

# **THE APPLICATION OF CLINICAL GAIT ANALYSIS TO RUNNING INJURIES**

**BY**

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# ABSTRACT

## Background

Clinical evaluation of the injured runner requires identification and correction of the multiple factors commonly implicated in running injury. Effective management of running injuries requires that the concerned health professional identify all implicated factors. In this regard it is essential that the relationship between running style and injury be determined, because if there is an association between the gait analysis variables descriptive of running style and injury, these would be important in the management of the injured runner. The Gait Analysis Laboratory at the Sports Science Institute of South Africa and the University of Cape Town with its three-dimensional Vicon 370 motion analysis system and Advanced Medical Technology Industry® strain gauge force platform is appropriate for collecting data to study running style. These data include the movement patterns and estimated mechanical power and work required to effect the observed movement of the ankle and knee. The forces applied by the supporting surfaces on the runners were collected. The data captured with the Workstation® programme (Oxford Metric, Oxford, England), was processed with GaitLab® (Kiboho Publishers, Cape Town, South Africa), collated in Excel® (Microsoft Corporation, Redmond, USA) and statistically analysed (StatSoft, Inc. (2000). STATISTICA for Windows [Computer program manual]. Tulsa, OK, USA). In this thesis a series of studies are presented with the aim of determining the relevance of running style to the assessment of the injured runner and the conventional treatment methods used to treat common running injuries.

## Study One

The aim of the study was to determine the repeatability of the gait analysis variables selected to describe running style. Data were collected from ten-(10) runners in test sessions on two consecutive days and from the group of seven-(7) runners in two test sessions on the same day. The speeds of the running trials of the consecutive day testing were faster on the second ( $3.9 \pm 0.5$  m/s) than on the first ( $3.8 \pm 0.5$  m/s) ( $p=0.031$ ). The speeds of the running trials of the same day testing were identical ( $2.8 \pm 0.4$  m/s). The test-retest correlation coefficients for all gait analysis variables selected ranged from  $r=0.75$  ( $p=0.012$ ) to  $0.95$  ( $p=0.000$ ) for the consecutive day tests. The test-retest correlation coefficients for all gait analysis variables selected ranged from  $r=0.81$  ( $p=0.027$ ) to  $0.99$  ( $p=0.000$ ) for the same day testing. The vertical impact force, knee angle in stance, ankle angle in terminal swing, ankle at initial contact and concentric ankle work were different between the first and second consecutive days of testing. There were no differences between the gait analysis variables measured in the two sessions on the same day of testing. The main finding of this study was that gait analysis variables descriptive of running style have greater repeatability when the repeated test sessions were conducted on the same day. Slow self-selected running speed trials had greater repeatability. Alterations in self-selected running speed caused differences between the running gait analyses variables measured on two separate days.

## Study Two

To clarify the relationship between the gait analysis variables and self-selected running speed alluded to in Study One a descriptive study of the gait analysis variables of 60 recreational runners was completed. The aim of this study was to determine the effect of self-selected running speed, foot-type and age on gait analysis variables. Sixty-(60) recreational runners ( $75.71 \pm 13.07$ , [range: 49-115] kg;  $1.76 \pm 0.09$ , [range: 1.54-2.01] m;  $34.88 \pm 13.08$ , [range: 18-70] years) with neutral (n=35), pronated (n=21) and supinated (n=4) feet were evaluated. Running biomechanics data were collected with standard gait analysis methods at  $3.1 \pm 0.5$  m/s, [range: 2.2-4.8 m/s]). Age and running speed were independent variables. There was no relationship between foot-type and the biomechanical variables measured. The horizontal braking and propulsive forces, vertical impact force peak magnitude and loading rate, and the vertical propulsive force peak increased with running speed. Greater running speed was associated with a plantarflexed ankle at initial contact and in stance and decreased knee flexion in stance. Ankle power absorption and eccentric work increased, whereas eccentric knee work decreased with greater running speed. Peak knee power generation and ankle power generation increased with running speed. The horizontal braking and propulsive, and vertical propulsive forces decreased with increasing age. An increase in age was associated with a more plantarflexed ankle in stance phase. Knee and ankle power absorption and generation all decreased with age. Running gait analysis variables are not influenced by the foot-type, but are related to self-selected running speed and the age of the runner. The findings of this study suggested that in all subsequent studies with a similar methodology, running speed and age would require control.

## Study Three

To further the evaluation of demographic factors in a running population initiated Study Two, a study was designed to determine the effect of gender on the gait analysis variables descriptive of running style. Ten (10) male and ten (10) female uninjured recreational runners matched for age, height, self-selected running speed, weekly running distance and best 10km race times were compared for running style gait analysis variables. The male runners were greater in mass than the female runners. There was a trend for the female runners to have greater vertical oscillation of the body compared with the male runners. The magnitude and loading rate of the vertical impact force vertical at 25ms of stance were lower in the female compared with the male runners. The knee was more extended in terminal swing and at initial contact phase in the female than the male runners. The joint power and work were similar between female and male runners. Female runners appear to prepare for and execute initial contact with a more extended knee than male runners. The difference in initial contact with the supporting surface is accompanied by lower impact forces in the female compared with male runners. The mechanical power and work supporting the knee and ankle in stance are similar in female and male runners. Studies designed to compare two or more groups of runners should take into consideration that gender may influence the running style gait analysis variables and have appropriate subject selection criteria.

## Study Four

The aim of this study is to determine the effect of the use of running shoes on the running style gait analysis variables compared with barefoot running. Thirty-five (35) injury-free male recreational runners undertook running trials in randomly administered barefoot, "neutral" and "antipronation" running shoe conditions. The magnitude and loading rate of the vertical impact force at 25ms of stance were greater in the barefoot compared with the "neutral" and

“antipronation” running shoes. The knee was more flexed and ankle more plantarflexed in the terminal portion of swing and at initial contact, in the barefoot compared with the “neutral” and “antipronation” running shoes. The peak knee power absorption and eccentric work were less in the barefoot compared with the “neutral” and “antipronation” running shoes conditions. The rating of perceived impact was greater in the barefoot compared with the “neutral” and “antipronation” running shoes. There were no differences in any of the gait analysis and perceptual variables between the “neutral” and “antipronation” running shoes. In the barefoot condition, runners prepare for contact with the supporting surface by flexing the knee and plantarflexing the ankle more compared with running with shoes. Barefoot running is associated with a high vertical impact force loading rate and the subjective perception thereof is appropriately reported by the runners. The instinctive response of the runner to the uncomfortable foot sensation associated with barefoot running appears to result in an alteration of the lower limb geometry and perhaps the alignment of the torso that is accompanied by lower knee power absorption and eccentric work compared with running with shoes.

## Study Five

Epidemiological evidence suggests that soft orthoses prescription has a role in injury prevention and treatment. The aim of the study is to determine the effect of orthoses “hardness” on running style gait analysis variables and the rating of perceived impact. Ten (10) injury-free male recreational runners were subjected to gait analysis, barefoot, in a laboratory shoe, and with three custom-made 4mm thick Ethylene Vinyl Acetate “soft” 25 Shore A, and “hard” 50 Shore A and 55 Shore A soft-orthoses. The mean running speeds of the five test conditions were similar. The magnitude and loading rate of the vertical impact force, and the vertical propulsive force were greater in all soft orthoses compared with barefoot. The knee was more flexed and ankle was more plantarflexed in the barefoot than soft orthoses conditions at initial contact. The ankle power absorption and generation, ankle eccentric and concentric loads, and knee power absorption and eccentric work were greater in all soft orthoses than barefoot. There were no gait analysis differences between the soft orthoses. The rating of perceived impact was greater in the barefoot ( $4.30 \pm 2.67$ ) than all individual soft orthoses conditions (F-ratio = 6.846,  $p = 0.000$ ). There was a trend for the RPI to reflect hardness of the soft orthoses conditions (running shoe:  $1.30 \pm 0.89$ , 25Shore A “soft” orthoses:  $1.35 \pm 0.97$ , 50Shore A “hard” orthoses:  $2.55 \pm 0.96$  and 55Shore A “hard” orthoses:  $2.60 \pm 0.94$ ). This result of the present study suggests that soft orthoses have a more profound effect on the runners’ perception of “hardness or softness” than on the gait analysis variables that describe running style. A hypothesis was proposed that soft orthoses of different hardness were equally beneficial in the treatment and prevention of running injuries, as the measured gait analysis effects were similar. The comfort offered by the soft orthoses may be guided by the perceived hardness and have a role in the expectation of injury treatment and prevention.

## Study Six

The aim of this study is to determine the effect of semi-rigid orthoses on the running gait analysis variables of recreational runners that are accustomed to the use of semi-rigid running shoe orthoses. Twelve (12) uninjured male and female recreational runners that routinely used semi-rigid orthoses as part of their training and racing were selected for the study. The runners were tested with and without semi-rigid orthoses in standard laboratory running shoes at self-selected running speed. Data were collected with clinical gait analysis methods. The perceived impact with and without orthoses were compared with a 10-point rating scale. The running speeds with orthoses and without orthoses were similar. The magnitude and the loading rate of the vertical

impact force at 25ms of stance were reduced with the use of orthoses. The ankle power absorption and eccentric work were reduced with the use of orthoses. There were no differences in the joint angles, other gait analysis variables or the rating of perceived impact between with- and without orthoses conditions. An enticing hypothesis is that the plantarflexed position of the foot within the shoe with the use of semi-rigid orthoses may account for the reduced eccentric load. In view of the association described between injury and eccentric joint load, the reduction in ankle eccentric load may account for the success of semi-rigid orthoses in the treatment of injuries in the leg and foot. The absence of any effect on knee joint eccentric load does not explain the reported benefits of semi-rigid orthoses for injuries at the knee.

## **Study Seven**

The aim of this study is to document the gait analysis changes that occur with a change from heel-toe to midfoot and Pose running. Twenty (20) heel-toe runners were instructed in running with midfoot and Pose running. Pose running was characterised by alignment of the vertical axis of the trunk with the mid-foot at contact with the supporting surface. A flexed knee position throughout the gait cycle and a rapid change in limb support was encouraged. Data were collected with clinical gait analysis methods. In comparison to midfoot and heel-toe, Pose running was characterised by shorter stride lengths and smaller vertical oscillations of the sacrum and left heel marker. Compared with midfoot and Pose, heel-toe running was characterised by greater magnitudes and loading rates of the vertical impact force of stance. In preparation for contact of the foot with the supporting surface the knee flexed more in Pose than in heel-toe and midfoot running. The ankle in terminal swing remained neutral in Pose compared with a dorsiflexed and plantarflexed position in heel-toe and midfoot running, respectively. The knee power absorption and eccentric work were less in the Pose than heel-toe and midfoot running. In contrast, there was greater ankle power absorption and eccentric work in Pose compared with heel-toe and midfoot running. Pose running displayed shorter stride and step lengths, and smaller vertical oscillations of the sacrum and left heel markers, a neutral ankle angle in terminal swing, lower eccentric work and power absorption at the knee, and higher eccentric work and power absorption at the ankle, than in midfoot and heel-toe running. The difference in alignment of the trunk between the novel and conventional running styles may account for the differences in eccentric joint load reported. The change in trunk alignment may change the position of the Centre of Mass and thereby the magnitudes of the lever arms at the knee and ankle that are central to the estimation of joint load. The model used to describe the gait analysis variables of running style did not however extend to the trunk. Trunk alignment and the Centre of Mass appear to be running style gait analysis variables that should be included in future gait analysis studies of running style and injuries as they may have a role in the understanding of the association between running injuries and running style, and the reduction in knee eccentric load with barefoot running. The merits of running style modification in the management of common running injuries warrant further investigation.

## **Study Eight**

The results of the preceding studies provide guidelines as to the demographic variables that would require control in the design of a study to determine the relationship between running style and injury. A running style comparison of runners with common running injuries with age, self-selected running speed and gender matched injury-free runners was undertaken. The aim of this study is to determine the relationship between running gait analysis variables and common running injuries, by comparing the running gait analysis variables of injured and injury-free runners. Seventeen (17) male and female runners diagnosed with Anterior Knee Pain Syndrome were

compared with forty-three (43) age, height, mass and gender matched injury free runners. Gait analysis data were collected. Running speeds were similar between the injured and injury-free runners. The horizontal propulsive force and the working rate of the vertical impact force at the peak magnitude were greater in the injury-free than injured runners. There were no differences in the joint angles between the injured and injury-free runners. The knee power absorption and the eccentric knee work were greater in the injured compared with the injury-free runners. The gait analysis variables that explain how a movement is brought about (ground reaction forces and joint power and work) rather than a description of the movement (joint angles) have an association with common running injuries. Specifically, the mechanical power and work generated within the musculotendinous structures that support the knee in stance (eccentric work), have a relationship with Anterior Knee Pain Syndrome. This was despite similar lower limb kinematics and ground reaction forces between injured and injury-free runners. Although no immediate explanation for the association between injury and eccentric joint load was apparent from a study of the variables collected in this study, the findings of subsequent studies appeared to be of assistance.

## **Discussion and conclusion**

Management of the injured runner demands identification and correction of the multiple factors commonly associated with injury. Management of running injuries requires that all implicated factors be identified and corrected. Clinical gait analysis in this work was applied to the evaluation of the gait analysis variables descriptive of running style with regard injury, and traditional and novel clinical interventions. The test-retest repeatability of the running style gait analysis variables selected was comparable with the literature. Age, gender and self-selected running speed were important in the comparison of two or more groups of runners. Injured runners had greater knee eccentric loads than injury-free matched controls. Running shoe use compared with barefoot running was associated with an increase in knee eccentric load. Semi-rigid orthoses reduced the eccentric load at the ankle but not the knee. Modification of running style from heel-toe to midfoot, and repositioning the trunk over the supporting foot was associated with reductions in impact force and eccentric load variables. Clinical gait analysis may be used in the dynamic evaluation of the injured runner, and the effects of selected clinical intervention methods that include semi-rigid orthoses and running style modification.

## GLOSSARY

- Anthropometric. Measurements that are taken to determine the dimensions of a particular segment or portion of the anatomy.
- Joint work: A mechanical estimation of the work that must be undertaken to support the knee in early stance (loading phase) and extend the knee in late stance (unloading phase)
- Impact. The collision of two objects with a transfer of energy between the two objects and the immediate environment.
- Midfoot. The plantar portion of the foot that represents the metatarso-phalangeal joint.
- Orthoses. Material of any nature that is purposefully placed within a running shoe to assist in running activities.
- Perception. The conscious interpretation of the situation or sensation that is the interpretation of stimuli from the environment by an individual.
- Pronation. A movement of the foot that allows the medial border of the foot to be in contact with the supporting surface, thereby assuming a pronated position.
- Recreational runner. A runner that participates in running activities for enjoyment and the gain of health benefits, and not for a professional purpose.
- Runway. A portion of the laboratory floor that is demarcated for the runners to keep within during the running trials.
- Supination. A movement of the foot that allows the outer border of the foot to be predominantly in contact with the supporting surface.
- Supporting surface. The floor or ground on which the running activity takes place.

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## **PUBLICATIONS ASSOCIATED WITH THE THESIS**

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2. Arendse RE, Noakes TD, Azevedo LB, Romanov N, Schweltnus MP, Fletcher G. Reduced eccentric loading of the knee with the pose running method. *Medicine and Science in Sports and Exercise* 2004 Feb. 36(2): 272-277.
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## **CONFERENCE PRESENTATIONS ASSOCIATED WITH THE THESIS**

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4. RE Arendse, MP Schweltnus The biomechanics of common running injuries. American College of Sports Medicine 2003 Annual Meeting San Francisco, USA.

## Introduction

According to generally accepted statistics, health professionals can expect to treat 37 to 56% of recreational runners who train steadily and occasionally participate in a long distance for running injuries (van Mechelen, 1992). The common running injuries are usually overuse in origin and occur when mechanical stress that is repetitively applied to susceptible musculoskeletal structures, accumulates and exceeds the capacity of those structures to maintain their integrity (Figure 1.1) (Messier et al., 1995). The musculoskeletal structures at the knee, leg and foot are most susceptible to running injuries and account for approximately 70 to 80% of all injuries (van Mechelen, 1992). Anterior Knee Pain Syndrome and Ilio-Tibial Band Friction Syndrome are common at the knee while Medial Tibial Stress Syndrome and Achilles' Tendonosis are common at the leg (James et al., 1978). The common foot running injury is Plantar Fasciitis.

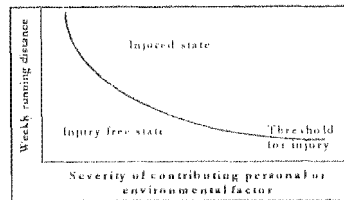


Figure 1.1. The relationship between weekly running distance, and personal and environmental factors and injury.

(Adapted from Messier et al., 1991)

Factors associated with excessive accumulation of mechanical stress within musculoskeletal structures commonly injured in runners may be grouped as those due to errors in the practice of the running activity, personal characteristics that predispose to injury and environmental conditions that may contribute to injury (Macera, 1992). There is strong evidence for the association between errors of the practice of running and running injuries. The evidence weakens for the association between personal characteristics of the runner and environmental conditions for the running activity, and running injuries. Establishing a cause-effect relationship between any of the factors in the three groups above, with running injuries is difficult, as there are too many variables that require control to complete a definitive study. Consequently, health professionals that manage common running injuries are charged with recognising and correcting factors associated with injury in injured runners. Therefore, concerned health professions need to be aware of all factors significantly associated with running injuries.

Running style can be defined as the gross movement patterns of the lower limb and the position of the trunk and head rather than the subtle intrinsic foot movements such as sub-talar pronation and supination and is not well described in the literature in relation to injury. Apart from a kinetic and kinematic description of the running style of elite and sub-elite distance runners (Cavanagh et al., 1977), and runners running backward (Devita and Stribling, 1991), there is little other documentation in the literature of running style.

The running style gait analysis variable of particular interest to the development of the most common running injury (Anterior Knee Pain Syndrome) in this thesis is negative work at the knee. Negative work at the knee can be estimated by the mathematical process of inverse dynamics (Winter, 1983) and represents the amount of work the structures supporting the knee must undertake to support the knee in stance. Downhill running is associated with greater quantities of negative work at the knee than level running (Buczek and Cavanagh, 1990) and it may therefore

be assumed that the structures that support the knee in stance are required to undertake greater amounts of work during downhill running. It appears intuitive to pose the question of whether the greater negative work at the knee is related to anterior knee pain commonly reported by runners after a strenuous downhill run. More specifically, is there an association between negative work at the knee and Anterior Knee Pain Syndrome which is reported to be the most common cause of knee pain in runners [James et al., 1978]).

While negative work at the knee may be the main variable of interest in this thesis, it is necessary to assess a variety of related kinetic and kinematic variables. This analysis is necessary to understand any observed changes in knee negative work. In particular, the gross movement patterns in the sagittal plane and the ground reaction forces should be interpreted together with the peak knee and ankle joint power and work variables.

