running that the hamstring muscles pull the support foot rapidly from the ground with the aid of the stretch-shortening cycle optimised from a short contact time (Zatsiorsky, 1995; Paavolainen *et al.*, 1999a). By pulling the support foot and not driving the swing leg forward of the body, gravity can drop the swing leg under the body at impact so the cycle can begin again. If the swing leg's centre of mass is vertically under the body's centre of mass during flight, they will both land vertically aligned if the hip flexors are not active.

- Lack of electromyography on Pose® runners inhibits specific comment on muscle activity. There appears conflicting data on gastrocnemius activity at terminal stance (for example, Winter, 1983; Reber *et al.*, 1993), although the leg and hip extensors are consistently silent during most of leg extension (Kyrolainen *et al.*, 2003).
- Pose® runners therefore, exhibit very different gait characteristics to traditional heel-toe runners, such as: A more vertically aligned body position at impact (running Pose®), shorter stance time, less knee flexion and extension during stance, less decrease in the centre of mass horizontal velocity at impact, increased knee flexion angular velocity from terminal stance until maximum swing angle, shorter step length, higher step frequency, and lower vertical oscillation. Therefore, Pose® runners exhibit a distinct biomechanical profile. This is the first attempt to create a universal biomechanical profile for running based upon the Gravitational hierarchical model.
- The Gravitational hierarchical model explained the 'extensor paradox.' The fact, maximum horizontal acceleration of the centre of mass occurred before maximum horizontal ground reaction force supported a gravitational torque as the motive force in running. Although further research is needed using accelerated running to determine if horizontal acceleration of the centre of mass also occurs before propulsive horizontal ground reaction force, similar to constant speed running.
- Therefore, both heel-toe and Pose® runners fall forwards via a gravitational torque refuting the theory that runners push off the ground. However, Pose® runners were better able to utilise the gravitational torque. The Gravitational hierarchical model is therefore a universal model of running, describing both Pose® and heel-toe running techniques and offers an attempt to create a universal profile for running.

7.3 POSE® METHOD TRAINING STUDY

Sixteen male recreational endurance heel-toe runners were recruited and randomly assigned into two groups for a repeated measures design. One group received a 7-hour Pose® intervention over 7-days while the other group remained as heel-toe runners.

Biomechanical and physiological (primary and secondary research variables) data including injury incidence were collected. The Pose® trained group improved their performance post-test on the 2400 m time trial run, significantly changed their biomechanical profile and recorded reduced injury incidence. Sixteen 2 x 2 mixed factorial ANOVAs with repeated measures were used to assess the main effects of group (control vs. treatment), and trial (pre to post changes) on the dependent variables (primary research variables). Tukey's tests of honestly significant differences assessed individual cell differences *post hoc*.

- The Ryan-Joiner's normality test found the data to be normally distributed.
- Levene's test for homogeneity of variance revealed no significant group variability.
- A 2 x 2 mixed factorial ANOVA assessed the main effects of group (control vs. treatment) and trial (pre to post changes) on the primary research variables.
- Significant interaction effects (Pose® runners pre-post-test) were found for stance time ($P = 0.012$), centre of mass to support limb at 25 ms ($P = 0.014$), centre of mass displacement during stance ($P = 0.030$) and step frequency ($P = 0.005$).
- Tukey *post hoc* tests revealed significant differences between the Pose® group pre and post-test for stance time ($P = 0.001$), centre of mass to support limb at 25 ms ($P = 0.042$), centre of mass displacement during stance ($P = 0.001$), knee flexion angular velocity during stance ($P = 0.005$) plus swing ($P = 0.043$) and step frequency ($P = 0.002$).
- It was suggested that the posterior and anterior ground reaction did not change because of its potentially strong correlation with gravity (Chang *et al.*, 2000). The propulsive horizontal velocity variable may have masked the higher horizontal acceleration of the centre of mass in the Pose® runners. Lack of significance for this variable may reflect the same running speeds and similar angles of inclination of the centre of mass.
- Mean heart rate in both groups for the 2400 m economy run reduced by 3 bpm.
- No significant statistical change was found in the Pose® and heel-toe group's economy data for the 2400 m economy run pre and post-test. Step frequency for the post-test rose slightly (0.9 steps) in the Pose® group.
- Pose® runners ran faster (although not statistically significantly) after the 7-hour intervention over 7-days on the 2400 m time trial by 24.7 s, while heart rate, and

perceived exertion did not change, indicating improved performance was owing to the Pose® intervention.