The specific gait analysis variables chosen in this thesis are not currently reported with regard to the effect of age, gender, foot-types or self-selected running speeds. Neither are there clear guidelines on which gait analysis variables descriptive of running style are relevant to the understanding of running injuries and commonly used clinical interventions such as running shoe, semi-rigid orthoses and soft orthoses prescription. Finally, it is not known how the gait analysis variables descriptive of running style would change if the spontaneously learned running style of runners is changed through a systematic method of running style modification. These gait analysis variables would have to be studied if running style is to be proposed as a significant component of the health professions management of running injuries.

The research question that is posed in this thesis is:

“What effect do various running conditions have on the gait analysis variables used to describe running style and what is the relevance of any changes to understanding injury pathomechanics, prevention and treatment?”

In the following chapters a review of the relevant literature, the methods used to study the biomechanical variables descriptive of running style in relation to the demographic variables such as age, gender and self-selected running speed, the effect of injury, and conventional and novel clinical intervention methods is presented in response to the research question. The research question is addressed by a series of objectives that include the following studies:

Study One	Determining the repeatability of the gait analysis variables used to describe running style
Study Two and Three	Exploring the relationship between the gait analysis variables used to describe running style and age, gender, foot-type and self-selected running speed in an uninjured, recreational, adult runner population
Study Four, Five and Six	Determining the effect of running shoe, soft and semi-rigid orthoses use on the gait analysis variables
Study Seven	Determining the effect of running style modification on the gait analysis variables
Study Eight	Determining the relationship between gait analysis variables and common running injuries in a recreational adult running population

## LITERATURE REVIEW

### Part One: Common running injuries

Regular physical activity increases longevity (Paffenbarger et al., 1986), and improves the morbidity and mortality rate of lifestyle diseases such as hypertension, diabetes and coronary artery disease (Centres for Disease Control, 1987). Of the variety of regular physical activities that may be engaged in to obtain these improved health benefits, long distance recreational running is perhaps one of the most popular and convenient. Approximately thirty million people in the United States of America in 1984 were known to regularly engage in regular long distance recreational running activities for the maintenance of a healthy lifestyle (Clancy, 1980b, Jacobs and Berson, 1986). The convenience of not requiring specialised sporting facilities or expensive equipment are perhaps reasons that have contributed to the popularity of long distance recreational running. However, in the quest to achieve improved health benefits, recreational runners risk an alarmingly high annual incidence of injuries.

The average long distance recreational runner, that steadily trains and occasionally participates in a long distance run, has an annual injury incidence rate of between 37 and 56% (van Mechelen, 1992). The consensus in the literature is that the annual incidence of running injuries is between 25 and 75% (van Mechelen, 1992, van Mechelen, 1995). Approximately 23.2% of all running injuries are reported to occur at the knee, 14.6% at the shin, 12.4% at the Achilles', 8.3% at the forefoot and the balance distributed over the hip, thigh, calf, heel, ankle, arch, and groin, in 1000 runners surveyed by Runners World (Sheehan, 1977). Seventy (70) to 80% of running injuries occur at the knee and distally (van Mechelen, 1992). The majority of running injuries are associated with overuse (Walter et al., 1989) and are listed below (Table 1.1).

In this chapter, a brief description of the clinical presentation, diagnosis and principles of management of common musculoskeletal running injuries; the aetiological factors; and the models that relate the aetiological factors and running injuries, will be undertaken.

For the purposes of brevity, only the common running injuries will be briefly described in this work. It is not the intention of the author to present a comprehensive review of the common running injuries, but rather construct a frame upon which the reader may base the clinical biomechanical principles in the later portions of the chapter.

#### 1.1. Anterior Knee Pain Syndrome

Anterior Knee Pain Syndrome (AKPS) typically occurs in the anterior portion of the knee in the absence of a history of acute trauma (Duffey et al., 2000). AKPS is known by many different names: Runner's knee (Sheehan, 1977), Peripatellar Pain (James et al., 1978), Medial Retinaculitis (Clancy, 1980b), PatelloFemoral Pain Syndrome (PFPS) (Clement et al., 1981), RetroPatellar Pain Syndrome (Minkoff and Fein, 1989), and PatelloFemoral Pain (Messier et al., 1991). Although the pain is usually slow and gradual in onset, it may occur rapidly after a physically demanding run (Pretorius et al., 1986). The pain is usually worse with running downhill, climbing down or up stairs, or sitting with a flexed knee for a prolonged period of time. The pain is localised to the peripatellar tissues and the inferior to infero-medial border of the patellar (Krivickas, 1997). The pain distribution pattern is consistent with the anatomical arrangement of thin bands that pass from the patellar horizontally to the borders of the knee joint and constitute the medial and lateral retinacula (Krivickas, 1997) (Figure 1.1).

Table 1.1. List of common and less common running injuries

Common running injuries	Less common running injuries listed by tissue of origin	
Anterior Knee Pain Syndrome	Bone stress injuries (percentage of all bone stress injuries in runners).	Tibia (49.1%),
Ilio-Tibial Band Friction Syndrome		Tarsal bones (25.3%)
Medial Tibial Stress Syndrome		Metatarsals (8.8%)
Achilles' Tendinosis		Femur (7.2%)
Plantar Fascial Injury		Fibula (6.6%)
		Pelvis (1.6%)
		Sesamoids (0.9%)
		Spine (0.6%)
	Muscle injuries	Acute and chronic compartment syndromes Acute tears of any of the lower limb muscles Chronic muscle tears of the gluteus, groin, hamstring and "calf"
	Overuse tendon injuries	Patellar, politeal and quadriceps tendinosis
	Bursal injuries	Pes anserine, medial collateral and pre-patellar bursitis
	Nerve entrapment syndromes	Tarsal tunnel syndrome and medial plantar nerve entrapment syndrome
	Skeletally immature athletes with apophyseal injuries	Osgood-Schlatter disease, Sinding-Larsen-Johansson syndrome and Sever's disease

Matheson et al., 1987; Leach, 1982; Krivickas, 1997; Toulouplous and Hershman 1999; Smart et al., 1980

The diagnosis of AKPS is based on a suggestive clinical history (above) and an examination conducted to exclude related knee pathology (Table 2.1.2). Although many factors have been implicated in the aetiology of AKPS, the exact pathology is not known, with many runners diagnosed with AKPS having no apparent reason for the injury (Kannus and Niittymäki, 1993). As will be discussed later in Part Two of this chapter, training errors appear to be among the most important factors in the aetiology of this injury, followed by a variety of postulated anatomical alignment abnormalities (James et al., 1978).

Three major contributors to AKPS include: (i) malalignment of the lower extremity and/or the patella; (ii) muscular imbalance of the lower extremity; and (iii) training errors. The relationships between lower limb alignment abnormalities and AKPS are discussed in the Part Two of this chapter. Bony abnormalities other than lower limb alignment abnormalities that may cause abnormal tracking of the patellar include a shallow intercondylar sulcus and deformed patellar facets. Muscular imbalance includes: weakness of the vastus medialis oblique muscle, decreased knee extensor strength and tightness of the lateral retinaculum (Davidson, 1993; Thomee et al., 1999; 2002).

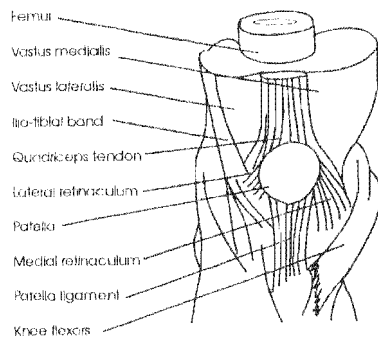


Figure 1.1. Retinaculæ at the anterior aspect of the knee

The intrinsic risk factors for the development of AKPS in an athletic population of 282 males and females were the subject of a prospective study. A shortened quadriceps muscle, an altered vastus medialis obliquus muscle reflex response time, decreased explosive strength, and a hypermobile patella correlated with AKPS (Witvrouw et al., 2000).

Table 1.2. Differential diagnoses of Anterior Knee Pain Syndrome

Differential diagnosis	History	Clinical features	Reference
Patellar tendinosis	Knee ache after exercise.	Pain at the lower pole of the patella and insertion of the tendon to the tibial tuberosity.	Messier et al., 1991
Chondromalacia patella	Degenerative condition of the cartilage on the posterior surface of the patella in contact with the patellar surface of the condyles of the femur.	Difficult to differentiate from AKPS on clinical or radiological grounds. Diagnosed exclusively by the arthroscopic features of degenerative change of the patellar cartilage.	Pretorius et al, 1986)
Patellar subluxation	History of an initial traumatic episode in which the "knee gave-way".		Davidson, 1993
Plica syndrome	Pain to the medial femoral condyle and the medial aspect of the patella.	Medial para-patellar plica commonly diagnosed on arthroscopy.	Leach, 1982).
Meniscal lesion	Medial joint pain, occasional lateral joint pain.	Degenerative type pain.	James and Jones, 1990

AKPS responds well to non-surgical treatment that includes correction of training errors and treatment of hip external rotators, hamstring, gastrocnemius-soleus muscle, vastus medialis obliquus and general quadriceps weakness and inflexibility (Post, 1998; Crossley et al., 2001). In addition, realignment procedures of the quadriceps with taping techniques, braces and stretching are used despite the paucity of evidence of their efficacy (Crossley et al., 2001). Seventy-seven percent (77%) of runners with AKPS respond well to a change in running shoes as part of a non-surgical management protocol (Pretorius et al, 1986). The prescription of running shoe orthoses is important in the non-operative management of AKPS (Crossley et al., 2001).

## 1.2. Ilio-Tibial Band Friction Syndrome

Lateral knee pain that is of spontaneous onset in the absence of a history of an acute traumatic episode but rather associated with a change in training history is characteristic of the Ilio-Tibial Band Friction Syndrome (ITB) (James and Jones, 1990). ITB classically presents after a well defined distance in running that is specific to each runner, and deteriorates if not correctly addressed (James and Jones, 1990). Although common in runners, ITB is also described in cyclists (Krivickas, 1997). Running downhill aggravates the pain, while walking often relieves the pain (Krivickas, 1997). The pain is localised to the lateral femoral epicondyle, approximately two centimetres proximal to the knee joint line and may extend to Gerdy's tubercle on the tibia (Krivickas, 1997). The distribution of the pain follows the distal attachment of the iliotibial band (Figure 1.2).

The pain of ITB may be reproduced by extending the knee from 90 degrees of flexion to approximately 30 degrees of flexion, while applying pressure over the lateral femoral epicondyle. At 30 degrees flexion, the ilio-tibial band slips over the lateral femoral epicondyle (Noble 1979). Variations of the width of the ilio-tibial band are reported and it appears that runners with broad ilio-tibial bands have a risk of impinging the edge of the band at the lateral femoral condyle in stance (Orchard et al., 1996). In addition, in runners with excessively inflexible lateral structures of the knee, the back-and-forth excursion of the ilio-tibial band across the lateral femoral epicondyle may cause friction between the ilio-tibial band and the lateral femoral epicondyle (Noble, 1979). The friction is thought to cause inflammation of the fibrous and bursal tissue deep to the distal ilio-tibial band (James and Jones, 1990). The inflamed fibrous tissue and bursa has been demonstrated ultrasonically and with magnetic resonance imaging (Muhle et al., 1999) and may account for the clinical symptoms of ITB (Ekman et al., 1994). Although a variety of anatomical abnormalities has been implicated in the aetiology of ITB (as will be discussed in Part Two of this chapter), training errors appear to be among the most important (James et al., 1978; Krivickas, 1997).

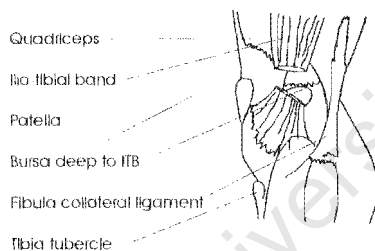


Figure 1.2. Iliotibial band fibre distribution at the lateral aspect of the knee

Non-operative management, which involves the correction of training errors and clearly identifiable anatomical factors, is the treatment of choice of ITB (James and Jones, 1990). Long distance runners with ITB who have weak hip abductors on manual muscle testing compared with their unaffected leg improve symptomatically and are able to return to the preinjury training program with improvement in hip abductor strength. (Fredericson 2000).

Although the majority of runners with ITB respond well to non-operative management, surgery is successful in the minority of runners that are resistant to non-operative treatment (Noble, 1979; Drogset, et al., 1999). Surgery consists of resection of a small triangular piece at the posterior part of the iliotibial band covering the lateral femoral epicondyle with the knee held in 60 degrees of flexion. The uniform good results, low morbidity, and quick return to sports demonstrate that this type of surgery offers a solution for selected cases of failed prolonged conservative treatment (Martens, 1989).

### 1.3. Medial Tibial Stress Syndrome

Injuries to the “shin” area of the leg account for between 2 and 31% of all running injuries and are common in the less well conditioned runner in the early season (van Mechelen, 1992). Injuries to the “shin” area of the leg may have a bony, periosteal/ fascial or muscular origin (Detmer, 1980). An anatomical classification of the origin of the “shin” injury refers to bone injuries as “Type I” with bone stress injuries as “Sub-type Ia” and stress fractures “Sub-type Ib”. “Type II” injuries refer to periosteal or fascial injuries. Muscular injuries are classified as “Type III”. Medial Tibial Stress Syndrome (MTSS) which would be within the “Type II” (Detmer, 1980 classification) refers to injury of the fascial origin of the soleus muscle or the periosteum beneath the origin of the tibialis posterior muscle (Figure 2.1.3) (Touliopoulos and Hershman, 1999).

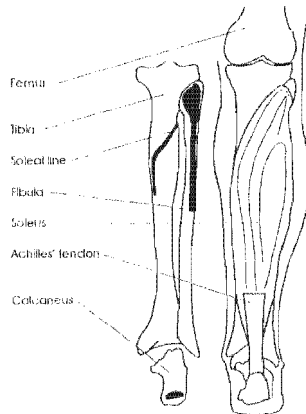


Figure 1.3. Periosteal origin of the soleus muscle may map the MTSS pain.

MTSS has previously also been termed Posterior Tibial Syndrome (James et al., 1978) and Tibial Stress Syndrome (Clement et al., 1981). The pain distribution of MTSS closely follows the anatomical origin of the soleus at the posterior aspect of the leg. The soleus muscle takes origin from the head and the upper third of the body of the fibula, from the soleal line of the tibia and the middle third of its medial border and from a tendinous arch between the tibia and fibula. In contrast the posterior tibial muscle takes origin from the upper two-thirds of the interosseus membrane, the medial aspect of the fibula, and the lateral aspect of the tibia (Romanes, 1981). Cadaver dissections have confirmed that the origin of the tibialis posterior muscle is not contiguous with the posterior medial border of the tibia (Michael and Holder, 1985). The difference in the fascial origins of the soleus and posterior tibial muscles helps in understanding the anatomical origin of the fascial injury in MTSS.

The exact cause of MTSS is unknown, but may be related to reduced bone density at the injury site due to remodelling of bone at the fascial origin in response to a loading stress (Michael and Holder, 1985). Histological investigation of bone and fascial tissue sampled from the site of injury of a runner with MTSS revealed new bone formation and prolific periostitis which supports the latter aetiological hypothesis (Michael and Holder, 1985).

Clinical experience suggests that excessive subtalar joint pronation may have a role in the aetiology of MTSS (Krivickas, 1997). Clinical observation suggests that subtalar joint pronation is controlled by eccentric contraction of the tibialis posterior, and that excessive subtalar joint pronation may cause abnormal increases in the eccentric activity of the same muscle. The increased eccentric activity is thought to place abnormal strain on the fascial and periosteal origin of the tibialis posterior with the eventual manifestation of injury. This mechanism is inconsistent

with the observation that the pain distribution follows the origin of the soleus rather than the tibialis posterior muscle in runners with MTSS (Michael and Holder, 1985). In this regard, the soleus does not have a direct role in the action of pronation and the importance of excessive subtalar joint pronation in the aetiology of appears doubtful. Nevertheless, a mechanical basis for the aetiology of MTSS remains a likely possibility and an area that requires further research.

“Shin-splints” is a term popularly used to describe the vague and non-specific cause of pain to the musculotendinous structures of the antero-lateral and postero-medial muscle compartments of the leg and is a Type II injury according to the Detmer Classification (Toulioplous and Hershman, 1999). Medial Tibial Stress Syndrome and shin splints are exacerbated by running and relieved by rest (Toulioplous and Hershman, 1999). MTSS refers to specific areas of inflammation within the leg and is distinct from “shin-splints” which is poorly localised. The two injuries are clinically differentiated by gently eliciting pain from the injured structures with careful palpation.

Non-operative treatment is successful in the most runners with MTSS (Moore, 1988). This prescription is based on clinical experience and includes (i) the identification and correction of training errors, (ii) stretching and strengthening programmes and (iii) correction of lower limb alignment abnormalities (Moore, 1988; Toulioplous and Hershman, 1999). A recent review of the literature revealed the most convincing evidence for effective prevention of MTSS was the use of shock-absorbing insoles (Thacker et al., 2002). Objective evidence for the prescription of heel cord stretching, alternative footwear and a graduated running program to prevent MTSS was lacking (Thacker et al., 2002).

Two injuries that may co-exist simultaneously (Kiuru et al., 2003) with MTSS and closely mimic it are stress fractures of the tibia (Detmer Classification Type Ia) and chronic exertional compartment syndrome (Detmer Classification Type III) (Toulioplous and Hershman, 1999). Bone stress injuries and chronic exertional compartment syndrome may be excluded with specific tests such as radiographs, radioisotope bone scans (Toulioplous and Hershman, 1999) and magnetic resonance imaging (Kiuru, 2003), and compartment pressure tests (Mollica and Duyshart, 2002), respectively. Definitive treatment includes fixation of stress fractures at risk of non-union or displacement, and fasciotomy of the muscle compartment with chronically elevated pressures (Turnipseed, 2002). The use of “shock absorbing” insoles and a reduction in the intensity of the running activity may have a role in preventing stress injuries (Gillespie and Grant, 2000).

#### **1.4. Achilles’ Tendinosis**

A clinical diagnosis of tendinosis may be formulated in runners with tendinopathy of the Achilles tendon when three common clinical signs are present. These include (i) a tender intratendinous swelling, (ii) a swelling that moves with the Achilles’ tendon and (iii) Achilles’ tendon tenderness that decreases or disappears when the tendon is put under tension (Maffulli et al., 2003). The Achilles’ pain may initially be present on initiation of running but be relieved once the run progresses (Grade One), deteriorate to being present throughout the run (Grade Two) and may eventually prohibit completion of the run (Grades Three). In the worst scenario, participation in running is prohibited by the pain (Grade Four). Achilles’ tendinosis must be distinguished from other injuries that have a similar presentation (Table 1.3).

Table 1.3. Differential diagnoses of Achilles' Tendinosis

Bone injuries	Calcaneal bone stress injuries and bruises Tibial bone stress injuries underlying the Achilles' tendon Exostosis of the posterior superior aspect of the calcaneus
Muscle injuries	Rupture of the soleus or the medial head of the gastrocnemius muscle Acute or chronic compartment syndrome of associated muscles
Bursal injuries	Retrocalcaneal and subcutaneous bursitis
Nerve entrapment syndromes such as are well described	Nerve entrapment of the medial branch of the posterior tibial nerve
Fascial injury	Plantar fascial injury

Smart et al., 1980

The pathological basis for Achilles' tendinosis is pathognomonic non-inflammatory degeneration of the tendon substance and contrasts the previous opinion that the substance of the tendon is inflamed, the so-called "Achilles tendinitis" (Khan et al., 1999).