- The mixed 2 x 2 factorial ANOVA revealed the Pose® method significantly changed the biomechanics (to match experienced Pose® runners; table 6.4.1) of heel-toe runners after the 7-hour Pose® running intervention.
- It appears 7-hours of Pose® running instruction is an adequate time to significantly make universal biomechanical changes in male recreational endurance heel-toe runners.
- These biomechanical changes were clearly related to improved performance (increased running speed) over a 2400 m run from a short intervention period negating physiological adaptation as the reason for the performance change.
- Running economy did not change or improve in the Pose® group, however, this was the first study to change technique and not subsequently increase oxygen consumption (economy decreases).
- A preliminary prospective three-month injury report revealed lower injury incidence in Pose® runners compared with the heel-toe runners.

7.4 FUTURE RESEARCH

Gravity's role in running should be quantified by measuring the horizontal acceleration of the centre of mass from maximal vertical ground reaction force until terminal stance in accelerated running. Maximum horizontal acceleration of the centre of mass and propulsive horizontal ground reaction force should be time matched to determine if acceleration occurs before the ground reaction force, similar to constant speed running. The biomechanical technique of Pose® running is based upon a theoretical framework of using body weight (gravity) to produce movement, which could then also be applied to other sports upon its substantiation, creating future research opportunities.

1. To quantify gravity's role in running by using accelerated running (data collected August, 2005). Measurement of the horizontal acceleration of the centre of mass from maximum vertical ground reaction force until terminal stance at 240 frames·s^{-1} provides an accurate horizontal acceleration of the centre of mass. The maximal horizontal acceleration of the centre of mass occurs before the maximum horizontal

ground reaction force. This supports the propulsive force in running is not ground reaction force but a gravitational torque.

2. Collect electromyography on Pose® runners and compare it with heel-toe runners.
3. Replicate the Pose® training study using elite runners and triathletes.
4. Replicate the Pose® training study using female runners.
5. Replicate the Pose® training study using sprinters.
6. Measure technique changes and differences between heel-toe/forefoot runners and Pose® runners for downhill, uphill and running against strong winds.
7. Evaluate running technique in children by assessing changes through maturation and their relation to Pose® method via performance and injury incidence.
8. Develop the theoretical framework of Pose® movement for other sports based upon the Pose® technique of body weight (gravity) as the key motive force (current research is being conducted in cycling, golf, rowing and climbing) in relation to performance and injury.
9. Apply the Pose® running technique in team sports and evaluate running and performance changes.
10. Specific research into injury mechanisms in Pose® and heel-toe runners should begin with a large retrospective study involving several hundred runners (current data collection in London, England and America).
11. Evaluate how Pose® running is learnt using dynamical system theory (pilot study March, 2006).

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APPENDIX 1

PARTICIPANT RECRUITMENT

SHEFFIELD HALLAM UNIVERSITY
SCHOOL OF SPORT AND LEISURE MANAGEMENT

RISK ASSESSMENT PROFORMA

PROCEDURE: ASSESSMENT No. DATE ASSESSED: ASSESSED BY: SIGNED: POSITION:

HAZARDS	RISKS AND SPECIFIC CONTROL MEASURES
1.	

RISK EVALUATION (OVERALL)

GENERAL CONTROL MEASURES

EMERGENCY PROCEDURES

MONITORING PROCEDURES

REVIEW PERIOD

REVIEWED BY: DATE:

POSE® METHOD RUNNING STUDY INFORMATION

Please read the following information regarding a study on the Pose® method of running that will be conducted at Sheffield Hallam University's centre for Sport and Exercise Science, Collegiate Crescent Campus and Loughborough university by Graham Fletcher.

The aim: is to make a biomechanical and physiological analysis of the Pose® method of running using male runners with a 10 km best time between 37-45 minutes.

Selection of participants: to take part in this study you must be:

- Male (18-30 years old);
- Able to run a 10 km personal best time between 37-45 minutes equating to 6-71/2 minute per mile pace.
- A runner who lands on the **heel** as the first point of ground contact.
- Able to make a time slot for data collection between May 24th-29th and June 6-13th 2003.

This study will be conducted using two groups:

Group 1: Control group
The first group will continue to run and train as normal while once a day for a week on your own, complete some drills, such as high knee lifts and butt kicks. This group will then need to attend the laboratory test and track run (between May 24th-29th and June 6-13th). A training log will then need to be kept for three months recording any injuries sustained. This can be handed in or emailed to Rick Velati.

Group 2: Pose® group
The second group will be trained in the Pose® method for one week with training sessions of 60-minutes each. This group will also need to attend the laboratory test and track run (between May 24th-29th and June 6-13th). A training log will then need to be kept for three months recording any injuries sustained. This can be handed in or emailed to Rick Velati.

Laboratory and track dates
Please fill in a time and day for both the lab and track pre and post tests (see sign up sheets).
Data collection dates:
Lab tests

- First lab test will be between May 26th and May 29th.
- Second lab tests will be between 9-11th June.

Procedure (what you need to do):
Please bring a pair of running flats (flattest pair of running shoes you have). A short tight fitting pair of running shorts. Please wear the same pair of shoes for both tests. You will need to sign the consent form and warm-up on arriving at the laboratory. Surface electrodes will be placed on five leg muscles to record the electrical muscle activity while you run (you will not feel any electrical impulses from this procedure). Reflective markers will be taped to certain points on your body so the cameras will be able to measure your running action. There will be a forceplate under the carpet that will record the forces you make when landing on the ground. Next you will practice running on the 16 m runway (the length of the lab) to ensure the markers and electrode wires do not

interfere with your natural running gait. Once you are comfortable with the running speed then five successful trials will be collected, at 3.35 $m \cdot s^{-1}$ (8-minute mile pace).

Running track data collection (2400 m economy and time trial run)

- First test May 24-25th (Saturday and Sunday between 8.30 am – 8 pm)
- Second test June 6th (Friday between 8.30 am – 8 pm)

You will select a 30-minute time slot between those times that suits your schedule on either day.

Procedure (what you need to do)
The warm up will consist of two laps at 8-minute mile pace. You will then be asked to run an economy run of 2400 m at 8-minute mile pace while oxygen consumption is collected by a portable gas analyser. Each 200 m section must be run evenly at a 1 minute per 200 m. Heart rate and time will be recorded from a polar heart rate monitor for the run and at the finish for the time it takes for your heart rate to drop to 120 beats per minute. Stride frequency will be recorded by a digital video camera for a 20 m section each lap.

Immediately following the economy run after removing the portable gas analyser a time trial will be run for 2400 m. Maximum, average heart rate and time will be recorded. Stride frequency will be recorded by a digital video camera for a 20 m section each lap. At the finish of the time trial run, the time heart takes to return to 120 beats per minute will be recorded. You will be asked to rate how hard the run felt using a Borg scale.

Please note:
Regardless of which group I am assigned too I will maintain for the one-week study:

- To allow 48 hours of light training prior to the track testing days (this is essential for valid data collection);
- To maintain a consistent diet and drinking procedure before testing and during the testing period;
- To maintain a training log of my training during the one-week testing period.
- And then maintain a training log of any injuries for 3-months after the study.

Please contact Graham Fletcher at icuchange@pacificcoast.net or Rick Velati at rick_velati@hotmail.com before May 20th, 2003 if you are interested in taking part in this study.

PARTICIPANT'S CONTACT SHEET

Name	Contact phone #	Time and day available for training

QUESTIONNAIRE

Name: Date:

Pre test: ☐

Post test: ☐

Please read carefully and circle he number that matches your opinion.

Please read the following item, and circle the number that best reflects your agreement with the statement.

Running technique is defined as the technical details and skill (pattern and sequence of movements) that determine the degree of excellence in accomplishing running movement.

Question	Not important at all	Fairly un-important	In-between	Fairly important	Extremely important
How important do you believe running technique is to overall performance?	1	2	3	4	5

INFORMED CONSENT

theCentrefor sport and exercise science

INFORMED CONSENT

Name: ______________________________
Address: ______________________________
____
______________________________ Tel: ____________

The full details of the tests have been explained to me. I am clear about what will be involved and I am aware of the purpose of the tests, the potential benefits and the potential risks.

The test results are confidential and will only be communicated to others such as my coach if agreed in advance.

I have no injury or illness that will affect my ability to successfully complete the tests.

My permission to perform this test is voluntary; I am free to stop the test at any point, if I so desire.

I ______________________________ acknowledge that there are risks and dangers inherent in physical exercise and declare that I know of no reason why I should not complete the tests described. Any questions I have about the test session have been answered, and the information given on the medical questionnaire is correct, and should be treated as confidential.

Signed: ______________________________ Date: ____________

Signature of guardian / parent if under 18 ______________________________

Signature of tester: ______________________________ Date: ____________

5

PRE-TEST MEDICAL QUESTIONNAIRE

theCentrefor

PRE-TEST MEDICAL QUESTIONNAIRE

Name:..

Date of Birth:......................... Age:.............. Sex:..............................

Please circle the appropriate response or fill in the blank.

1. How would you describe your present level of activity?

   Sedentary   Moderately active   Active   Highly active

2. How would you describe your 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. 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?	....
Were you an occasional smoker?	Yes No
	.........per day
Were you a regular smoker	Yes No
	.........per day

5. Do you drink alcohol? Yes No
   If you answered Yes, do you have?

   An occasional drink   A drink every day   More than one drink a day

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

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

8. 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 form 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			

9. Is there a history of heart disease in your family? Yes No
If **Yes**, please give details..
....
....

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

11. Have you had to suspend normal training in the last two weeks? Yes No
If the answer is **Yes**, please give details..
....
....

12. 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 to any question preceded by a * please ask your GP to complete the 'Doctors Consent Form' provided.