The aetiology of Achilles' tendinopathy is unknown, but a variety of mechanisms have been proposed. Mechanical reasons such as excessive whipping of the Achilles' tendon, as occurs with abnormal pronation, is thought to impair the already reduced vascular supply of the Achilles' tendon and contribute to degenerative changes of the Achilles' (Smart et al., 1980). A second mechanical reason for Achilles' tendinopathy is the development of eccentric load-induced microtrauma that stresses the peritendinous structures and leads to inflammation (Nichols, 1989). The concept of load-induced microtrauma causing tendinopathy is supported by the observation of a greater number of microtears in the middle third of the substance of the Achilles' tendon in runners' with than without injury (Gibbon et al., 1999).

Areas of localised decreased arterial blood flow within the tendon substance is proposed to lead to local hypoxia and impaired metabolic activity and nutrition (Paavola et al., 2002). This is thought to cause a persistent inflammatory reaction that may eventually lead to chronic tendon overuse injury and degeneration. Angiographic injection techniques that have demonstrated a zone of relative avascularity between 2 and 6 cm proximal to the tendon insertion support this hypothesis (Lagergren and Lindholm, 1958). In contrast, microvascular perfusion studied with laser Doppler flowmetry has demonstrated the blood flow to be substantially lower near the calcaneal insertion but distributed evenly throughout the tendon (Åström and Westlin, 1994). It is unlikely that reduced blood flow alone would lead to tendinopathy, but in combination with other factors may lead to injury.

One of the factors most commonly implicated in tendinopathy is training errors. Training errors such as excessive running mileage and training intensity, hill running, running on hard or uneven surfaces, and wearing poorly designed running shoes are strongly associated with Achilles' tendon injury (Paavola et al., 2002). Metabolic causes of tendinopathy include corticosteroid injections and rheumatic conditions including gout, pseudogout, rheumatoid collagenolysis and Ankylosing Spondylitis (Smart et al., 1980).

The non-operative treatment of Achilles' tendinosis is based on cessation of the activities that induce the symptoms of the disease. The identification and correction of training errors and related

anatomical alignment abnormalities supplement this (Smart et al., 1980). Short-term improvements in patients with chronic Achilles tendinosis after progressive load eccentric training, a rehabilitation program that is based on increasing the length, tensile strength, and force of the muscle-tendon unit are reported (Alfredson et al., 1998). The rationale behind this treatment concept is contrary to the opinion expressed above in which eccentric load is implicated in microtears of the peritendinous structures. In view of the clinical benefits associated with this rehabilitation technique further investigation is warranted.

### 1.5. Plantar Fascial Injury

Plantar Fascial Injury (PF) is heel pain commonly associated with but not exclusive to running (Snider et al., 1983). PF is an overuse injury that is characterised by pain that originates at the medial border of the calcaneus and extends for a variable length of the plantar aponeurosis (Krivickas, 1997). The pain initially presents as early morning pain and stiffness (Brighton, 1997). The pain is noted with walking or running after prolonged inactivity, but improves once the activity is established (Krivickas, 1997). Deterioration of the injury may result in the persistence of the pain with exercise and may eventually lead to cessation of future running activity (Krivickas, 1997).

The plantar aponeurosis is a thickened central portion of the deep fascia of the sole, and extends from the medial aspect of the calcaneus to the flexor sheaths of the toes (Romanes, 1981) (Figure 1.4). The plantar aponeurosis takes up approximately 60% of the stress of static weightbearing and the beam action of the metatarsal 25% (Donatelli, 1985). The stress within the plantar aponeurosis is increased with extension of the toes as occurs at toe-off (Franco, 1987). The plantar aponeurosis by its loaded condition is at risk of injury. Therefore, direct trauma to the plantar aponeurosis with the development of microtrauma may result in injury (Brighton, 1997). The view that microtrauma is responsible for the clinical symptoms is supported by the histological examination of plantar fascia tissue resected from runners diagnosed with PF resistant to conservative treatment, which demonstrated extensive connective tissue degeneration (Snider et al., 1983).

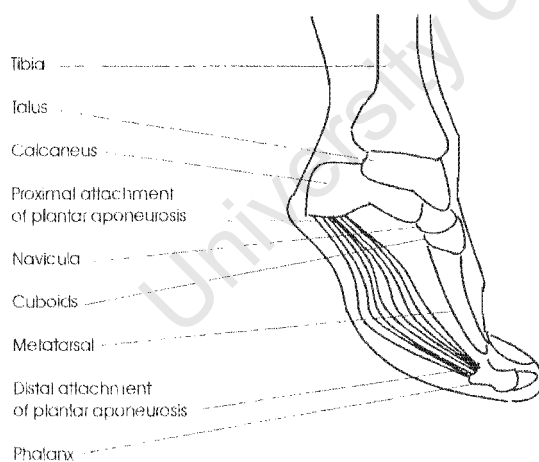


Figure 1.4. Plantar aponeurosis extends from calcaneus to toe flexor sheaths

Other medical conditions that may closely mimic plantar fascial injury include tarsal tunnel syndrome and a calcaneal bone stress injury (Schepesis et al., 1991). Seronegative spondyloarthropathies such as Ankylosing Spondylitis may present in a similar fashion to plantar fascial injury but are usually bilateral (Gerster et al., 1977). Fifty-five percent (55%) of runners may be predicted to sustain this injury based on a clinical examination (Warren and James, 1987).

A variety of anatomical factors is implicated in the aetiology of plantar fascial injury as will be discussed in Part Two of this chapter.

Radiographs may reveal the presence of a plantar calcaneal spur, but which may not be diagnostic as this may be present in the asymptomatic population. Magnetic Resonance Imaging clearly shows marked thickening of the proximal plantar fascia with increased intrasubstance signal intensity and perifascial edema in patients diagnosed with PF (Narvaez et al., 2000).

Conservative measures include rest, ice application, the use of a cushioned heel-cup, non-steroidal anti-inflammatory drugs, appropriately prescribed running shoe orthoses and running shoes (Schepesis et al., 1991; Krivickas, 1997). Although the mechanism is unknown, strengthening of the intrinsic muscles of the foot and lower limb stretching may assist in the treatment of PF (Krivickas, 1997). Cortisone infiltration of the affected area and surgical release of the plantar fascia with debridement of degenerative tissue are indicated only after convincing failure of conservative treatment (Brighton, 1997). Surgical release of the plantar fascia for runners with persistent pain and disability, despite comprehensive non-operative treatment is reported to be associated with satisfactory results at 25 months of follow-up (Snider et al., 1983).

### **1.6. Relevance of running injuries to the aims of the thesis**

Running injuries occur most commonly at and distal to the knee. Diagnosis of the injuries is dependent on careful history of the symptoms, localisation of the pain during clinical examination, and exclusion of the differential diagnoses by relevant special investigations. These injuries respond well to conservative treatment. The relationship between Anterior Knee Pain Syndrome and running style is addressed in Chapter Six of this work, with the aim of determining the merits of including gait analysis of running style in the assessment of the injured runner. Preliminary results of the study to determine the relationship between Ilio-Tibial Band Friction Syndrome, Medial Tibial Stress Syndrome and Achilles' Tendinosis, and running style are described in Appendix One.

## 2. Part Two: Aetiological factors

Running injuries have a multifactorial aetiology (James et al., 1978, James and Jones, 1990, van Mechelen 1992, van Mechelen, 1995). The factors implicated in the aetiology of running injuries may be grouped as 1. The characteristics of the running practice, 2. The characteristics of the runner and 3. The characteristics of the running environment, (van Mechelen, 1992). In this part of Chapter Two, the aetiological factors are summarized and the reader is referred to comprehensive reviews for further detail.

### 2.1. Characteristics of the running practice

Mechanical load is placed on musculoskeletal structures within the lower limb during running. A training load that does not place an excessive mechanical load on the musculoskeletal structures is assumed to be safe. However, a training error may lead to the accumulation of excessive stress within the lower limb musculoskeletal structures and risk injury. The characteristics of the running practice in which errors may occur include the weekly running distance, running frequency, weekly running time, training speed, changes in running activity, and warm-up, cool-down and stretching activities (Clancy, 1980a; Walter et al., 1989; Macera et al., 1989; Marti et al., 1988; Powell et al., 1986; Jacobs and Berson, 1986; Blair et al., 1987).

The multifactorial aetiology of running injuries makes it impossible to quantify the magnitude any of the training variables needed to constitute a risk for injury. Nevertheless, a linear risk between injury and weekly running distance is reported in 2500 runners in a 10km race, (Koplan et al., 1982). The relationship between injury and weekly running distance was confirmed in a ten-year follow-up of 535 runners surveyed in the latter study, in which 31% of male runners had stopped running because of injury, and 53% had sustained at least one injury during the follow-up period (Koplan et al., 1995). The association of running distance with injury is supported by the observation that injured runners run greater weekly distances ( $20.0 \pm 7.50$  miles/week;  $32 \pm 12$  km/week) than uninjured runners ( $15.0 \pm 7.50$  miles/week;  $24 \pm 12$  km/week) (McQuade, 1986).

In spite of the multifactorial aetiology of running injuries, the association between injury and weekly running distance is so strong that the frequency of training sessions does not appear to have any additional effect. The division of the total weekly distance into smaller, more frequently completed running distances does not appear to reduce the risk of injury (van Mechelen, 1992). In addition to the total weekly running distance, the time spent running daily too is a risk for injury. Thirty minutes of running daily appears to be a critical threshold above which the risk of running injuries is increased (Colbert et al., 2000).

Sudden changes in training habits (Jacobs et al, 1986), described as “running too often, too fast, or too long” (Franklin et al., 1979) are a risk for injury because susceptible musculoskeletal structures are exposed to unaccustomed loads which exceed their resilience and lead to injury. This hypothesis has support in the observation that an increase in training volume is associated with a greater risk of anterior thigh and hamstring injuries (Satterthwaite et al., 1999).

The relationship between stretching, warm-up and cool-down habits, and running injuries has not been established. Stretching before exercise produced small and statistically non-significant reductions in muscle soreness. Stretching 24 hours after exercising reduced muscle soreness by approximately 0.9 mm on a 100 mm scale (95% confidence interval -2.6 mm to 4.4 mm). Muscle soreness and a risk of injury are not reduced by stretching before or after exercise (Herbert and Gabriel, 2002). One reason offered as to why stretching does not prevent injury is that stretching

does not have an effect on muscle compliance during eccentric activity, when most injuries are believed to occur (Shrier, 1999).

It is suggested that a runner at risk for injury may be able to reduce the onset of injury by maintaining the training load below a specific individually determined threshold and limiting rapid changes in training activity. The multifactorial nature of the aetiology of running injuries means that maintaining safe running practices is not a guarantee against injury. The identification of the risk factors other than training errors is therefore important and the relevant factors are described below.

## 2.2. Characteristics of the runner

The multifactorial aetiology of running injuries suggests that in the absence of an abnormality of the running practice, factors such as the personal characteristics of the runner may be a risk. Personal characteristics that may contribute to the accumulation of mechanical stress within musculoskeletal structures of the lower limb and have the potential to cause injury include gender, age, running experience, height and mass, psychological factors, a history of previous injury and lower limb alignment factors (Macera et al., 1989; Marti, 1988; Walter et al., 1989; Montgomery et al., 1989; Jacobs and Berson, 1986; Powell et al., 1986; Neely, 1998).

### 2.2.1. Gender

Recent epidemiological evidence suggests, “females undertaking strenuous exercise alongside males are at increased risk of injury” (Bergman and Miller, 2001). Studies of mixed gender populations exposed to the same exercise activity and training environment, have found an increased risk of injury in females (Bergman and Miller, 2001; Gemmell, 2002). Differences in the anatomical distribution of the injuries, with males at increased risk of hamstring and calf problems, and females at increased risk of “hip injuries” are reported (Satterthwaite et al., 1999). The difference in injury rates may be related to anatomical differences that include greater quadriceps angles (Horton and Hall, 1990), narrow feet (Hennig, 2001) and hormonal abnormalities in female compared with male runners. In addition to structural differences, females are reported to have functional differences that include lower vertical impact forces and greater rates of subtalar joint pronation than males. The latter difference in lower limb function between the genders suggests that there may be differences in the amount of stress generated within susceptible structures. Functional differences between the genders are investigated later in this work (Study Three) and lay the foundation for the study into an association between running style and injury (Study Eight).

### 2.2.2. Age

Running injury rates do not appear to increase with age (van Mechelen, 1992). This contrasts the observation that the injury risk in sports such as squash and soccer tend to increase with age, and which is attributed to an increased risk of injury with musculoskeletal tissue degeneration (Taimela et al., 1990). A “well-runner” effect on this apparent absence of increased running injury risk with age is suggested. This refers to the attrition of runners due to injury, with continued participation in running, so that only the “well” runners continue to participate into old age. Hence the older runners that continue to run do not appear to be at increased risk of injury (van Mechelen, 1992). Older runners reduce the magnitudes of the ground reaction forces when they are allowed to self-select running pace and thereby may assume a running method (style) that is protective. The relationship between the age of the runner and the gait analysis variables that are descriptive of running style is determined later in this work (Chapter Four). The findings of this

study suggest that age is an important variable that should be controlled in a study of the association between running style and injury (Chapter Six).

### 2.2.3. Running experience

Inexperienced runners have higher injury rates (Satterthwaite et al., 1999). The inexperience of these runners may lead to the adoption of training methods that are a risk of injury (Chorley et al., 2002).

### 2.2.4. Previous injury

Injured tissue that does not heal completely, does not function as well, persists or is less protective than before the injury is a risk for a recurrence (van Mechelen, 1992). A prior injury is therefore an important risk factor for future injuries (Chorley et al., 2002). Other explanations for the higher risk of injury following an initial injury include an intrinsic susceptibility of the injured tissue for repeated injury or another intrinsic abnormality that is not corrected (Macera, 1992). The exact mechanism by which a first injury may predispose to a subsequent injury remains unknown.

### 2.2.5. Lower limb alignment abnormalities

Lower limb alignment abnormalities are commonly implicated in running injuries. (Neely, 1998). This follows the opinion that a perfect lower limb alignment was immune to injury, despite “feats of endurance... on a regular basis”, and that “structural imbalance” is important for running injuries (Sheehan, 1974). The lower limb alignment abnormalities are grouped as those intrinsic and those extrinsic to the foot. Three selected lower limb alignment abnormalities that may be considered intrinsic to the foot include the rearfoot and forefoot orientation, and arch height (Dahle et al., 1990).

#### 2.2.5. a. Lower limb alignment abnormalities intrinsic to the foot

##### 2.2.5. a.A. Rearfoot alignment

The rearfoot consists of the calcaneus and the talus. The lower articular surface of the talus articulates with the superior surface of the calcaneus at the subtalar joint (Romanes, 1981; Bruckner, 1987; Kapandji, 1987; Barbaix et al., 2000). The alignment of the talus and calcaneus is estimated from the orientation of the posterior aspect of the calcaneus and leg, with the talus in a neutral position (Schuster, 1977; Subotnick, 1977; Phillips et al., 1985). The rearfoot angle may be measured with a mechanical device that aligns the borders of the calcaneus with the long axis of the leg (Kaye and Sorto, 1979) or by well described clinical methods (Oatis, 1988; Elveru et al., 1988; Dahle et al., 1990). A series of studies have been completed to determine the relationship between rearfoot alignment and injury (Table 2.1).

The results of at least one of the studies reviewed in Table 2.1 suggest an association between rearfoot alignment and an acute traumatic injury. A similar relationship between rearfoot alignment and overuse running injuries is not apparent in the remaining studies reviewed. Although a consistent relationship between rearfoot valgus angle and injury is not apparent in the studies reported above, the merit of evaluating rearfoot alignment and injury in the management of the individual runner is not disputed.

Table 2.1. Relationship between rearfoot valgus angle ( $^{\circ}$ ) and injury

Injured	Uninjured controls	Clinical diagnosis	Reference
8.70 $\pm$ 2.7*	7.22 $\pm$ 2.6	Acute ankle injury	Baumhauer et al., 1995
6.27 $\pm$ 0.95 NS	6.67 $\pm$ 0.95	AKPS	Messier et al., 1991
Soldiers with a rearfoot valgus of 4-5 degrees have a 1.65: 1 risk of injury		Stress fractures	Hughes, 1985
No difference between injured and uninjured		ITB	Schwellnus, 1993

\* Significant difference between the injured and uninjured groups ( $p < 0.05$ ); NS: not significant

### 2.2.5. a.B. Forefoot alignment

The orientation of the forefoot relative to the rearfoot is largely determined by the bony configuration of the transverse tarsal joint (Oatis, 1988; Kannus, 1992). Measurement of the forefoot alignment in clinical practice, involves placing the runner in a non-weightbearing position, with the talus in a neutral position. Forefoot varus, valgus and neutral orientations are described when the forefoot orientation in relation to the rearfoot is inverted, everted and neutral respectively (Somers et al., 1997; Glasoc et al., 2000). Forefoot varus occurs in 86.6%, forefoot valgus in 8.75% and neutral forefoot in 4.58% of a normal asymptomatic population of 234 normal feet (Garbalosa et al., 1994). The recognition of the presence of the entire range of forefoot alignments in an asymptomatic population suggested that the severity of forefoot abnormality rather than its presence may be a risk for injury (Garbalosa et al., 1994). The results of the studies in Table 2.2.2 evaluate this theory.

Two of three studies documented found significant associations between the severity of forefoot varus and injury (Table 2.2.2). Measurement of the forefoot alignment appears to be important to identify in the evaluation of the injured runner. Prospective studies of this alignment abnormality are required to establish a cause-effect relationship between forefoot alignment and injury.

Table 2.2. Relationship between forefoot varus angle ( $^{\circ}$ ) and injury

Injured	Uninjured controls	Clinical diagnosis	References
5.3 $\pm$ 0.5*	4.1 $\pm$ 0.3	ITB	Schwellnus, 1993
4.20 $\pm$ 1.99 NS	3.53 $\pm$ 1.96	Acute ankle injury	Baumhauer et al., 1995
Soldiers with forefoot varus of 1-17 $^{\circ}$ have a 8.3: 1 risk of injury*		Stress fractures	Hughes, 1985

\* Significant difference between the injured and uninjured groups ( $p < 0.05$ ); NS: not significant

### 2.2.5. a.C. Arch height

The medial longitudinal arch is the most prominent of three arches that support the plantar vault, the others being the anterior and lateral arches (Lapidus, 1963). From distal to proximal, the medial longitudinal arch is comprised of the first metatarsal, the medial cuneiform, the navicular, the talus and calcaneus (Kapandji, 1987).