If blood samples are to be taken, please answer the following questions:

a)	Are you suffering from any known serious infection?	Yes	No
b)	Have you had jaundice within the previous year?	Yes	No
c)	Have you ever had any form of hepatitis?	Yes	No
d)	Are you HIV antibody positive?	Yes	No
e)	Have you had unprotected sexual intercourse with any person from an HIV high-risk population?	Yes	No
f)	Have you ever been involved in intravenous drug use?	Yes	No
g)	Are you hemophiliac?	Yes	No

* If the answer to any of the above is **Yes** then please discuss the nature of the problem with your Sport and Exercise Scientist.

Signature:..

Signature of Parent or Guardian if the subject is under 18:...

Date:....................

PARTICIPANT'S PERSONAL DETAILS SHEET

Name	10 km time	Age	Current injuries

APPENDIX 2

RUNNING TRACK TESTS

TRACK DATA COLLECTION SHEET ECONOMY RUN

Date and time ____________________/____________________

Pre test: ☐

Post test: ☐

Name/number	Oxygen	Stride frequency	Av HR	Max HR	Rec HR

TRACK DATA COLLECTION SHEET TIME TRIAL RUN

Date and time ____________________/____________________

Pre test: ☐

Post test: ☐

Name/number	Time	Stride frequency	Av HR	Max HR	Rec HR	Borg scale

TRACK SIGN UP SHEET

The economy and time trial run will take pace at Loughborough university track. Please select a convenient day and time for both pre and post tests.

Date	Time	Name	Date	Time	Name
May 24th	8.30 am		May 24th	2.30 pm	
May 24th	9.00 am		May 24th	3.00 pm	
May 24th	9.30 am		May 24th	3.30 pm	
May 24th	10.00 am		May 24th	4.00 pm	
May 24th	10.30 am		May 24th	4.30 pm	
May 24th	11.00 am		May 24th	5.00 pm	
May 24th	11.30 am		May 24th	6.00 pm	
May 24th	Mid-day		May 24th	6.30 pm	
May 24th	12.30 pm		May 24th	7.00 pm	
May 24th	1.00 pm		May 24th	7.30 pm	
May 24th	1.30 pm		May 24th	8.00 pm	
May 24th	2.00 pm		May 24th	8.30 pm	

Date	Time	Name	Date	Time	Name
May 25th	8.30 am		May 25th	2.30 pm	
May 25th	9.00 am		May 25th	3.00 pm	
May 25th	9.30 am		May 25th	3.30 pm	
May 25th	10.00 am		May 25th	4.00 pm	
May 25th	10.30 am		May 25th	4.30 pm	
May 25th	11.00 am		May 25th	5.00 pm	
May 25th	11.30 am		May 25th	6.00 pm	
May 25th	Mid-day		May 25th	6.30 pm	
May 25th	12.30 pm		May 25th	7.00 pm	
May 25th	1.00 pm		May 25th	7.30 pm	
May 25th	1.30 pm		May 25th	8.00 pm	
May 25th	2.00 pm		May 25th	8.30 pm	

Date	Time	Name	Date	Time	Name
June 6th	8.30 am		June 6th	2.30 pm	
June 6th	9.00 am		June 6th	3.00 pm	
June 6th	9.30 am		June 6th	3.30 pm	
June 6th	10.00 am		June 6th	4.00 pm	
June 6th	10.30 am		June 6th	4.30 pm	
June 6th	11.00 am		June 6th	5.00 pm	
June 6th	11.30 am		June 6th	6.00 pm	
June 6th	Mid-day		June 6th	6.30 pm	
June 6th	12.30 pm		June 6th	7.00 pm	
June 6th	1.00 pm		June 6th	7.30 pm	
June 6th	1.30 pm		June 6th	8.00 pm	
June 6th	2.00 pm		June 6th	8.30 pm	

VIDEO DATA COLLECTION SHEETS

Each participant had a test name/number for each test, which was filmed using a sheet of paper before each economy and time trial run for the stride frequency data collection. This enabled each participant to be clearly identified for each test. An example is given below for participant 1 for each test.

Pre economy 1

Post economy 1

Pre time trial 1

Post time trial 1

Borg scale (Borg, 1970)
Original rating scale

6	
7	Very, very light
8	
9	Very light
10	
11	Fairly light
12	
13	Somewhat hard
14	
15	Hard
16	
17	Very hard
18	
19	Very, very hard
20	

APPENDIX 3

LABORATORY TESTS

ROUTE MAP

Sheffield Hallam University **Visitors Guide**

- SHU homepage
- Visitors homepage
- Our location
- Plan your route
- Travel information
- How to get to
  - City Campus
  - Collegiate Crescent
  - Psalter Lane
- Campus plans
  - City Campus
  - Collegiate Crescent
  - Psalter Lane

The route to Collegiate Crescent

We can provide you with personalised driving directions to the University or use the general information below.