Measurement of the height of the arch varies from a high level of accuracy using precision calipers (Wen et al., 2000) to gross estimation with visual inspection (Dahle et al., 1990). The standing foot angle (Sommer and Vallentyne, 1995) and the ratio of navicular height with the truncated foot length [distance between posterior portion of the calcaneus to the centre of the first metatarsophalangeal joint] are valid descriptions of arch height (Williams and McClay, 2000). The navicular differential [difference in height of the navicular bone from the supporting surface in non-weightbearing and weightbearing positions] measures the flexibility of the arch (DeLacerta,

1980; Gross, 1995), The prediction of arch height from footprint parameters that include arch angle, footprint index, arch index, arch length index and truncated arch index is invalid (Hawes et al., 1992).

Table 2.3. Relationship between arch height and injury

Injured	Uninjured controls	Clinical diagnosis	References
8.90± 2.89*	5.56± 2.32	Shin splints	DeLacerda, 1980
Navicular differential (°)			
0.238±0.058*	0.251± 0.041	AKPS	Duffey et al., 2000
arch index			
0.24± 0.01NS	0.24± 0.01	AKPS	Messier et al., 1991
Arch index			
20.0±4.4NS Arch height (mm)	19.3±4.9	Unspecified injuries	Hreljac et al., 2000
A high arch is associated with a 39.6% risk of stress fractures			Giladi et al., 1985

\* Significant difference between the injured and uninjured groups ( $p < 0.05$ ); NS: not significant

An arch that is more flexible (greater navicular differential) appears to be associated with injury to the leg (shin splints) (Table 2.2.3). A low arch (low arch index) is associated with injury to the knee (Table 2.2.3). However a high arch is also associated with a risk of injury (stress fractures) (Table 2.2.3). The absence of an association between arch height and arch index, and injury in the studies by Messier et al., 1991 and Hreljac et al., 2000, respectively reveal a lack of consensus between these specific variables and injury. Arch height has some association with injury, with the injuries specific to whether the arch is excessively high or low.

#### 2.2.5. a.D. Foot-type

Pronated and supinated foot-types represent the extremes of the spectrum of foot types that runners are commonly recognized to have (McPoil and Hunt, 1995). Neutral foot-types are the most common and span the range between the pronated and supinated foot-type spectrum. Normal feet include neutral foot-types and feet with some features of either pronated or supinated foot-types (McPoil and Hunt, 1995). Foot-type may be distinguished on clinical criteria (Table 2.2.4). Subtalar joint pronation in the neutral foot is hypothesized to be essential for attenuating the impact forces created during running (Donatelli, 1985). The excessively pronated foot contacts the supporting surface in a posture that does not allow the normal subtalar joint pronation to occur and is therefore unable to effectively attenuate the impact forces during running (Donatelli, 1987). Abnormal stress created within susceptible musculoskeletal structures during abnormal foot movements such as excessive subtalar joint pronation is also considered a possible mechanism by which injury occurs (Donatelli, 1987). The supinated foot is too inflexible to allow subtalar joint pronation to occur and consequently is unable to attenuate the impact forces of running either (James et al., 1978). Abnormal leg movement associated with a high arch suggests that the supinated foot may cause injury by causing abnormal movement which creates abnormal stress within susceptible structures (Nigg et al., 1993). This suggests a “J-shaped” relationship between injury and foot-type where pronated and supinated foot-types are the extremes of foot-type morphology and have a strong association with injury (Freychat et al., 1996).

Table 2.4. Clinical classification of foot-type

	<b>Pronated foot-type</b>	<b>Neutral foot-type</b>	<b>Supinated foot-type</b>
<b>Rearfoot alignment</b>	Calcaneus is noticeably everted [>3 <sup>0</sup> from a perpendicular through the calcaneus] (a) Or Standing calcaneal >10 <sup>0</sup> (b)	A neutral foot is one that does not meet the criteria for classification as either pronated or supinated, in the absence of any other structural abnormalities (a)	Calcaneus is noticeably inverted [>3 <sup>0</sup> from a perpendicular through the calcaneus] (a)
<b>Medial border</b>	Medial border of the foot bulges due to excessive protrusion of the talar head to the medial side of the foot (a)		Medial border of the foot does not bulge (a)
<b>Arch height</b>	Medial arch is low (a) Longitudinal arch angles <135 degrees (b)		Medial arch high (a)
<b>Forefoot alignment</b>	Forefoot is abducted on the rearfoot (a)		Forefoot is adducted on the rearfoot (a)
<b>Secondary clinical signs</b>	Medial bowing of the Achilles' tendon secondary to calcaneal eversion (c)		
<b>Plantar signs</b>	Callus formation beneath 1 <sup>st</sup> and 2 <sup>nd</sup> metatarsal heads, and the medial aspect of the calcaneus (c)		

(a) Dahle et al., 1991; (b) Jonson and Gross, 1997; (c) Franco, 1987

Subtalar joint pronation in the neutral foot is hypothesized to be essential for attenuating the impact forces created during running (Donatelli, 1985). The excessively pronated foot contacts the supporting surface in a posture that does not allow the normal subtalar joint pronation to occur and is therefore unable to effectively attenuate the impact forces during running (Donatelli, 1987). Abnormal stress created within susceptible musculoskeletal structures during abnormal foot movements such as excessive subtalar joint pronation is also considered a possible mechanism by which injury occurs (Donatelli, 1987). The supinated foot is too inflexible to allow subtalar joint pronation to occur and consequently is unable to attenuate the impact forces of running either (James et al., 1978). Abnormal leg movement associated with a high arch suggests that the supinated foot may cause injury by causing abnormal movement which creates abnormal stress within susceptible structures (Nigg et al., 1993). This suggests a "J-shaped" relationship between injury and foot-type where pronated and supinated foot-types are the extremes of foot-type morphology and have a strong association with injury (Freychat et al., 1996).

The terms supinated and pronated foot-types are occasionally used interchangeably with pes cavus (high-arch) and pes planus (flat-foot), respectively (Franco, 1987). The substitution of these terms may not be entirely correct, as pes planus and cavus are considered to be morphologies distinct from the foot movements of pronation and supination (Franco, 1987). Both pes cavus and planus are associated with injury by virtue of the hypothesis that they do not facilitate attenuation of

impact forces during running (Tibero, 1988). However they are not associated with injury due to abnormal movement of the foot and thereby may be distinct from the abnormal movements of pronation and supination. The association between foot-type and injury is largely hypothetical with the strongest evidence gained from a single case series study in which 58% and 20% of injured runners had pronated and supinated foot morphology (James et al., 1978). No cause-effect relationship between foot-type or its individual descriptors such as rearfoot and forefoot alignment, and arch height, and injury is reported in the literature (Neely, 1998). Foot-type identification in the individual runner with an injury may have merit, and until this association is excluded, is recommended in running injury management.

An area that has not been addressed in the literature is the relationship between foot-type and the gait analysis variables used to describe running style. An association between foot-type and the gait analysis variables used to describe running style may provide insight into mechanisms by which intrinsic foot alignment abnormalities may cause injury. The relationship between foot-type and running style is explored later in this work (Chapter Four) and the findings of the study reveal weaknesses in the gait analysis methods used to describe running style. In the following paragraphs of this chapter, the lower limb alignment abnormalities proximal to the foot that are considered to have a relationship with running injuries are discussed (Dahle et al., 1991).

## 2.2.5. b Lower limb alignment abnormalities proximal to the foot

### 2.2.5. b.A. Musculotendinous inflexibility

Inflexibility of the hip internal rotators, knee flexors, ankle plantarflexors (James et al., 1978; Kannus, 1992, James and Jones, 1990) and the iliotibial band are intuitively associated with an increased risk of injury (Krivickas, 1997). Inflexibility as indicated by short or tight hamstrings is associated with unspecified overuse running injuries (Hreljac et al., 2000). However, attempts to associate hamstring inflexibility with specific injuries such as shin splints has not been successful (Messier and Pittala, 1988) (Table 2.5). A cause-effect relationship between inflexibility of individual musculotendinous structures and specific injuries requires further investigation.

Table 2.5. Relationship between musculotendinous inflexibility and injury

Injured	Uninjured controls	Clinical diagnosis	References
-3.7±11.6* Hamstring length difference (cm)	3.2±10.2	Unspecified injuries	Hreljac et al., 2000
47 NS Total hamstring length (cm)	47	Shin Splints	Messier and Pittala, 1988

\* Significant difference between the injured and uninjured groups ( $p < 0.05$ ); NS: not significant

In the absence of musculotendinous abnormalities such as fibrous contractures, passive rotation of a joint is dependent on the flexibility of the muscles, tendons and ligaments crossing the joint. Restricted plantarflexion is hypothesised to encourage a pronated foot posture (Kannus and Niittymäki, 1994). As abnormal pronation is considered a risk for knee injury, it appeared intuitive to evaluate the relationship between AKPS and passive plantarflexion range of movement (Table 2.6). Maximum plantarflexion did not have an association with Anterior Knee Pain Syndrome (Duffley et al., 2000). Greater passive plantarflexion was associated with Plantar Fascial Injury (Messier & Pittala, 1988) (Table 2.6). As this is inconsistent with the mechanism proposed to cause excessive pronation, the exact mechanism by which Plantar Fascial Injury is caused is not known.

Table 2.6. Relationship between ankle plantarflexion ( $^{\circ}$ ) and injury

Injured	Uninjured controls	Clinical diagnosis	References
63.67 $\pm$ 1.50*	56.58 $\pm$ 2.09	Plantar Fascial Injury	Messier & Pittala, 1988
Plantarflexion ( $^{\circ}$ )			
43.9 $\pm$ 0.8 NS	41.9 $\pm$ 0.7	AKPS	Duffey et al., 2000
Plantarflexion ( $^{\circ}$ )			

\* Significant difference between the injured and uninjured groups ( $p < 0.05$ ); NS: not significant

In addition to the musculotendinous structures commonly evaluated in the injured runner, specific skeletal structures proximal to the foot have also been evaluated with regard a risk for a running injury. The latter include the quadriceps angle (Q-angle), leg length discrepancy, femoral anteversion, knee alignment and the Miserable Malalignment Syndrome (Neely, 1998) and are described below. Less commonly evaluated causes of skeletal malalignment include alignment of the distal tibia relative to the vertical in the frontal plane, knee angle in stance, talocrural joint orientation in the frontal plane, horizontal plane orientation of the patella, and patella alta or baja (Gross, 1995) are described in detail in the literature (Gross, 1995; Neely, 1998).

### 2.2.5. b.B. Quadriceps angle

The quadriceps angle (Q-angle) represents the difference in action of quadriceps applied force through the patellar, from the effective force through the patellar ligament (Krivickas, 1997). The Q-angle is measured as the acute angle between an imaginary line connecting the midpoint of the patella to the ipsilateral Anterior Superior Iliac Spine (ASIS) and a second line drawn through the midpoint of the patella to the ipsilateral tibial tuberosity (Figure 2.2.1.) (Kendall et al., 1993).

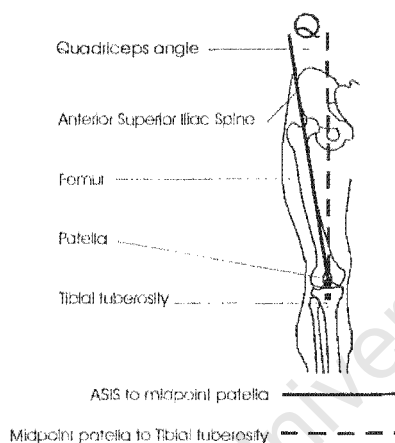


Figure 2.1. Quadriceps angle (Q-angle) is measured from bony landmarks

The normal Q-angle is greater in females (15.8 $\pm$ 4.5 degrees) than males (11.2 $\pm$ 3.0 degrees) (Horton and Hall, 1989). There is no difference in the Q-angle between the extended and flexed knee (both positions measuring 24.3 $\pm$ 8.2 degrees) (Caylor et al., 1993). An excessive Q-angle is suggested to lead to abnormal or lateral tracking of the patellar, which may contribute to injury of the knee (Neely, 1998). In this regard, studies that evaluated the relationship between Q-angle and a group of injuries including ITB, AKPS, PF and MTSS are described (Table 2.7).

Table 2.7. Relationship between Quadriceps angle ( $^{\circ}$ ) and injury

Injured	Uninjured controls	Clinical diagnosis	References
17 $\pm$ 1*	12 $\pm$ 1	ITB	Schwellnus, 1993
17.19 $\pm$ 0.60*	11.05 $\pm$ 0.38	AKPS	Messier et al., 1991
12.5 $\pm$ 0.5	11.2 $\pm$ 0.5 NS	AKPS	Duffey et al., 2000
12.4 $\pm$ 5.1	11.1 $\pm$ 5.5 NS	AKPS	Caylor et al., 1993
13.00 $\pm$ 1.46	13.58 $\pm$ 1.30 NS	Plantar Fascial injury	Messier and Pittala, 1988
15.92 $\pm$ 1.15	13.58 $\pm$ 1.30 NS	ITB	Messier and Pittala, 1988
14.12 $\pm$ 1.07	13.58 $\pm$ 1.30 NS	"Shin splints"	Messier and Pittala, 1988

\* Significant difference between the injured and uninjured groups ( $p < 0.05$ ); NS: not significant

Q-angles greater than 17 $^{\circ}$  were associated with ITB and AKPS. However, consensus of the association of both ITB and AKPS and a large Q-angle is not apparent as this relationship is not evident in all studies of Q-angle with knee injury. Neither is a relationship between Q-angle and leg ("shin splints") and foot injury (Plantar Fascial Injury) demonstrated. A prospective study found a Q-angle of more than 15 $^{\circ}$  to be a significant risk for stress fractures (Cowan et al., 1996). However, 22% of physically active females with a Q-angle of more than 20-25.5 $^{\circ}$  did not have any symptoms of pathology (Horton and Hall, 1989). The results of a clinical trial to study the risk for knee injury found that the Q-angle had no predictive value for determining the non-operative outcome of AKPS (Kannus and Niittymäki, 1994).

There is evidence of a relationship between Q-angle and running injuries at the knee. However, the evidence for this relationship originates from case-control retrospective cohort designed studies which do not allow cause-effect associations to be determined. The relationship between Q-angle and running injuries appears to be the strongest of all the lower limb alignment abnormalities. However, further study of this variable is required to understand the mechanism by which the abnormal Q-angle may cause injury. The relevance of this and other lower limb alignment abnormalities described in this chapter to the aim of the thesis is discussed below (2.3).

#### 2.2.5. b.C. Leg length discrepancy

Leg length discrepancy is commonly determined clinically as the difference in distance between the Anterior Superior Iliac Spine (ASIS) and the medial malleolus between the legs (Bloedel and Hauser, 1995, Blustein and D'Amico, 1985). Occasionally the distance between the ASIS and the lateral malleolus is compared (Woerman and Binder-Macleod, 1984). A discrepancy noted by this method is termed a true leg length difference and contrasts the difference in leg length that may occur as a result of posture (apparent leg length discrepancy) (Woerman and Binder-Macleod, 1984). Leg length may be determined reliably by independent testers and the values obtained are valid when compared with radiological evaluation of the leg length (Gogia and Braatz, 1986).

Leg length discrepancy may be associated with a pronated foot posture, with both the longer leg (Blustein and D'Amico, 1985) and the shorter leg (Subotnick, 1985) proposed to cause excessive pronation in an attempt to minimise the length discrepancy. Although leg length differences may cause injury by causing abnormal movement of the foot, it is also suggested that injury may occur from abnormal skeletal loading due directly to the length discrepancy (Subotnick, 1985). The relationship between leg length discrepancy and injury is described (Table 2.8).

Runners with a difference in leg length of more than 0.48 cm have an association with ITB (Schwellnus, 1993) while those with smaller leg length differences do not (Messier et al., 1995). AKPS does not appear to have an association with length discrepancy (Duffey et al., 2000). The identification and correction of leg length discrepancy may be important in the evaluation of runners with ITB.

Table 2.8. Relationship between leg length difference (cm) and injury.

Injured	Uninjured controls	Clinical diagnosis	References
0.48±0.07*	0.17± 0.04	ITB	Schwellnus, 1993
0.41±0.05NS	0.45± 0.05	ITB	Messier et al., 1995
0.6±0.1NS	0.5± 0.1	AKPS	Duffey et al., 2000

\* Significant difference between the injured and uninjured groups ( $p < 0.05$ ); NS: not significant

### 2.2.5. b.D. Knee alignment

The knee is a hinge joint that permits flexion and extension, with limited abduction-adduction and internal-external rotation (Romanes, 1981). Ideally the long axis of the tibia does not deviate by more than approximately 6 to 7° valgus from that of the femur (Apley and Solomon, 1993). In clinical practice, abnormal knee alignments include genu valgus (the distal tibia is angled laterally with relation to the long axis of the femur) and genu varus (the distal tibia is angled medially with relation to the long axis of the femur) (Kendal et al., 1993).

A genu varus abnormality may be identified clinically from the distance between the femoral condyles with the medial borders of the feet placed together. In contrast, a genu valgus abnormality is clinically identified by the distance between the medial malleoli with the medial borders of the knees placed together (Montgomery et al., 1989). In genu varus, the medial border of the foot may be raised from the supporting surface with the runner in a non-weight bearing posture. With weightbearing, the foot is thought to be forced into a pronated position in order to accommodate the ventral portion (sole) of the foot on the supporting surface. Similarly, a supinated foot posture is associated with the genu valgus alignment abnormality (Gross, 1995). Knee alignment abnormalities may be related with injury due either to the abnormal foot posture assumed or from the compensatory movements that occur (Table 2.9).

Table 2.9. Relationship between knee alignment and injury

Injured	Uninjured controls	Clinical diagnosis	References
5.1±2.4* [Medial tibial intercondylar distance (cm)]	3.6±3.4	AKPS	Milgrom et al., 1991
No difference between injured and uninjured		ITB	Schwellnus, 1993

\* Significant difference between the injured and uninjured groups ( $p < 0.05$ ); NS: not significant

Conflicting reports of an association between knee alignment and ITB is revealed (Table 2.2.9) with a genu varus alignment abnormality (identified as a medial tibial intercondylar distance of more than 5.0cm) associated with AKPS (Milgrom et al., 1991) while no difference between injured and injured runners was found in another (Schwellnus, 1993). The findings of a third prospective study strengthen the association between knee alignment abnormalities and injury; and suggest that the risk of injury from abnormal knee alignment is related severity of abnormality and accompanying level of physical activity (Cowan et al., 1996).

### 2.2.5. *b.E. Hip orientation*

Hip ante- and retro-version refers to the orientation of the neck of the femur in relation to the plane of the femoral heads (Crane, 1959). In the ante-verted position, the femoral neck is orientated anteriorly in relation to the plane of the femoral heads and vice versa (Crane, 1959). The ante- and retro-verted position of the hips may be estimated from the rotation of the hip after correction for joint laxity (Fairbank et al., 1984). Runners with hip anteversion appear to have internally rotated hips and vice versa (Neely, 1998). Hip anteversion (Stannish et al., 1984) and retroversion (by more than 650) (Giladi et al., 1987) are hypothesized to be a risk for injury. There is no controlled clinical data to support these observations.