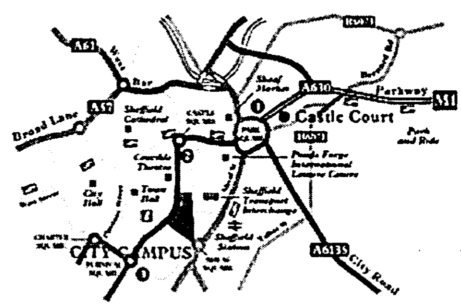
From junction 33 of the M1, follow signs for A630 Sheffield City Centre. Continue on the A630 until the dual carriageway ends at a roundabout with traffic signals (Park Square) ❶.

Take the fourth exit from the roundabout signposted City Centre, then the third left turn into Arundel Gate ❷. The Crucible Theatre is on your right and the City Campus on your left. Continue along the dual carriageway and go straight ahead (second exit) at the first roundabout ❸.

At the second roundabout, take the third exit onto the ring road ❹. Continue through the traffic lights to the next roundabout and take the first exit signposted A625 (Castleton) ❺.

The Collegiate Crescent Campus is approximately 750 metres (1/2 mile) along on the right.

Travelling by bus? take the 81, 82, 83, 84, 85 or 86 from Pinstone Street (outside the Town Hall) if visiting the Ecclesall Road end of the Campus. If visiting the Clarkehouse Road end of the campus, take the 50 (Dore) from the Transport Interchange or Church Street or the 60 (Ranmoor or Crimicar Lane) from Church Street or directly outside the train station. For Clarkehouse Road Schools (Health and Social Care/Social Studies and Law) you need to get off at the Hallamshire Hospital.



KISTLER FORCE PLATE CALIBRATION

LAB COPY

REAR

[illegible] LABS LTD PAGE 02

KISTLER R.J 6734

Kistler Instrumente AG Winterthur, Switzerland

[illegible]

KALIBRIERSCHEIN
KRAFT: MEHRKOMPONENTEN

CALIBRATION CERTIFICATE
FORCE: MULTICOMPONENT

Typ	Type	9281CA
Serien-Nr	Serial No	1031850

			F_x	F_y	F_z
Mehrkomponenten Kraftplattform	Multicomponent Force Plate				
Kalibrierter Bereich 4	Calibrated Range 4	kN	0 ... 8	0 ... 5	0 ... 20
Kalibrierter Bereich 2	Calibrated Range 2	kN	0 ... 0,5	0 ... 0,5	0 ... 2

Messungen	Measurements								
Kanal Nr / Channel No		1	2	3	4	5	6	7	8
Signal / Signal		X1+X2	X3+X4	Y1+Y4	Y2+Y3	Z1	Z2	Z3	Z4
Bereich 4 / Range 4*	pC/N	1,647	1,879	1,886	1,842	0,966	0,964	0,958	0,952
Bereich 3 / Range 3*	pC/N	3,693	3,759	3,773	3,683	1,932	1,927	1,918	1,904
Bereich 2 / Range 2*	pC/N	18,529	18,785	18,940	18,430	9,680	9,653	9,598	9,541
Bereich 1 / Range 1*	pC/N	37,059	37,569	37,881	36,879	19,360	19,305	19,197	19,082
		270.78	266.63	265.44	271.52	517.6	518.98	521.92	525.21

		$F_x \to F_y$	$F_y \to F_x$	$F_x \to F_z$	$F_y \to F_z$	$F_z \to F_x$	$F_z \to F_y$
Übersprechen Bereich 4 / Crosstalk Range 4	%	0,3	0,7	-0,2	0,1	-0,1	-0,1
Übersprechen Bereich 2 / Crosstalk Range 2	%	0,3	0,7	-0,1	0,1	-0,1	-0,2

* Gemessen
* Berechnet (±0,5%)

* Measured
* Calculated (±0,5%)

Umgebungstemperatur	Ambient Temperature	°C	23
Relative Feuchte	Relative Humidity	%	45

Kalibriert durch	Calibrated by	F. Heymann
Datum	Date	29.08.01

Wir bestätigen, dass das oben identifizierte Gerät nach den vorgeschriebenen Verfahren geprüft wurde. Alle Messmittel sind auf nationale Normale rückführbar, die Bezugsnormale über die von Kistler betriebene SCS (Swiss Calibration Service) Kalibrierstelle Nr. 049, akkreditiert nach EN 45001.

We confirm that the device identified above was tested by the prescribed procedures. All measuring devices are traceable to national standards, the reference standards through the SCS (Swiss Calibration Service) Calibration Laboratory No. 049, operated by Kistler and accredited per EN 45001.