## 2.3. Relevance of characteristics of the runner to the thesis

Clinical experience has led to the suggestion that lower limb alignment abnormalities are important in the aetiology of running injuries (James et al., 1978). Evidence in this regard is available from a variety of case-control respective cohort studies which are weighted stronger than a case series report in an evidence-based context. However, there is a paucity of controlled trials that are strong enough to provide a cause-effect relationship between the various lower limb alignment abnormalities and injury (Neely, 1998). An excessive quadriceps angle appears to have a stronger relationship with injury than does abnormal foot posture. The consistent method of measuring the Q-angle compared with the widely differing methods used to describe subtalar joint pronation may account for this discrepancy. There is in addition no consensus in the literature of the relationship between specific lower extremity alignment abnormalities and running injuries (Neely, 1998).

Understanding the exact mechanism by which the lower limb alignment abnormalities may cause injury is discussed here with specific reference to the Q-angle. The Q-angle is chosen in this regard as it is perhaps the best described lower limb alignment abnormality and has the strongest relation with injury when compared with the other lower limb alignment abnormalities described here. Ideal conditions to study the relationship of the Q-angle with knee injury, would require that the movements of the femur, tibia and patella be visualized directly during running. This would allow the hypothesis of abnormal alignment of the patella in the patellar groove to be evaluated. However, although this may be possible in future with the use of spectrophotogrammetry, this is currently not the case. The use of skin markers to determine the underlying bone movement is not accurate as there is too much skin movement over the underlying bone to be certain of accuracy. On the other hand, the use of intra-cortical bone pins not practical in the ideal experimental set-up as technical failures and the likelihood of pain may inhibit natural movement of the lower limb (Stacoff et al., 2000).

The measurement of rearfoot movement and internal tibial rotation (Heiderscheit et al., 2000), and coupling of the foot-leg- and -thigh segments (Heiderscheit et al., 1999) has been undertaken with regard understanding the mechanics of the Q-angle. Apart from a delay of achieving maximum internal tibial rotation in stance in the high Q-angle group, no other significant findings were observed in these studies. They serve to demonstrate the difficulty associated with measuring subtle kinematics of lower limb alignment abnormalities.

The clinical merits of measuring these alignment abnormalities should not be ignored, as more accurate methods of evaluating them may be developed in future to assist in understanding their mechanisms of action. With relevance to the research questions of this thesis, as will be discussed in the following part of this chapter, the kinematic and kinetic measurements that are undertaken are gross and are not conducive to the study of the subtle movements and the generation of small

quantities of mechanical joint work in individual structures anticipated of an abnormal Q-angle. Therefore, apart from the foot-type of the runner, no other lower limb alignment abnormality is evaluated in this work.

## 2.4. Characteristics of the running environment

Running shoes, orthoses and running surfaces are environmental factors that from clinical experience are considered to have a role in the aetiology of running injuries. They constitute an important part of the evaluation of the injured runner by health professionals and may have a role in determining the success of treatment.

### 2.4.1. Running shoes

“The most important and difficult decision” likely to face the runner in his or her athletic career is the choice of running shoe (Pagliano, 1978). This statement still holds significance in view of the multiplication of the various brands and models of running shoes from approximately sixteen in 1967 to many hundred at the end of the twentieth century (McKenzie et al., 1985). The importance of the correct running shoe is weighted by the opinion that an incorrect choice may predispose to injury (Pagliano, 1978) and adequately designed and manufactured running shoes may “eliminate” many of the problems associated with running (James et al., 1978).

These statements are relevant today as the structure of the running shoe has remained consistent for more than a quarter of a century (Figure 2.2.2). Running shoes have three components:

1. Upper which is usually the most recognizable portion of the shoe, and inner-sole (sockliner),
2. Midsole to which the upper and outer-sole are bonded, and within which the cushioned components of the shoe are constructed and
3. Outer sole that is in contact with the supporting surface (McPoil, 2000).

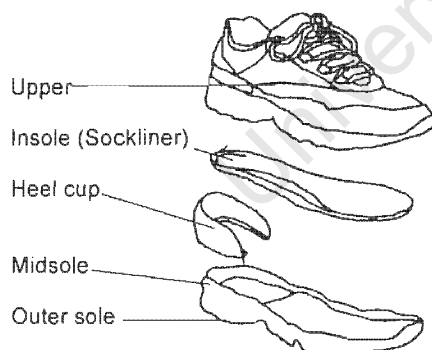


Figure 2.2. Structure of the running shoe

The shape of the portion of the outsole of the running shoe in contact with the supporting surface is called the last (Figure 2.3). A straight lasted running shoe has a straight appearance, the curve

being just 8 degrees from the long axis of the running shoe (A). A curve-lasted running shoe appears “banana-shaped” with the curve of the running shoe at approximately 22 degrees from the long axis of the running shoe (B). A curved lasted running shoe is more flexible and is commonly chosen for racing rather than training (McKenzie et al., 1985).

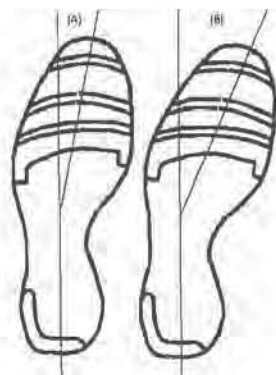


Figure 2.3. Straight (A) and curve lasted (B) running shoes

The upper of a running shoe is the material that envelops the foot (Figure 2.2.4). This is usually constructed from lightweight breathable material such as Nylon® mesh with suede. The upper is comprised of the following structures from anterior to posterior: (A) the “vamp” which extends from the toes to the heads of the metatarsals, (B) the “quarter” which extends from the vamp to the back of the heel, and (C) the “foxing” which covers the back of the heel (McPoil, 2000). The toe box is the rigid structure at the front of the running shoe that accommodates the toes. (D) The tongue covers the dorsal aspect of the foot and protects from the eyelets and shoelaces. The inner-sole (sockliner) does not contribute to shock absorption. It absorbs perspiration and lines the inside of the running shoe (Cook et al., 1990).



Figure 2.4. The anatomy of the upper of running shoes  
(A) vamp; (B) quarter; (C) foxing; (D) tongue

The heel counter supports the heel at the posterior aspect of the shoe (Figure 2.4) and is manufactured from stable thermoplastic (McPoil, 2000). The heel counter controls pronation and reduces the transmission of load to the skeleton and the activity of the triceps and quadriceps (Jørgensen, 1990). The Achilles’ tendon pad and collar protect the Achilles’ from direct trauma and abrasion (McKenzie et al., 1985). The confinement of the heel fat pad by the heel counter has been shown to increase the shock absorbency of the heel fat pad (Jørgensen and Ekstrand, 1988). The upper is attached to the midsole with a lasting. Running shoe rigidity varies with the proportions of type of lasting used (McPoil, 2000) (Table 2.10).

Table 2.10. Relationship between running shoe rigidity and lasting

Last	Design	Rigidity of the running shoe
Slip	Upper that is folded over and joined to the underlying midsole with broad stitching	Running shoe is flexible
Combination	Combination of slip and boarding lasting used to bond the upper to the midsole	Flexibility is dependent on the proportion of the last used.
Board	Upper material is attached to a firm cardboard structure which is bonded to the midsole	running shoe is rigid

The midsole is composed of either heavy and hardwearing polyurethane (PU) or softer, less durable ethylene vinyl acetate (EVA). In most running shoes, the midsole is thicker in the posterior portion (heel area) than the anterior portion (toe area). This allows the foot to assume a forward sloped position. The midsole may be a single unit or composed of many units of varying density (hardness) (Figure 2.4). A single density midsole running shoe is light, flexible and used for racing. A multiple density midsole shoe is heavier, rigid and used for training. Multiple density running shoes provide individualized support for specific types of feet. For the pronated-type foot, the softer units (25 Shore A) of the midsole are positioned on the lateral portion of the sole, with the firmer units (35- 45 Shore A) on the medial portion (Figure 2.5). This is postulated to restrict excessive pronation by limiting medial movement of the calcaneus and talus (Adidas Research and Innovation Labs, 1998).

The midsole may have a variety of additional cushioning mechanisms incorporated into its structure. These may include additional cushioning pads, single or multiple air units that may be independent or linked, gel sachets, and specially formed thermoplastic waves designed to dissipate force.

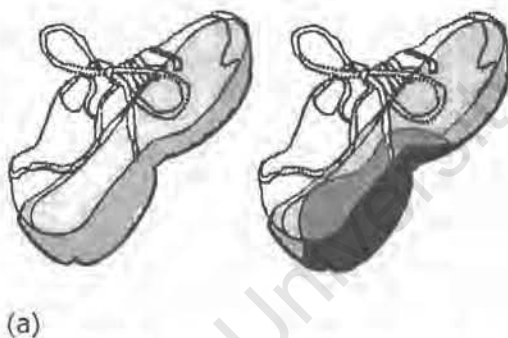


Figure 2.5. Midsole structure of the "neutral" and "anti-pronation" shoes

(a) "Neutral" shoe has a single density midsole, while the (b) "anti-pronation" shoe has a midsole composed of a firm medial portion [intensely shaded area] with the rest of the midsole similar to that of the "neutral" shoe.

The shape of the heel tends to vary between running shoe brands and models. Running shoes with a conventional lateral flare of 160 are associated with greater initial pronation than non-flared and rounded heel running shoes. Heel shape does not alter the ground reaction forces. Heel shape (flare) may therefore have a relationship to injuries associated with abnormal pronation (Nigg and Morlock, 1987).

Running shoes display a reduction in shock absorption capacity with progressive mileage. Mechanical testing has demonstrated a 40% reduction in the shock absorption capacity at between 250 to 500 miles. A 30% reduction in shock absorption of running shoes is evident at 500 miles in runners that used similar running shoes.

Attempts to demonstrate differences in shock absorption of soft, medium, or hard midsole shoes, with peak tibial acceleration, was unsuccessful in two independent studies (Hardin and Hamill, 2002; Nair and Marshall, 1994). These results that research methods used to detect subtle differences in shock absorption with running shoes of different hardness are not sensitive enough. An alternative finding in a recent study is that midsole hardness may have an effect on lower-extremity electrical muscle activity rather than on impact forces. Muscles appear to be “tuned” for impact activities and that the “tuning” changes with midsole hardness (Wakeling et al., 2001, 2002). A strong individual response of runners’ muscle activation patterns to midsole hardness is apparent and a significant group response is not apparent (Nigg et al., 2003).

The outer sole is the only portion of the running shoe in contact with the supporting surface. There are areas of varying densities of durable carbon rubber, which maximize traction in the medio-lateral and antero-posterior directions (McPoil, 2000).

Running shoe prescription guidelines are largely based on the clinical experience of treating runners with injuries and lower limb alignment abnormalities (Table 2.11) (Gross, 1995). However, it should be noted that each runner-shoe combination has unique interactions, and that empirical prescription of running shoe for the general population may not necessarily be optimal for the individual runner (Bates et al., 1983).

Table 2.11. Running shoe prescription guidelines

<b>Foot-type</b>	<b>Hypomobile or pes cavus foot</b>	<b>Pes planus foot</b>
<b>Running shoe shape</b>	curve last	straight last
<b>Upper to midsole bond</b>	slip last	board last
<b>Midsole structure</b>	soft single-density midsole	Firm multiple-density midsole
<b>Additional features</b>	extra cushioning	firm heel counter
<b>Rational</b>	deformation of the running shoe assists in energy dissipation during ground impact with protective effects	running shoe rigidity assists in the control “hypermobility” of the foot (Gross, 1995).

\*Adapted (Gross, 1995)

Correct shoe fit is important for the runner to benefit from the specific design features of the running shoe. The female foot is shorter and narrower than that of the male foot when expressed as a percentage of stature and therefore female runners require specially designed and prescribed running shoes and not scaled-down versions of the running shoe designed for males (Wunderlich and Cavanagh, 2001).

The habitual use of running shoes has been implicated in the persistently high incidence of running injuries (Robbins and Gouw, 1990). This opinion is based on the anecdotal observation that the incidence of running injuries is lower in habituated barefoot than shod populations (Robbins and Gouw, 1990). Data suggest that either the cushioning intrinsic to the running shoes (Robbins and

Hanna, 1987; Robbins et al, 1988) or the runners' unsubstantiated expectation of protection from the cushioning (Robbins and Waked, 1997), may blunt intrinsic protective mechanisms and thereby lead to injury. Furthermore, the increased rate of injury to the knee observed with the increased popularity of running shoe prescription raised the possibility of an association between the two factors (McKenzie et al., 1985).

Barefoot running is employed by few successful runners, the majority preferring running shoes. A few documented successful barefoot runners include Abebe Bikila, the 1960 Olympic marathon champion, Ron Hill, the 1968 10 000m Olympic champion and Zola Budd-Pieterse, the 5000m world record holder (O'Neill, 1974, Noakes, 2001). Possible reasons for the popularity of running shoes over barefoot running includes the greater availability of speed offered by the "better gripping power" and safety from "pounding, bruising, cutting etc." (O'Neill, 1974). The relevance of the discussion of running shoes conducted here to the aims of the thesis is discussed below.

#### 2.4.2. Running shoe orthoses

Occasionally the basic structure of the running shoe is found to be not sufficient for the individual runner in terms of comfort and safety from injury. In this circumstance it is not unusual to have a purpose built orthoses inserted within the running shoe to enhance the comfort and safety features of the running shoe. Running shoe orthoses in this regard are of three types: soft, semi-rigid and rigid (Table 2.2.12).

Table 2.12. Comparison of running shoe orthoses

Type of orthoses	Soft	Semi-rigid	Rigid
Composition	soft materials such as leather, paper, Sorbathane, Spenco and ethylene vinyl acetate (a)	manufactured from heat-moulded thermoplastics (b)	non-compliant materials such as graphite, fibreglass or steel (b)
Effect on intrinsic foot movement	Limited effect (b)	Substantial effect (b, c)	Substantial effect
Effect on impact forces	Good impact attenuation (b)	Good impact attenuation (b)	Impact attenuation is minimal (b)
Lifespan	Limited (b)	Long (b)	Long (b)

(a) Murphy, 1986; (b) Gross and Napoli, 1993; (c) Gross et al., 1991

##### 2.4.2. a. Soft orthoses

Epidemiological research suggests that soft orthoses protect runners from injury (Schwellnus et al., 1990; Fauno et al., 1993). The exact mechanism by which soft orthoses provide protection from injury is not known. Soft "Saran" inserts (soft orthoses) used with military boots attenuates the ground reaction forces and provide protection for the forefoot and rearfoot (deMoya, 1982). The tibial peak strain measured with accelerometry is reduced with the use of soft orthoses in military boots during walking (Ekenman et al., 2002). In contrast, ethylene vinyl acetate and viscoelastic insoles do not have an effect on the vertical component of the ground reaction forces (Nigg et al., 1988).

Materials such as PeLite (soft) and PPT (hard) commonly used to manufacture soft orthoses do not have a measurable effect on the loading rate of the lower spine during jogging, when studied with accelerometers and electromyography (Ogon et al., 2001). The conflicting results of the laboratory tests of soft orthoses suggest that the mechanism by which soft orthoses affords

protection from injury is not known. The “hardness” of soft orthoses may be graded with a variety of experimental methods (Table 2.13). In a search for alternative explanations for the protection offered by soft orthoses, the concept of footwear comfort was explored. Soft orthoses randomly prescribed to half of 206 military personnel reported a comfort rating of at least 2.3 points higher on a visual analogue scale, than those without orthoses (Mundermann et al., 2001). The incidence of stress fractures to the foot, knee and lower back, and pain at different locations was reduced by 1.5 to 13.4% in the soft orthoses group compared with the no orthoses group. The findings of the study lead to the proposition that the comfort provided by the soft orthoses is important in injury prevention (Mundermann et al., 2001). The exact mechanism is still not apparent. The relevance of soft orthoses to the aims of the thesis is discussed below.

Table 2.13. Comparison of methods used to test the hardness of soft orthoses

Laboratory method	SHORE method (a)	Exeter Research Impact Testing System (ERITS) (b)	Modified ERITS (c)
Materials tested Method	Plastic and rubber Durometer is used to determine the resistance of the material to penetration.	Plastic and rubber Known mass (8kg) is dropped from a known height (0.05m) onto the material for a predetermined number of times (25 pre-impact and 10 impacts).	Plastic and rubber Material under evaluation is dropped together with a known mass onto force plate. An accelerometer is attached to the known mass.
Unit measure	SHORE or durometer hardness value. A and D are scales used to measure soft and hard materials, respectively. The higher the SHORE value in either A or D, the harder the material.	Mechanical measures include peak acceleration and time to peak acceleration.	Amount of deformation and recoil after deformation of the material is determined.
Outcome	Soft (0) to hard (100).	High peak acceleration and a short time to peak are characteristic of a hard material	Hard material is characterised by minimal deformation with little recoil

(a) Denoth, 1986; (b) McCaw et al., 2000; (c) Komi et al., 1987

#### 2.4.2. b. Semi-rigid orthoses

Semi-rigid orthoses (Table 2.2.12) are prescribed on the assumption that “structural balance” is a central to treatment and prevention of running injuries (Sheehan, 1974; Drez, 1980). Semi-rigid orthoses are proposed to align the pronated foot and reduce abnormal movement at the subtalar joint (Gross et al., 1991). Correction of the rate of pronation rather than the total amount of pronation is considered important in injury treatment (James and Jones, 1990). In an in-vitro study of cadaveric feet in a frame to which a vertical load of 900N was applied axially, the shoe with semi-rigid (functional) orthotic combination (-1.16±3.51%strain) was found to reduce the strain

within the plantar-aponeurosis over the barefoot ( $4.29 \pm 2.20\%$  strain) and shoe without orthoses conditions ( $5.20 \pm 1.95\%$  strain) (Kogler et al., 1996). In addition to impact attenuation, semi-rigid orthoses may be beneficial in the treatment of plantar facial injuries by reducing the strain within the aponeurosis. In a case-series of 180 injured runners, 78% of the injured runners were treated successfully with the prescription of semi-rigid orthoses (James et al, 1978). Similarly, 78%, 76.7%, 73.9%, 73.9%, 73.1%, and 68.8% of runners diagnosed with patellofemoral syndrome, leg length abnormalities, pronation defects, Plantar Fascial injury, Achilles' tendinosis and Shin Splints, respectively, reported complete cure of the symptoms with the prescription of semi-rigid orthoses (Gross et al, 1991; Gross, 1995). Although these case series suggest good results with appropriately prescribed semi-rigid orthoses, controlled clinical trials are necessary to confirm these early observations. In this regard, a caution is issued that running shoe orthoses do not necessarily control the injury pattern of most runners (McKenzie et al, 1985). In this regard, the mechanisms by which semi-rigid orthoses are hypothesized to function are described in the following section of this chapter and a controlled clinical trial to determine the effect on the gait analysis variables descriptive of running style is described in this work (Study Six). The relevance of the discussion conducted here with regard the aim of the thesis is discussed below.