Referenz-Geräte	Reference Equipment	Typ / Type	Serien-Nr / Serial No
Sensor (Gebrauchsnormal)	Sensor (Working Standard)	Kistler 9067/68	128843/107070/474351
Ladungsverstärker	Control Unit	Kistler 5233A1Y0380	683227
Spannungskalibrator	Voltage Calibrator	Knick S10	313665

ISO 9001 certified

PARTICIPANT'S LABORATORY BOOKING SHEET

Day/date	Car driver	Morning	Afternoon	Evening
Monday May 26th				
Tuesday May 27th				
Wednesday May 28th				
Thursday May 29th				
Monday June 9th				
Tuesday June 10th				
Wednesday June 11th				

LABORATORY DATA COLLECTION SHEET

Name:___________________________ **Date and time:** ________
______

Weight: ______________ **Height:** ______________

Filename: _______________________

Consent/medical: ☐ **Pre-test:** ☐

Questionnaire: ☐ **Post-test:** ☐

Trial	Accept	GRF hit	Time	EMG	Clean

APPENDIX 4

POSE® METHOD INTERVENTION

POSE® RUNNING INFORMATION SHEET
(Dr. N. Romanov and Graham Fletcher M.Sc)

A general overview of the theory of the Pose® method can begin with the laws of Thermodynamics. The law states that any system in nature goes from a higher order to lower level of energy. Therefore, any system needs to be built by an outside force. A plant needs the sun in order to build its cell structure. Running is the same, where the structure (body) needs to be able to utilise higher order forces (gravity) and energy (muscle contractivity and elasticity) in the most effective order. By making the most effective use of gravity, the flow of energy loss is least costly. The continuous use of muscle activity is limited by the body's ability to breakdown adenosine triphosphate (ATP). To accomplish an effective use of the available forces and energy in running, an economical skilful technique is paramount. Specifically, this relates to where force should be applied to continue movement, and the order in which these forces should be applied.

A brief discussion of linear kinematics can highlight the Pose® method's structure. The force of gravity when released (potential energy) is transferred to kinetic energy. A pencil held in the fingers above a table has potential energy and, when it is released it is transferred to kinetic energy. Following the pencil example, a pencil balanced on its end has potential energy, which becomes kinetic energy when it over-balances. The over-balancing of the human body from one support limb to the other, in running, immediately has kinetic energy, and the more skilful application of this energy can result in a more economical running gait. Kinetic energy can also be greatly increased by the body's velocity. The greater the velocity of the general center of mass (GCM) in flight increases the body's kinetic energy.

Focusing on the position of the support limb in relation to the GCM, the line of gravity is restricted from exerting its pull due to the position of the support limb being forward of the line of gravity at toe-off. The heel strike is also known as a breaking force. The term breaking in running is illogical in itself. Momentum will continue to remain constant in the absence of other forces, so breaking momentum each stride reduces forward velocity. The Pose method teaches that the support limb must break contact with the ground immediately:

1) to not hinder the gravitational line of pull
2) to maximise muscle elasticity, using the law of the coefficient of restitution- the greater elastic value the higher energy return. This can only be achieved by a rapid action, which is best achieved by a mid-foot strike.

The following, from a previous article, illustrate the actual body movements needed to achieve this theoretical model.

1) S (spring-like) shape of the body (the "running pose") - the element of running technique used for utilizing muscular elasticity and integration of the body into a single system.
2) Free falling – utilizes gravity as one of the main forces, driving the body forward horizontally.
3) Changing support –integrates forces that remove the foot from the ground while allowing gravity to pull the body horizontally forwards.
4) Pulling the support foot straight (vertically) up-wards using the hamstring muscles – allowing the foot to break contact with the ground quickly.

Developing these concepts, further, beginning with point (1) it is essential to understand that body position is integral to all movement. The body position determines the position of the GCM and the GCM determines the direction of the whole body. Once the body leaves the ground the path of the GCM cannot be altered, so the position the body is in before take-off is essential. At foot-strike, the position of the body is paramount because it affects how much the lower limb (particularly the knee) is loaded.

Point two, is interesting, because the need to apply an external force to initiate movement is obvious, but the question is what force to utilise? Current thinking is to apply Newton's third law of motion and push off from the ground. Following this logic to its natural conclusion, leads to wishing the runner, can push harder or faster, both requiring greater strength. Many seeking greater strength have unfortunately turned to illegal substances for the answer. However, there is another external force, which if utilised correctly, can be more effective. The following quotation written in 1912 by Graham - Brown in the British Medical Journal reveals the logic of this idea.
"*It seems to me that the act of progression itself- whether it be by flight through the air or by such movements as running over the surface of the ground-consists essentially in a movement in which the centre of gravity of the body is allowed to fall forwards and downwards under the action of gravity, and in which the momentum thus gained is used in driving the centre of gravity again upwards and forwards; so that, from one point in the cycle to the corresponding point in the next, no work is done (theoretically), but the mass of the individual is, in effect, moved horizontally through the environment.*"

Developing point three and four is again re-thinking our current running action ideas. Muscle force is predominantly focused upon when coaching or discussing running, yet another muscle property can greatly aid in limb movement. This is muscle elasticity. The musculotendinous junctions in the feet, Achilles and quadriceps tendon allow for storage and use of muscle elasticity, just as an elastic band can store elastic / strain energy when stretched. The key to effectively utilsing this energy to move the legs, is the speed at which the runner can change support. This means the speed at which you can remove your foot from the ground before the elastic energy has dissipated from those musculotendinous junctions.

This article has attempted to develop more fully some of the concepts of the Pose® method of running and highlight their differences with current running theory.

POSE® INTERVENTION RUNNING DRILLS

Summary of the week

Days 1-2	Developing the concept
Days 3-4	Reinforcing the concept
Days 5-7	Individual technique and skill development

Overall aims and objectives

Develop cognitive models, perception of falling and pulling the foot from the ground and finally auto correction of technique.

Practical daily outline

Introduce the concept: theoretically and practically. Utilise specific drills to gain a feel of the concept of falling and pulling the foot from the ground. Video each participant too aid learning. Give verbal and written feedback after each session.

Day 1

Short theoretical session in a classroom

There are four forces involved in running: gravity, ground reaction force, muscle force and muscle elasticity. Gravity, ground reaction force and muscle elasticity are free in reference to internal energy costs. Pose questions on how does gravity work in running and which external force moves the body forwards?

Show body tipping and falling forwards and assess muscle forces involved. Clarify gravity causes the tipping and no muscle forces were needed to fall. Explain then how to continue moving forwards by pulling the foot from the ground. Explain the use of muscle elasticity and its role in aiding pulling the foot from the ground. Emphasise the timing of falling and pulling the foot from the ground through the key concept of shoulder, hip and ankle vertical alignment.

Key to learning:

Increase participant's perception of the movement. Ascertain how they felt after each drill and running activity.

1) Use Pose® biomechanical model as standard to compare against.
2) Develop their perception but note their perceptions may be wrong so increase the correct perception.
3) They have to perceive two things: to feel falling and to pull the foot from the ground immediately they begin to fall forwards.

Drills

Warm-up: Video each participant running prior to intervention.

Falling position:

- Stand on heels and try and fall forwards. Try the same thing with the leg behind and in front.

Interaction with support:

- Stop participants in a freeze frame. Ask them where their weight is on their feet.
- Lift heels to see if weight is on the ball of the foot.
- Unlock knees and rapidly lift heels
- Keep weight on the ball of the foot at all times.

Move the body as an integrated system:

- Push participant back and forth and side-to-side while maintaining an integrated body position.

Weight position in relation to foot and centre of mass:

- Place a hand on their chest and take the participants weight as they fall forwards. Feel weight move from foot to chest.
- Repeat but let go this time.
- Repeat but demonstrate how small a lean is needed to fall forwards.
- Repeat and show where participant's foot lands in front of their body.
- Repeat, but ask them to pull their foot as they fall.

Feel pull of the foot from the ground:

- Hold their heel as they pull the foot from the ground
- Push foot down as they resist.

Video running and give feedback.

Summary:
Understand the model of gravity's work on the body, body leads leg and the foot is pulled from the ground as they fall forwards.

Day 2
Perception drills for falling

- Hand on belly button and feel vertical relationship to the ball of the foot.
- Repeat and fall forwards.
- Repeat and feel how small and angle is needed to fall.
- Run with fingers on belly button.
- Repeat with eyes closed; use partner.
- Arms stretched out behind the back and run.
- Hands pushing on hips and run.
- Hand on chest with partners and run.
- Partners fingers on back and run.

Range of motion of the lower-limb:
Emphasise a decreased range of motion. Show using running shoes the position of the foot, on landing and flight and impact again. Do not drive the leg forwards.

- Run and video for feedback

Rubber bands to illustrate a correct leg action

- Leg behind and in front as they run with the bands attached to their ankles.
- Run with partners in front and behind with hands on their shoulders.

Reduce effort needed by only using hamstrings to pull the foot.
Reduce effort needed by only using the minimal amount of hamstrings to pull the foot.
Technique problems to look for:

- Landing ahead of the centre of mass with the foot; do not drive with hip flexors.
- Landing on toes; feel ball of the foot on landing.
- Landing rigidly; relax and land with a neutral ankle.
- Landing on the sides of the foot; use pull up toes drill.
- Landing on the sides of the foot and rigidly; use Pony, tapping, slow light running.
- Landing hard, decelerate foot with hamstrings.