#### 4.3. Running surfaces

Running surfaces may be described with regard to hardness, inclination and camber. Hard running surfaces are considered a risk for injury as greater impact forces are hypothesized to be applied to the runner than with soft running surfaces (James et al., 1978). Quantification of the amount of exposure to the hard running surface in terms of weekly running distance appears to supersede the risk associated with the hardness of the running surface (Marti et al., 1988, Walter et al., 1989). Running on a declined surface is associated with a reduced ability of the knee extensor muscles to absorb force (Sharwood et al., 2000), and it is therefore intuitive that hill running may be associated with a greater risk of injury. However, no consistent relationship between hill running and injury is reported in the available epidemiological literature (Clement et al., 1981, Jacobs and Berson, 1986, Macera et al., 1989, Walter et al., 1989). Roads with a large camber have the potential to cause a functional leg length discrepancy. The leg length discrepancy in this regard may increase the risk of injury to the runner with excessive load placed on at least one of the limbs (Bovens et al., 1989).

#### 2.5. Relevance of environmental factors to the thesis

Clinical experience has led to the opinion that running shoes, provide the runner with protection from impact forces and control of abnormal movement of the foot. Soft orthoses are suggested to augment the attenuation from excessive impact forces, while semi-rigid orthoses assist in the control of abnormal movement of the foot for the individual runner. These mechanisms are discussed in the following part of this chapter. A trend evident in the literature and recently expressed at an international meeting (Footwear Symposium of the International Society of Biomechanics, Zurich 2001) is that the evidence to support the mechanisms proposed whereby running shoes and orthoses function is lacking. Perceptual variables that reflect the comfort offered by the footwear may provide an alternative explanation. Changes in the hardness of the running condition, as occurs with a change in the environmental factors from barefoot to shod running is accompanied by a change in running style (de Wit et al., 2000). The running style changes are considered to occur in response to differences in the impact perceived by the runner under the different running conditions (Hennig, 1996). The effects of running shoes, soft and semi-rigid orthoses on the gait analysis variables descriptive of running style are explored in this work by means of a comparison of barefoot and shod running (Study Four), and orthoses of different hardness (Study Five).

### 3. Part Three: Running injury models

Overuse running injuries occur when the accumulation of mechanical stress within susceptible tissues exceeds the ability of those tissues to withstand the stress (critical limit) or the rate of damaged caused to the tissues by stress accumulation exceeds the rate of the tissue repair process (Stannish, 1984; Nigg, 1995; Krivickas, 1995). Successful clinical interventions prevent an initial injury or the recurrence of a previous injury by maintaining the stress within the injured tissue to below a critical limit.

This hypothesis may be evaluated by determining the relationship between injury of the tissue and the stress within that tissue, and the changes in the tissue stress with various clinical interventions. While injury of a tissue may be clinically diagnosed, measurement of the stress within a tissue is more complex. Ideally the stress within the tissue should be measured directly. Although direct tissue strain has been measured with a strain gauge, this measurement technique is not popular because of the ethical considerations and medical complications associated with it (Komi, 1990). Consequently research has focused on the estimation of stress within the tissues by non-invasive methods.

Movement of, and forces acting on the lower limb in stance, are the gait analysis variables popularly measured in this regard. It is assumed that these gait analysis variables represent the dynamics within the tissues that are commonly injured. The estimation of the stress at a joint with standard gait analysis techniques (mechanical joint work) has materialised with the increase in computing power that has allowed processing of large data files manageable. In the following sections of this work, the impact forces, lower limb movements and mechanical joint work variables and their relationship the stress within injured tissues, are discussed.

#### 3.1. Impact forces and injury

The ground reaction force is a representation of the Centre of Mass acceleration during locomotion. In other words the ground reaction force is representative of the activity that is required to effect the movement of a runner (Lake, 2000). At initial contact with the supporting surface, there is a rapid increase in both the vertical and horizontal components of the ground reaction force that represents the acceleration of the whole body centre of mass toward the supporting surface.

The peak magnitude and rate of application of the vertical ground reaction force is commonly measured with regard injury (Messier et al., 1991; 1995; Duffey et al., 2000). The acceleration of the whole body Centre of Mass away from the supporting surface is represented by the vertical and horizontal propulsive forces. Typical curves that represent the interaction of the Centre of Mass of the runner with the supporting surface are represented below (Figure 3.1).

The kinetic data that are commonly measured to understand running injuries and the various clinical interventions to treat and prevent injury include the loading rate and magnitude of the vertical impact force peak, the vertical propulsive force peak, and the horizontal braking and propulsive force peaks (Clarke et al., 1983; de Wit et al., 2000; McCaw et al., 2000). All ground reaction force variables are commonly expressed in multiples of body weight (BW).

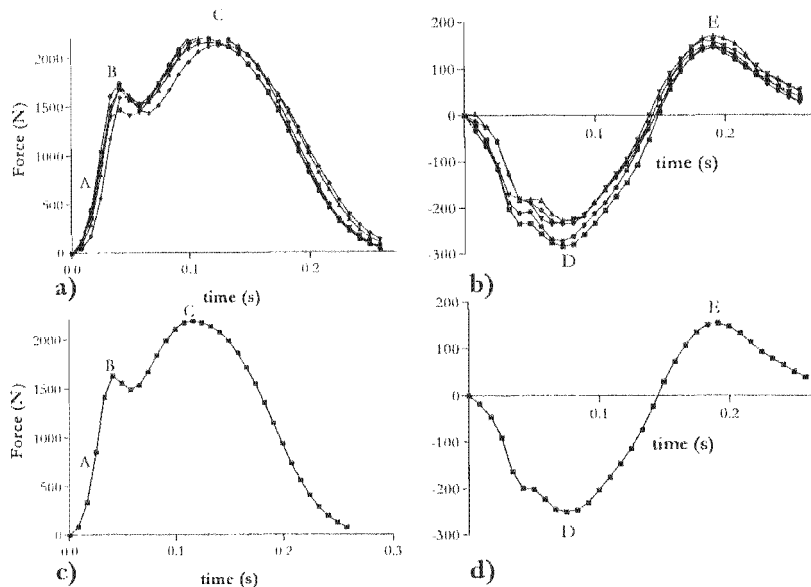


Figure 3.1. Typical curves of the ground reaction force in running

- a) Vertical component of the GRF for an ensemble of five trials,  
 b) Horizontal component of the GRF for an ensemble of five trials,  
 c) Vertical component of the GRF averaged for five trials,  
 d) Horizontal component of the GRF averaged for five trials  
 A: Loading rate (gradient of the curve to peak vertical impact force) (N/s),  
 B: Peak vertical impact force (N),  
 C: Peak vertical propulsive force (N),  
 D: Peak horizontal braking force (N),  
 E: Peak horizontal propulsive force (N)

### 3.1.1. Impact force-injury models in sub-primate animals

Impact forces are the first gait analysis variables discussed in regard running injuries. The relationship between impact force and injury originates from the observation that sub-threshold impact forces applied repetitively to the limbs of sub-primate animals (guinea pigs) were associated with degenerative joint changes (Simon et al., 1976). Unyielding support surfaces that were assumed to be consistent with a high impact force environment, too were associated with joint injury in controlled animal (sheep) trials (Radin et al., 1982). Criticism of these early studies has focused on the argument that sub-primate animals were not suitable for studying the effect of sub-threshold force application, as the joints studied may not have evolved to accommodate the applied stress (Nigg, 2001).

### 3.1.2. Impact force-injury models in runners

The repetitive impact force application to the lower limbs of long distance runners may in the light of the results of the animal trials above be assumed to have a relationship with injury. An analysis of the ground reaction forces measured during running in a laboratory appeared to be a plausible method of determining the relationship between impact force and injury. The relationship between impact force and injury is described in the series of tables below (Table 3.1-2.3.3).

Table 3.1. Comparison of the vertical impact forces (BW) between injured and uninjured runners

Running injury	Vertical impact force (BW)		References
	Injured	Uninjured	
AKPS	1.65± 0.09 NS	1.79± 0.08	Messier et al, 1991
AKPS	1.74± 0.03*	1.66± 0.31	Duffey et al, 2000
ITB	1.64± 0.04 NS	1.75± 0.04	Messier et al, 1995
Heterogeneous group of injuries	2.4± 0.41*	2.13± 0.42	Hreljac et al, 2000

\* Significantly differently between injured and uninjured runners ( $p < 0.05$ ); NS: Not significant

The association between a high impact force magnitude and rate of application to the lower limb with injury to the knee (AKPS) and other unspecified injuries (heterogenous group) is intuitive (Table 3.1; Table 3.2). Unfortunately, this relationship is not consistent in related studies (Table 3.1; Table 3.2). Specifically, although AKPS and ITB both are injuries to the knee, the relationship between impact forces magnitudes and application rates and injury are different. ITB is not associated with high impact force magnitudes or application rates in comparison with AKPS and other heterogenous group of injuries (Table 3.1). The vertical components of the ground reaction force were compared between injury-free runners and runners with AKPS (Duffey et al, 2000, Messier et al, 1991), ITB (Messier et al, 1995) and a heterogeneous group of running injuries (Hreljac et al, 2000) in a retrospective cohort case-control study design.

Table 3.2. Comparison of the vertical impact force loading rate (BW/s) between injured and uninjured runners.

Running injury	Vertical impact force loading rate (BW/s)		References
	Injured	Uninjured	
AKPS	56.46± 4.52 NS	53.88± 3.10	Messier et al, 1991
AKPS	Not reported	Not reported	Duffey et al, 2000
ITB	49.11± 2.43 NS	54.32± 1.78	Messier et al, 1995
Heterogeneous group of injuries	93.1± 23.8*	76.6± 19.5	Hreljac et al, 2000

\* Significantly differently between injured and uninjured runners ( $p < 0.05$ ); NS: Not significant

This suggests that the selected ground reaction force measurement are not specific enough to represent the stress created within individually injured structures within the same anatomical region. Alternatively, the mechanism of injury for individual types of injuries (AKPS and ITB) may be different and may not exclusively be related to application of high magnitudes and rates of impact force application. The generation of high stress within the tissues about the knee during the propulsive portion of stance may in this regard be an alternative mechanism associated with AKPS is caused (Table 2.3.3). However, no relationship between ITB and propulsive forces is displayed either, suggestive of the limitations of ground reaction forces to represent stress accumulation within the tissues.

The inconsistent relationships described between injury and the selected ground reaction force variables may be related to the nature of the biomechanical variable chosen. The ground reaction force reflects the total body centre of mass acceleration due to gravity, which is a gross measurement and does not necessarily represent the stress in a distal limb segment or the accumulation of stress within individual tissues (Lake, 2000).

Table 3.3. Comparison of the vertical propulsive forces (BW) between injured and uninjured runners.

Running injury	Vertical active forces (BW)		References
	Injured	Uninjured	
AKPS	2.53± 0.06*	2.34± 0.06	Messier et al, 1991
AKPS	Not reported	Not reported	Duffey et al, 2000
ITB	2.43± 0.04 NS	2.48± 0.03	Messier et al, 1995
Heterogeneous group of injuries	2.73± 0.30 NS	2.69± 0.29	Hreljac et al, 2000

\* Significantly differently between injured and uninjured runners ( $p < 0.05$ ); NS: Not significant

### 3.2. Relevance of abnormal impact force to the thesis

The inconsistent relationships described between injury and the selected ground reaction force variables may be related to the nature of the biomechanical variable chosen. The ground reaction force reflects the total body centre of mass acceleration due to gravity, which is a gross measurement and does not necessarily represent the stress in a distal limb segment or the accumulation of stress within individual tissues (Lake, 2000). Axial accelerometry in contrast may have potential in representing stress at a regional level (Lafortune and Hennig, 1992). The measurement of ground reaction forces to evaluate stress within injured tissues may be inappropriate for the representation of stress within injured tissues. Rather ground reaction forces are invaluable with regard understanding the forces that bring about a specific movement pattern, such as occurs with a change in running style with a change in the running condition. The ground reaction forces are used in all the subsequent studies in which the running style is described with gait analysis.

### 3.3. Abnormal foot movement and injury

Clinical experience has fostered the assumption that foot movement may represent the stress within tissues that are commonly injured in runners (James et al., 1978). Subtalar joint pronation and supination are the foot movements commonly observed, and are considered essential for walking and running by stabilising the lower limb joints, and reducing the forces within the foot and lower limb (Donateli, 1985). Subtalar joint pronation is considered abnormal when it occurs at an inappropriate time or for a prolonged period of time in stance, and disrupts the normal function of the lower limb (Donatelli, 1987).

#### 3.3.1. Mechanics of subtalar joint pronation

Subtalar joint pronation may be initiated either by the reduction of the internal rotation of the proximal segments at the foot fixed to the supporting surface (Donatelli, 1985) or by the passive eversion of the calcaneus at initial contact with the supporting surface (Tibero, 1987). Calcaneal eversion is followed by medial movement of the head of the talus and internal rotation of the talus body (Tibero, 1987). The rotation of the talus is transferred to the tibia by the talo-tibial coupling or mitred hinge mechanism (Eng and Andrews, 1987). Internal rotation of the tibia is controlled by eccentric contraction of the muscles that insert to the plantar aspect of the foot (Donateli, 1985). The position of pronation is achieved when the calcaneus is everted, the talus head medially displaced, the talus body rotated and the tibia internally rotated (Figure 2.3.2).

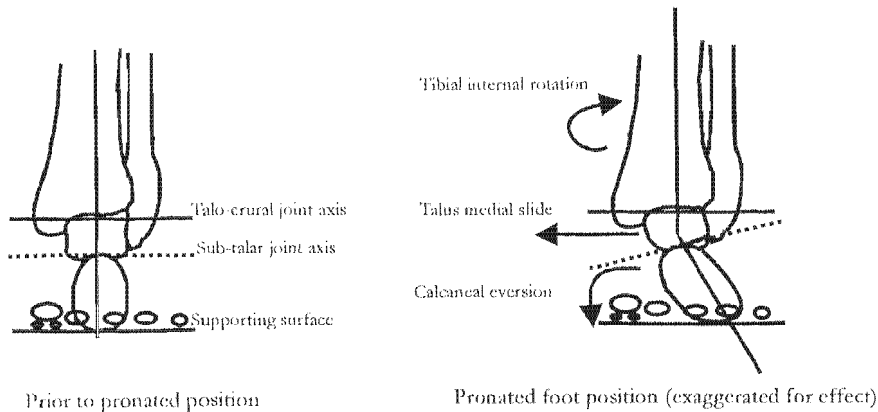


Figure 2.3.2. Talo-tibial coupling mechanism

Adapted (Subotnick, 1985)

### 3.3.2. Imaging of subtalar joint pronation

The relationship between abnormal foot structure and abnormal foot movement originates from the results of two-dimensional (2D) imaging studies in which runners with a pronated foot-type displayed greater pronation movements than runners with a neutral foot-type (Bates et al., 1979). The laboratory method used to measure foot movement in this regard is still commonly used (Figure 2.3.3). In the earliest studies, the angle formed at the intersection of a line bisecting the posterior aspect of the leg (gastrocnemius muscle) and the heel (calcaneus) was used to estimate the amount of subtalar joint movement (pronation). Reflective and non-reflective markers at similar anatomical points were later used to refine the early 2D and 3D imaging methods (Engsborg and Andrews, 1986; McCulloch et al., 1993; Eng and Pierrynowski, 1994).

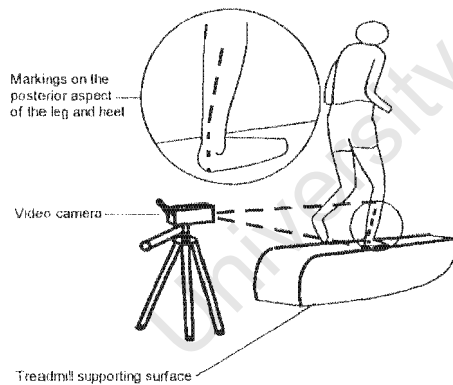


Figure 3.3. Kinematic analysis of foot movement

As abnormal foot structure (especially a pronated foot-type) is associated with injury (James et al., 1978), it appears reasonable to assume that abnormal foot movement may represent stress in the injured tissues. A pathomechanical model to explain how abnormal pronation is associated with injury is proposed (Figure 3.4). By elaboration of this model, abnormal movement of the foot is implicated in the aetiology of Anterior Knee Pain Syndrome (AKPS), Ilio-Tibial Band Friction Syndrome (ITB), Medial Tibial Stress Syndrome (MTSS), Achilles' tendinosis and Plantar Fascial Injury (PF) (Smart et al., 1980; Krivickas, 1997; Michael and Holder, 1985; Tibero, 1987).

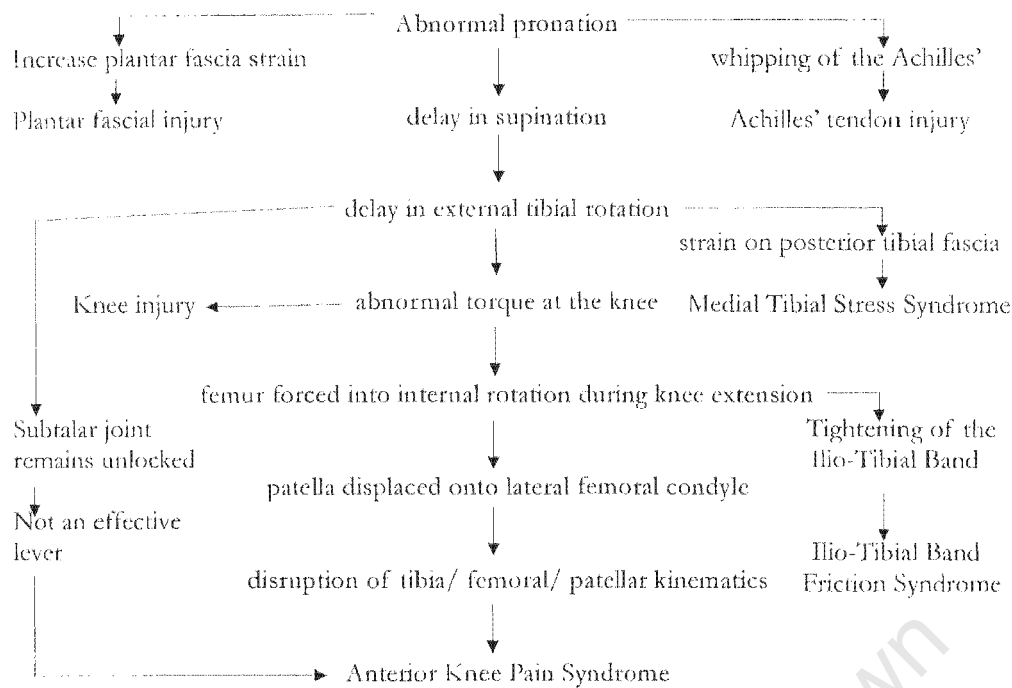


Figure 3.4. Pathomechanical model of abnormal pronation and injury

Measurement of foot movement has been used by various authors to estimate the amount of stress generated within susceptible tissues and be a risk for injury (Table 3.4). This has been undertaken because of the technical difficulties associated with direct measurement of the stress within the tissues of interest by invasive methods.

Table 3.4. Comparison of the maximum pronation angle between injured and uninjured runners

Clinical diagnosis	Maximum pronation angle ( $^{\circ}$ )		References
	Injured	Uninjured	
MTSS	191.1 $\pm$ 3.9*	189.2 $\pm$ 3.8	Viitasalo and Kvist, 1983
PF	More pronation* (no values)	Less pronation (no values)	Warren and Jones, 1987
MTSS	8.68 $\pm$ 0.58*	6.13 $\pm$ 0.86	Messier and Pittala, 1988
PF	8.72 $\pm$ 1.17 NS	6.13 $\pm$ 0.86	Messier and Pittala, 1988
ITB	7.55 $\pm$ 0.99 NS	6.13 $\pm$ 0.86	Messier and Pittala, 1988
ITB	12.94 $\pm$ 0.86 NS	11.19 $\pm$ 0.89	Messier et al, 1995
AKPS	12.1 $\pm$ 0.6 NS	11.6 $\pm$ 0.7	Duffey et al, 2000
ITB	8.20 $\pm$ 1.28 NS	11.33 $\pm$ 1.16	Messier et al, 1991
Not specified	7.6 $\pm$ 3.9 NS	6.9 $\pm$ 4.4	Hreljac et al, 2000

\*  $p < 0.05$  significant difference between injured and uninjured ; NS : not significant,  $p \geq 0.05$

### 3.3.3. Abnormal subtalar joint pronation and injury

The almost universal relationship between abnormal pronation and common running injuries suggested in the Pronation-Injury flow chart (Figure 3.4) suggests that a strong association between injury and pronation will be found in a review of related studies (Table 3.4). A greater maximum pronation angle is associated with MTSS and PF (Viitasalo and Kvist, 1983, Warren

and Jones, 1987, Messier and Pittala, 1988) but not with ITB and AKPS (Messier and Pittala, 1988; Messier and Pittala, 1988; Messier et al, 1995; Duffey et al, 2000; Messier et al, 1991; Hreljac et al, 2000). Derivatives of the maximum pronation angle such as the rate of pronation, initial pronation velocity, the initial pronation value and the total amount of pronation measured, have a similar relationship with injury to that described above. There is no consensus on the association between abnormal foot movement and injury in the studies reviewed. In this regard, it is important to re-evaluate whether measurement of abnormal foot movement is the most appropriate method to represent stress at the injured tissue sites.

### 3.4. Relevance of abnormal foot movement to the thesis

While considerable scientific effort is apparent with regards determining the relationship between abnormal movement patterns and injury, this is focused largely on the intrinsic movements of the foot. The intrinsic movements in this regard include subtalar joint pronation and internal tibial rotation (Bates et al., 1979; Stacoff et al., 2000). In contrast, the relationship of movement pattern of the proximal segments of the lower limb and body with injury has not received much attention. Reports of the gross movement patterns of the lower limb and body are limited to the study of running at different speeds (Mann and Hagy, 1980), on different surfaces (Wank et al., 1998), on inclined vs declined vs horizontal supporting surfaces (Swanson and Caldwell, 2000), comparing runners of differing abilities (Cavanagh et al., 1977) and running in a backward direction (Devita and Stribling, 1991). The large between subject variability of kinematic variables used to measure subtalar pronation and technical errors described above may contribute to the lack of consensus between injury and abnormal intrinsic foot movement. In contrast, the swing and stance phase lower limb kinematics are well described and remain unexplored with regard injury. The lower limb kinematic variables are described below (Figure 3.5) and are used in the study of injury in runners, particularly with exploring pathomechanical models that integrate the Central Nervous System with mechanical principles.

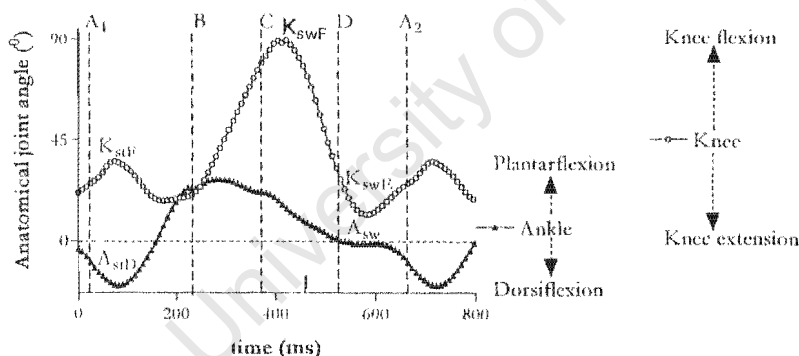


Figure 3.5. Typical sagittal plane ankle and knee angles curves

A: Heel-strike (initiation of stance phase), B: Toe-off (termination of stance phase), C: Heel-strike of the contralateral limb, D: Toe-off of the contralateral limb  
 KswF: Peak knee flexion angle during swing phase, KswE: Peak knee extension angle during swing phase, Kst: Peak knee flexion angle during stance phase, Asw: Ankle angle at KswE, Ast: Peak ankle dorsiflexion angle during stance  
 A<sub>1</sub> to A<sub>2</sub>: Complete gait cycle, A<sub>1</sub> to B: Single limb stance phase, B to A<sub>2</sub>: Swing phase, B to C: Double float phase, C to D: Single limb stance of the contralateral limb

The curves are based on those used to describe lower limb sagittal plane movement during running at different speeds (Mann and Hagy, 1980) and during barefoot and shod running (de Wit et al., 2000).

### 3.5. Mechanical joint work and injury

The preceding discussion suggests that there must be a more appropriate method to represent the stress within injured tissues. In conventional gait analysis, the total stress across all tissues at a joint may be represented by the mechanical power and work estimated with an inverse dynamics mathematical approach (Novacheck, 1995).

Joint power is the product of the moment of force and angular velocity of the limb segments adjacent to the joint of concern (Ounpuu, 1990). The angular velocity is a measurement of the limb segment rotation about the joint centre (Ounpuu, 1990). The joint moment is the product of the ground reaction force (GRF) and the perpendicular distance of the joint centre (lever arm) from the GRF (Vaughan, 1996). The magnitude of the lever arm may be influenced by the position of the whole body centre of mass which determines the path of the GRF past the joint centre or by the lower limb geometry which determines the position of the joint centre (Figure 3.6). The magnitude of the lever arm is essential to determining the quantity of mechanical joint power.

The joint power measured by the inverse dynamics method is typically negative in the loading phase of stance and positive in the propulsive phase of stance (Figure 3.7). The rationale for positive and negative power and work values determined with the inverse dynamics method is represented below (Figures 3.8 and 3.9) and based on that previously described (Stefanyshyn and Nigg, 2000).

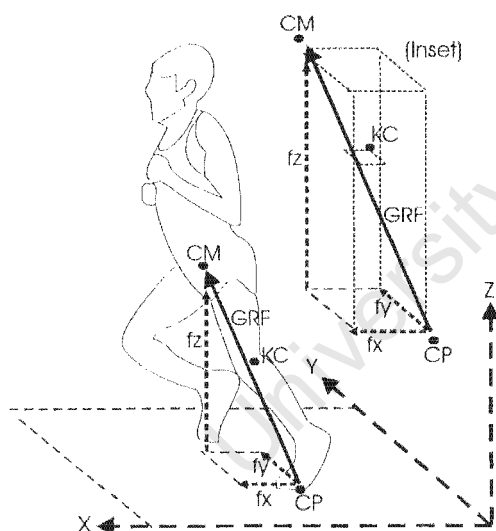


Figure 3.6. Relationship between centre of mass and lever arm at the knee

To determine the magnitude of the lever arm at the knee, it is necessary that the runner cross a force plate that is able to provide information of the components of the ground reaction force in the directions of the global reference system (X [forward], Y [laterally] and Z [vertically]). The centre of pressure (CP) indicates the point of contact between the runner and the force plate. The ground reaction force (GRF) represents the acceleration position of the whole body centre of mass (CM). The orientation of the CM with regard the CP, determines the direction of the GRF. The magnitude

of the GRF is represented by the fore-aft ( $f_x$ ), medial-lateral ( $f_y$ ) and vertical ( $f_z$ ) components in the respective directions of the global reference system. The knee joint centre (KC) is identified from the position of the prominent bony anatomical and virtual landmarks. The magnitude of the lever arm is determined as perpendicular distance of the KC from the GRF. Therefore the magnitude of the lever arm may be determined by either the position of the CM which determines the path of the GRF past the KC or the lower limb geometry which determines the position of the KC. The orientation of the CM with regard the CP may determine the path of the GRF and hence the length of the lever arm at the knee.

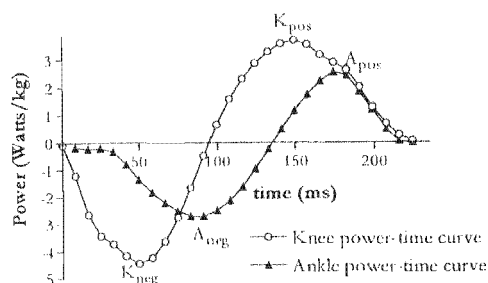


Figure 3.7. Typical knee and ankle power-time curves in stance

$K_{neg}$ : Peak knee power absorption (negative power peak),  $A_{neg}$ : Peak ankle power absorption (negative power peak),  $K_{pos}$ : Peak knee power generation (positive power peak),  $A_{pos}$ : Peak ankle power generation (positive power peak)

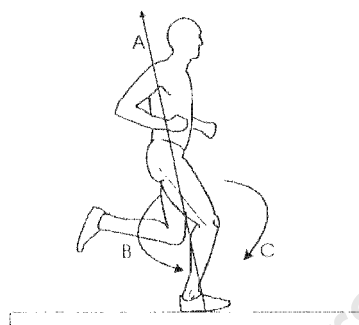


Figure 3.8. Rationale for estimation of eccentric joint load in early stance

At initial contact, the ground reaction force (A) passes posterior to the knee joint. The ground reaction force creates an external knee flexion moment that encourages the knee to flex into a collapsed posture (B). An internal knee extension moment is created by the musculotendinous structures anterior to the knee to prevent the knee from flexing (C). The nett moment that is produced at the knee in early stance is negative because the internal knee moment is extension while the knee movement is opposite in direction (i.e. the knee is flexing). The mechanical load undertaken by the structures crossing the knee at this point in stance is by the same definition negative and termed eccentric joint load.

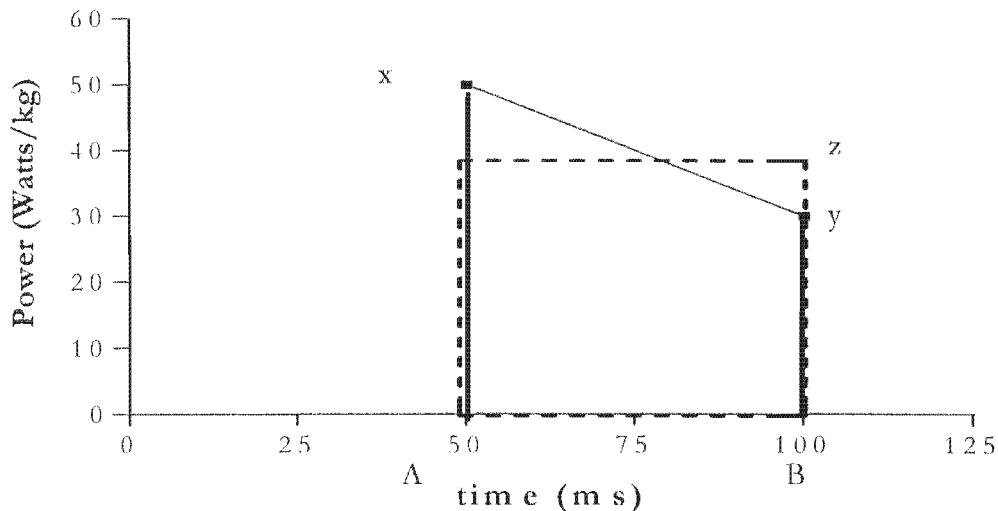


Figure 3.9. Trapezoidal integration of the power-time curve to estimate work  
 Formulae to integrate the power time curve  $[Work=(X+Y)/2.(B-A)]=[Z.(B-A)]$   
 (Stefanyshyn and Nigg, 2000)

The peak power absorption and generation values of the knee and ankle represent instantaneous measures of power generated in stance by the lower limb joint structures. The negative and positive joint work values represent the total amount of work undertaken during the period of stance that represent loading of the lower limb and propulsion from the supporting surface, respectively. The variables require gross simplifications of the human anatomy and function to circumvent the complexity presented by the apparent redundancy of structures at a joint (Vaughan 1996; Duncan et al., 1997). Consequently, the contribution of power and work by individual structures to the total estimated values is not known. Complex mathematical models based on specific physiological criteria may be used to estimate the individual contributions of the various anatomical structures to total estimated work values (optimisation) are but are currently not appropriate as a clinical tool (Crowninshield and Brand, 1981).

An assumption that is made in the clinical application of mechanical joint work variables is that negative and positive mechanical joint work represents eccentric and concentric muscle-tendon activity, respectively (Buczek and Cavanagh, 1990) Therefore, muscle-tendon units that are active across a joint (determined by electromyography) during the period in which negative or positive mechanical joint work occurs, are assumed to undergo eccentric or concentric activity, respectively (Swanson and Caldwell, 2000).

This method of determining muscle-tendon activity ignores the possibility that the muscle-tendon complex may be electrically active during either eccentric, concentric or isometric activity. Since it is currently not possible to have precise information on muscle activity during running, and a rather large assumption is made when describing a muscle-tendon complex to be either eccentrically or concentrically active if electrically active in a period of negative or positive mechanical joint work, respectively.

### 3.5.1. Running conditions and mechanical joint work

In an application of this method of quantifying muscle-tendon load, downhill running was associated with greater negative mechanical joint work than level running. It was suggested the greater negative (eccentric) mechanical joint work during downhill running may be related to the phenomenon of delayed onset muscle soreness observed after that activity (Buczek and Cavanagh, 1990).

In a related study, the negative mechanical joint work values were higher at the knee than the positive mechanical joint work values and it was assumed that the knee extensor mechanism was primarily involved in impact attenuation rather than propulsive function (McClay and Manal, 1999). In contrast, the predominant positive mechanical joint work values at the ankle in stance suggest that the plantarflexors have greater importance in propulsion than impact attenuation (McClay and Manal, 1999).

Electromyographic analysis of the knee musculature has shown the vastus medialis, intermedius and lateralis to be more active during the loading than the propulsive phase of stance (Montgomery et al., 1994) and supports the suggestion that they are important for impact attenuation (McClay and Manal, 1999). The activity of the adductor magnus, lower gluteus maximus and tensor fascia latae during early stance phase suggest they too may have a role in impact attenuation (Montgomery et al., 1994). The peak electrical activity of the gastrocnemius, soleus and tibialis anterior in early stance phase appears necessary to control forward rotation of the tibia on the ankle (Reber et al., 1993).

### 3.5.2. The relationship between mechanical joint work (eccentric load) and injury

The exact mechanism by which eccentric activity may cause injury is not known (Albert, 1995). Micro-tears of the connective tissue during activities that cause eccentric contraction may be fundamental to the development of delayed onset of muscle soreness (Albert, 1995). It appears reasonable that microscopic tissue damage with eccentric activity that accumulates and exceeds a critical limit is in excess of the healing rate, and therefore manifest as injury.

A relationship between eccentric load and injury in the upper limb is described. Lateral epicondylitis or "tennis elbow" is associated with incorrect technique in tennis such as a flexed elbow during the single-handed backstroke (Jifeld, 1992). The incorrect technique is associated with greater stress within the muscle-tendon structures of the elbow (Leach et al., 1992). In contrast, with an extended elbow single-handed backstroke, the upper limb stress is transmitted to the shoulder girdle that is better at assimilating the stress (Leach et al., 1992). In addition, if the force applied to the wrist extensor muscles exceeds the force required to maintain an extended wrist, the wrist is forced into flexion and the wrist extensor muscles undergo eccentric contraction (Wu et al., 2001). Eccentric contraction of the wrist extensor musculature may generate excessive stress at the origin of the wrist extensor muscles from the lateral epicondyle (Wu et al., 2001). The stress accumulation is hypothesised to cause microtears of the tendinous origin of the wrist extensors and clinically manifest as injury (Leach et al., 1992).

Not all eccentric activity is associated with injury. Controlled eccentric exercise is associated with an increase in muscle isometric strength and an increase in muscle cross-sectional area with an increase in jump height performance (Lindstedt et al., 2001). Furthermore, it is suggested that controlled eccentric exercises may increase the length, tensile strength, and force of the muscle-tendon unit and may be beneficial in the rehabilitation of Achilles' tendon injury (Alfredson et al., 1998).

An alternative relationship between mechanical joint work and injury to that of excessive eccentric load has been suggested (Novacheck, 1998). It is proposed that kinetic energy is stored as potential energy within selected muscle-tendon complexes during the loading phase of stance and that the potential energy is released during propulsion as kinetic energy (movement). Due to the mechanical properties of the muscle-tendon structures not all the stored (potential energy) is returned as movement (kinetic energy) (Novacheck, 1998). Some of the stored energy is retained within the muscle-tendon complex as heat. Accumulation of excessive heat within the tendon may cause tenocyte necrosis and tendon matrix degradation. If matrix degeneration exceeds matrix regeneration, as may occur with a sudden increase in the training load, the tendon becomes inflamed or degenerated with the clinical manifestation of injury (Novacheck, 1998). A first step to evaluating role of mechanical joint work in the aetiology of running injuries is to determine the factors that may affect its magnitude.

### 3.5.3. Mechanical joint work (eccentric load) and running speed

Hip and knee negative mechanical joint work increases with greater excursions of the lower limb joints that occurs with an increase in running speed (Novacheck, 1995) and negative gradient of the supporting surface (Buczek and Cavanagh, 1990). The lower limb geometry that occurs at different running speeds are so distinct they are considered different styles of running, viz. jogging, running and sprinting (Figure 2.3.10).

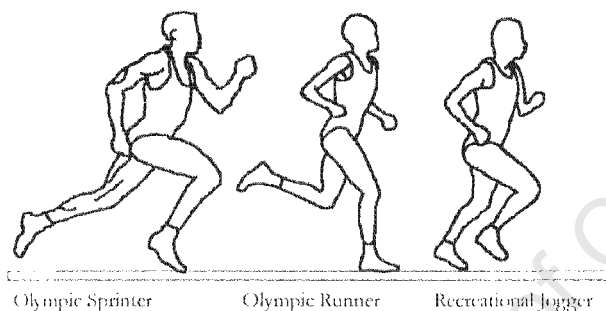


Figure 3.10. Running speed is associated with characteristic running styles

Similarly, running style is specific to downhill, uphill or level running (Swanson and Caldwell, 2000). In this regard, it is acknowledged that each runner has a unique running style that is representative of the runner's individual anthropometrical and physiological attributes (Cavanagh, 1977).

### 3.5.4. Relationship between mechanical joint work (eccentric load) and running style

The pattern of movement of the body segments of the runner in motion defines the running style (Cavanagh, 1977). Running style is subjectively determined from the visual interpretation of the runner's body segments movement, such as the overall action, body angle, arm swing, foot placement and leg lift (Subotnick, 1985). Additional visual information of running style may be gained from observing stride length and frequency (Subotnick, 1985). However, information of the running style that is not obvious is the force that the runner impacts upon the supporting surface or the mechanical joint work required to effect movement of the individual body components. In this regard, the change that occurs in lower limb geometry with a change in forward to backward running, and with heel-toe to midfoot running, is accompanied by characteristic/ specific changes in the ground reaction force and mechanical joint work variables.