Hips and muscle integration:

- Standard hip drill, front back, behind and sides and run after each one.
- Standing and push person from all sides while holding them. Ensure body remains integrated.
- Run and video for feedback.

Body integration drills: check their perception:

- Partner running with eyes closed. Feel lightness and integration.
- Push from behind and resist with whole body and then run.
- Press back on partners hands hard and then run.
- Run while partner pressing down on their head to feel no vertical movement.

Summary:
Reinforce their perceptions. Can they feel falling and pulling of the foot from the ground? Do they feel lightness and body integration?

Day 3

Reinforcing the concept

Increase their perception for falling and speed of pulling the foot from the ground.

- Run with arms in front and behind.
- Partners push the shoulder from the side intermittently to check rapid change of support while running.

Pulling:

- Use rubber bands to increase feel of hamstring work.
- Standing band work and running with bands
- Short sharp downhill run to feel pulling action
- Individual holds bands and pulls vertically upwards from the shoulders and push out to the side for increased tension. Pull foot vertically upwards.

Pattern of movement reinforcement:

- Pony drill
- Tapping drill
- Skipping drill
- Front lunge drill
- Run 200 m and video for feedback

Summary:
Can they feel falling as they run? Can they pull the foot from the ground as they run?

Day 4

Reinforce fall and pull

- Press-up position without bands face down and upwards. Pull for hamstring work.
- Press-up position with bands face down and upwards. Pull for hamstring work.

Run 400 m and video for feedback:

- Use a metronome or count to develop stride frequency of over 180 per minute.

Observe mistakes:

- Keep knees flexed; do not extend leg at toe-off
- Maintain a vertical alignment on landing.
- Do not land ahead of the centre of mass.
- Do not leave the support leg behind.
- Fall.
- Do not fix the ankle on landing.
- Hips not integrated.

Look for:

- Lightness.
- Body integration.
- Pose position on landing
- Ease of running
- No pressure, tightness or pain.
- Fall and pull action.

Summary:
Give specific drills for each individual from feedback.

Days 5-7
Individual technique development

Day 5
Warm-up:
- Pony, tapping and skipping
- Cross steps.

Drills:
- Jumps

Run and video for feedback:
Run on gravel to emphasise pulling of the foot.
Summary:
Give individual drills and comments.

Day 6
Partner work with hips and hamstring and run.
Run and video give feedback individually.
Summary:
Give individual feedback.

Day 7
- Jumps on one leg; movement in the hips not knee.
- Feel hip, knee, ankle and ball of foot light and loose.
- Harder hip work with partners
- Run and video
- Show them day 1 and today for comparison.

Summary:
Final comments and feedback.

CONTROL GROUP'S DRILLS

Please read carefully the description of the drills and the daily format. Follow the daily format on your own for each of the seven days.

Drill description
Marching drill
Raise the right knee to hip level with each stride
Butt kicks

Daily routine

Please complete each day on your own. Repeat drills for each leg for as long a distance or time as you can accommodate comfortably while holding form.

Day 1	Marching drill, high knee lifts and butt kicks repeat four times for each leg.
Day 2	Marching drill, high knee lifts and kicks outs repeat four times for each leg
Day 3	Marching drill, kicks outs and bounding repeat four times for each leg
Day 4	Butt kicks, kick outs repeat six times for each leg and bounding four times 50 m.
Day 5	Butt kicks six times, high knee lifts repeat four times for each leg and bounding four times 50 m.
Day 6	Marching drill repeat four times, high knee lifts four times and bounding six times 50 m
Day 7	Butt kicks six times, kick outs four times for each leg and bounding six times 50 m.

TESTIMONIAL

Testimonial

Name: BRENDAN KEILTHY **Date:** 11/01/03

Please write a statement about your experience of learning the Pose method of running.

After the fourth day of learning to run Pose I felt a complete change in the way I ran. Running became a lot easier and less tiring than the way I ran originally.

The concept of Pose method running makes complete sense and after really taking it on board running fast or slow became really enjoyable.

Originally after a 400m sprint or a 5 mile run my knees especially would ache significantly followed by tenderness in the calf muscles. However after running the same distances in Pose none of this pain could be felt. In fact I felt as if I could quite easily run the same distance again.

Throughout the training I became more and more confident on improving my time trial significantly, however I was disappointed on the improvement of only 24 s. I strongly believe had it not been for the lack of sleep during the exam period, and especially a bad nights sleep before the post test, I would have easily improved my time by at least 45 seconds.

Without a shadow of doubt, Pose method running is the most efficient and enjoyable way to run. I can only hope I can maintain the pose method for years to come.

Signed: B. Keilthy

BRENDAN KEILTHY

INJURY RECORD SHEET

Name

Date	**Cause of injury**	**Type or description of the injury**	**Days off running**