In addition to the lower limb geometry and temporal distance variables commonly used, the ground reaction force and mechanical joint work may also be used to describe running style.

Factors representative of the constitution of the runner such as age, gender, lower limb alignment and state of fatigue, have an effect on the running gait analysis variables other than lower limb kinematics. In this regard, despite similarity of the lower limb kinematics of the two groups, runners younger than 55-years had lower peak vertical impact forces than runners older than 55-years (Bus, 2001). Female runners had lower peak vertical impact forces and greater maximum pronation values than male runners (Hennig, 2001). Runners with an abnormally large Quadriceps angle did not have lower limb kinematics different to runners with a smaller Quadriceps angle (Heiderschmidt 2000). A fatigued compared with a non-fatigued state was characterised by an increased running cadence and an increase in the loading of the medial aspect of the foot (Willson and Kernozek, 1999). These findings suggest that in addition to the lower limb kinematics, the gait analysis variables such as ground reaction force and temporal distance parameters should be studied to describe changes in running style due to factors intrinsic to the runner.

### 3.5.5. Natural running style adaptation

Environmental factors extrinsic to the constitution of the runner such as running shoes, the hardness of the supporting surface, and the use of a treadmill, result in natural adaptation of the running style that are reflected in the gait analysis variables descriptive of running style. Barefoot running, running on a hard surface and treadmill running are characterised by a flatter foot placement and a more flexed knee at initiation of stance (de Wit et al., 2000). These are accompanied by changes in the magnitude of the peak vertical impact forces compared with running with shoes, on soft supporting surfaces or during overground running, respectively. A reduction in the loading rate of the vertical impact forces was noted with the use of running shoes and running on soft surfaces while the vertical propulsive forces were reduced in treadmill running. These results suggest that the effect of environmental factors on running style may be described with both the lower limb kinematic and ground reaction force variables.

The adaptation of running style to each of the intrinsic and environmental conditions is described by the changes in individual gait analysis variables. It appears that the runner consciously or subconsciously perceives changes in the internal or external environment and formulates a movement pattern that is most appropriate. In this regard, runners are able to perceive high impact states (McCaw et al., 2000) and modify their running style to avoid heel contacts (Milani et al., 1997) by flexing the knee and plantarflexing the ankle in preparation for and at initial foot contact (de Wit et al., 2000). Heelstrike transients may constitute some of the sensory information of the running condition (Hennig, 1996) and unattenuated sensory receptors of the sole of the feet are required for unhindered locomotion (McDonnel and Wardenflood, 1992).

The ability to perceive the internal and external environments appears necessary to formulate an appropriate running style to the conditions to which the runner is exposed. However, whether a specific running style adopted carries the least risk of injury or is the most mechanically efficient is not known. Rather it appears that such a running style is reactive to the sensory information presented to the runner. The differences in running style between barefoot and shod running is perhaps most relevant in this regard (de Wit et al., 2000).

### 3.5.6. Learned running style formulation

In contrast to a reactive running style formulation, a learned running style formulation refers to the conscious learning of a movement pattern that is independent of the environmental conditions presented to the runner.

The conscious modification of running style reported in the literature is limited to teaching runners to run backward (Figure 3.11) (Morton, 1986; Devita and Stribling, 1991; Flynn and Soutas-Little, 1995), and to change from heel-toe to midfoot running (Williams et al., 2000).

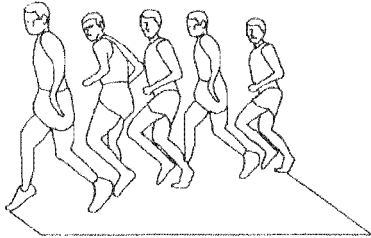


Figure 3.11. Backward running is an impractical running activity

Despite being largely impractical apart from being conducted in controlled environments for the purposes of rehabilitation (Morton, 1986), backward running has been demonstrated to have lower patello-femoral compressive forces compared with forward running, and consequently may have application in the management of running injuries such as Anterior Knee Pain Syndrome (Flynn and Soutas-Little, 1995).

Race-walking is a type of locomotion that is learnt to achieve a locomotion speed equivalent to that of running (Figure 3.12) (Murray et al., 1983). Race-walking is characterized by a faster cadence and longer strides compared with “walking fast”. The greater stride length is achieved by hyperextension of the knee and greater transverse pelvic rotation. The trunk rotates transversely and flexes laterally as a consequence of the pelvic motion. The specific style of locomotion is different from the natural motion that occurs during “walking fast” and is an example of a learnt activity necessary to achieve walking at a pace equivalent to running.

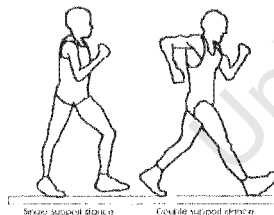


Figure 3.12. Race walking has a distinctive style with double support and a long stride length

A learnt running style that is in a forward direction, yet distinct from heel-toe running, is the Pose method of running (Figure 3.13). Pose method running occurs when contact with the supporting surface is made exclusively with the midfoot, the torso, pelvis and supporting foot aligned throughout stance to encourage the runner to “fall” forward with a rapid change in limb support as described later in this work (Study Seven). The “fall” with a change in limb support is vital to

achieve forward movement in Pose running. The potential application of Pose method running to the treatment and rehabilitation of running injuries is proposed in later portions of this thesis (Study Seven).

### 3.6. Relevance of mechanical joint work to the thesis

While most natural and some learned running styles have been described with lower limb kinematic, temporal distance and ground reaction force variables, there is a paucity of information of the associated mechanical joint work. This situation exists despite the potential that mechanical joint work may represent the stress within tissues commonly injured in running. It would be valuable therefore to describe the mechanical joint work in various running styles reactive to a variety of internal and external running conditions, and proactive running styles, to evaluate their role in either the cause or treatment of common running injuries.

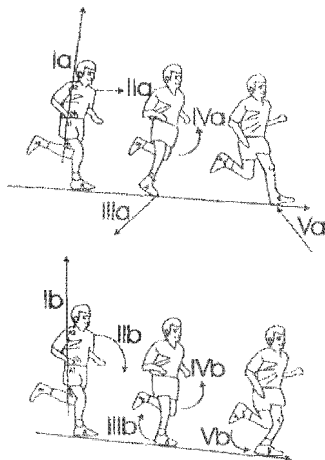


Figure 3.13. Comparison of heel-toe and Pose method running

#### Heel-toe running

Ia. The trunk is angled so that the centre of gravity (Centre of mass) is behind the foot at initial contact (Subotnick, 1985). IIa. The forward swinging leg moves the Centre of Mass over the supporting foot in stance (James et al., 1978). IIIa. The knee and ankle are extended and propel the runner forward and upward, hereby producing a propulsive force against the supporting surface (Mann and Hagy, 1980). IVa. The opposite leg swings forward by flexing the hip (Novacheck, 1995). Va. The opposite leg contacts the supporting surface with the knee and ankle extended, producing a braking force.

#### Pose method running

Ib. The pelvis is pushed forward to align the trunk vertically with the ipsilateral shoulder. IIb. The trunk alignment places the Centre of Mass anterior to the supporting foot, encouraging the runner to "fall" forward. IIIb. The supporting foot is rapidly lifted thereby avoiding forward "propulsion" from the supporting surface. IVb. The opposite leg is swung forward by flexing the hip. Vb. The opposite foot is rapidly swung into position to support the "falling" runner, while maintaining the trunk alignment in Ib.

### 3.7. Summary

Running injuries appear to occur as a result of the accumulation of stress within a tissue in excess of the ability of the tissue to repair or be resistant to the stress. Despite early clinical opinion and

the results of biomechanical studies, abnormal movement of the foot and excessive impact forces do not appear representative of stress within tissues injured during running. A case has been made that mechanical joint work may be representative of the stress within the injured tissues in running. Mechanical joint work is a function of running style, and hence changes in running style either reactively or proactively may have consequences in the cause and treatment of running injuries.

**The aim of this thesis is to determine the changes in gait analysis variables with variations in running conditions including the shod condition, with soft and semi-rigid orthoses and a conscious change in the style of the runner.**

It is hoped that the variables obtained from standard clinical gait analysis of running style may contribute to the understanding of the aetiology of common running injuries and an improvement of existing patho-mechanical models of injury.

**Information that is apparent to the reader at this point include:**

1. The inability of the abnormal impact force and abnormal movement patterns of the lower limb to represent the mechanical joint work (stress) within injured musculotendinous structures of the lower limb, and the potential for the estimation of mechanical joint work to aid in understanding injury mechanisms, serve as the motivation for a study of the relationship between running style and injuries and
2. The gait analysis variables that may be practical to the study of running style and injury, include the ground reaction forces, lower limb joint movements and the joint work and power required to effect the observed movement.

### **3.8. Research milestones**

**The research milestones that will be addressed in the following studies of this thesis include:**

1. Determination of the repeatability of the gait analysis variables used to describe running style (Study One);
2. Exploration of the relationship between the gait analysis variables used to describe running style and age, gender, foot-type and self-selected running speed in an uninjured, recreational, adult runner population (Studies Two and Three);
3. Determination of the effect of running shoe, soft and semi-rigid orthoses use on the gait analysis used to describe running style (Studies Four, Five and Six);
4. Determination of the effect of running style modification on the gait analysis used to describe running style (Study Seven) and
5. Determination of the relationship between gait analysis used to describe running style and common running injuries in a recreational adult running population (Study Eight).

## STUDY ONE

### Repeatability of gait analysis variables selected to describe running style

#### 1. Introduction

Running style is a “learned response to a given set of anthropometric and physiological constraints” (Cavanagh et al., 1977) so that the movement of the body components is made in such a way that the minimal amount of mechanical work is done (Beckett and Chang, 1968). A runner’s style is so unique that it often allows recognition of an individual runner in a group. Recognition of running style is often made from the characteristic overall body action. A detailed description of a running style however requires that the overall body action be dissected into individual variables. These variables may include body angle, arm swing, foot placement, rear leg lift, and length of stride (Subotnick, 1985). Gait analysis of the runner allows the description of the temporal distance parameters, lower limb geometry, dynamic interaction in a laboratory of the runner with the supporting surface (de Wit et al., 2000) and the mechanical work required to effect the observed movement (Swanson and Caldwell, 2000). The repeatability of the gait analysis variables selected for the description of running style as described in the literature review is not known. The aim of this study is therefore to determine the short-term repeatability of the methods employed to evaluate the gait analysis variables commonly used to describe laboratory running style at self-selected running speeds.

#### 2. Method

##### 2.1. Subjects

Seventeen 17 runners [12 males and 5 females], (mean±SD: 32.2±9.8 years; 70.08±10.98 kg; 1.73±0.08m) recruited from the student population at the University of Cape Town, participated in the study. The runners were randomly allocated to two groups to measure the test-retest repeatability of the data collection method in the barefoot condition.

##### 2.1.1 Consecutive day testing

In the first group, ten [seven males and three females] of the seventeen runners were subjected to repeat testing on two consecutive days. The repeatability of the data was determined from the test-retest correlation of the running trial data between the two consecutive days.

##### 2.1.2 Same day testing

Seven [five males and two females] of the seventeen runners participated in the second group of the repeatability test. The runners were tested before and after a 1000m run on an indoor running track at SSISA within a single day. The repeatability of the data was determined from the test-retest correlation of the running trial data before and after the 1000 m run. Gait analysis was undertaken in the Gait Analysis Laboratory at the Sports Science Institute of South Africa (SSISA) and familiarisation runs on the indoor track facility at SSISA.

#### 2.2. Informed consent

Detailed information about the nature of the testing procedure was provided to all participating runners. Informed consent as prescribed and approved by the Research Ethics Committee of the University of Cape Town was obtained from all runners prior to participation in the study.

## 2.3. History

A detailed history was sought from each runner as described under the various headings below.

### 2.3.1. Personal history

The age, gender, occupation and contact details of all runners were recorded. Past and present running injuries, surgical procedures and medical illnesses were recorded on a validated self-administered questionnaire.

### 2.3.2. Training history

The training history was recorded with a self-administered questionnaire. The running experience of each runner was determined from the total number of years the runner had engaged in regular running activities. Additional training history sought from each runner included: distance run in a single training session (km) and number of weekly training sessions. The weekly training distance (km) was determined from the product of the latter two variables. Performance running history included: personal best 10 km, 21km, and 42.2 km race times (hours: minutes) in the 12 months prior to the test session.

### 2.3.3. Running shoe and orthoses history

The brand, model and either United Kingdom or United States of America size of the running shoe used by the runners was recorded. The characteristics of any orthoses used by the runner were recorded. The orthoses were either: commercial or customised, full-foot length or half-foot length, soft, semi-rigid or rigid, and recorded appropriately.

## 2.4. Clinical examination

### 2.4.1. Lower limb alignment evaluation

An experienced sports physician examined the right lower limb alignment of each runner as described below. The right lower limb was clinically examined as it was assumed that this may have an effect on the gait analysis data that was collected and analyzed from the same limb. At this point in the study of the gait analysis variables descriptive of running style, the effect of the lower limb alignment (foot-type) on the concerned variables was not known, and this information only became apparent after completion of the subsequent study that is described in the next chapter (Chapter Four). The results of the study described in Chapter Four would not however change the protocol followed in this study, should they have been available beforehand. The examination was visually completed with the runner in a full weight bearing standing position and a clinical method that is validated and described to be repeatable with an interrater reliability of 0.72 (Dahle et al., 1991). No instrumentation was used. The presence or absence of a bulge to the medial border to the foot (Figure 1A) and height of the medial longitudinal arch was noted (Figure 1B). Simultaneously, the alignment of the forefoot with the rearfoot was described as abducted, neutral or adducted. The alignment of the rearfoot with the leg was described as valgus, varus or neutral (Figure 2A). Internal, neutral or external rotation of the thigh and leg segments with the medial borders of the feet positioned together was observed (Figure 2B). Based on the collective assessment of the right lower limb alignment, each runner was classified according to the described criteria as having a pronated, supinated or neutral foot type (Dahle et al., 1991).

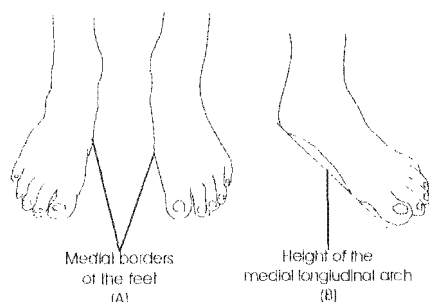


Figure 1. The shape of (A) the medial border and (B) height of the medial arch

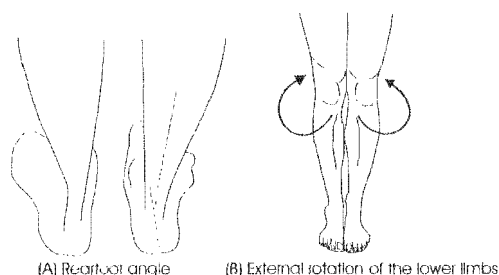


Figure 2. (A) Alignment of the rearfoot and (B) rotation of the lower limb are noted

The alignment of the rearfoot is observed from the angle formed by a line bisecting the rear of the leg and the calcaneus.

A pronated foot was recognised from the following characteristics: the calcaneus was noticeably everted (more than 13 degrees from a perpendicular through the calcaneus), the medial border of the foot bulged medially due to protrusion of the talus on the medial side of the foot, the medial arch was low, and the forefoot abducted on the rearfoot (Dahle, 1991). In contrast a supinated foot-type was described as one in which the rearfoot was noticeably inverted (more than 13 degrees from a perpendicular through the calcaneus), there was no bulge of the medial border of the foot, the medial border was described as high, and the forefoot adducted on the rearfoot (Dahle, 1991). A neutral foot was one that did not meet the criteria for classification as either pronated or supinated, in the absence of any other structural abnormalities (Dahle, 1991).

#### 2.4.2. Anthropometric measurement

The height (m), mass (kg) and distance between the Anterior Superior Iliac Spines (m) were recorded for each runner in the standing position with the feet spaced approximately 20cm apart. Bilateral anthropometric measurements included thigh and calf segment lengths and circumference (m); knee, ankle and foot widths (m); foot length (m) and malleolar height (m) (Vaughan et al., 1999). A precision beam caliper and a cloth tape were used to record all measurements.

### 2.5. Gait analysis procedure

All testing was conducted with the runners barefoot. Therefore, the gait analysis procedure comprised two components: a familiarisation run and a laboratory test, both conducted at SSISA.

#### 2.5.1. Familiarisation runs

The runners were assumed not to be habituated to barefoot running. To allow the runners to become accustomed to barefoot running all runners were encouraged to participate in the familiarisation component of the running trials. The familiarisation component consisted of a

barefoot run of 1000m on an oval, 140m-circumference indoor tartan track at a self-selected running speed.

### 2.5.2. Laboratory procedure

The runners were given the opportunity to familiarize themselves with running trials in the gait analysis laboratory at self-selected running speed. Once the runners were comfortable at accelerating to their desired self-selected running speed on the runway, they were requested to maintain the self-selected running speed and their natural running style for all subsequent running trials. The start position of the runner was then manipulated so that the runner made contact with a strain gauge force plate (AMTI Inc., Newton, MA, USA) with the right foot. The AMTI® force plate was mounted flush with the surface of the runway at a distance of approximately six (6) metres from its beginning. The runners were unaware of the position of the force plate. A running trial was considered successful when the runner made contact exclusively with the force plate with the right foot and there was no alteration in running style as determined subjectively by the investigators. Any trials in which the runner was considered to target the force plate, as observed from the runner with the naked eye and on review of the animation from the collected gait analysis data, were repeated. Ten running trials were collected for each runner, stored on a personal computer for analysis as described later in this chapter.

### 2.5.3. Running speed selection

Running trials were undertaken at a self-selected running speed. A self-selected running speed was described to each runner as a running speed that they could select independently, with which they (each runner) felt comfortable, and would be representative of the running speed they (each runner) followed in an easy training run. The runners were requested to maintain consistency of the running speed for all trials in the gait analysis laboratory. To assist the runners to “set” the running speed, they were given the opportunity to complete a 1000m familiarisation run in the barefoot condition on an indoor track facility at SSISA. The running speed for each trial is described below.

### 2.5.4. Running style

All runners naturally employed a heel-toe running style.

## 2.6. Instrumentation

### 2.6.1. Walkway

The runners were tested on an 11m long runway in the Gait Analysis Laboratory. The surface of the runway was covered with a durable industrial-type carpet. The carpet covered the AMTI® force plate which was mounted flush with the surface of the walkway and effectively concealed the force plate.

### 2.6.2. Marker set

The modified Helen-Hayes marker set was used to collect kinematic data (Vaughan et al., 1999). Fifteen (15) retro-reflective 25mm diameter spheres were attached to selected bony positions on the pelvis and lower limb to determine the movement of the segments of interest. The retro-reflective spheres were mounted with 2-way adhesive tape to the skin of the runner, after carefully shaving excess hair from the attachment points. The spheres were directly attached to the following bony prominence: on the pelvis: the anterior superior iliac spines bilaterally (RASIS and

LASIS), and sacrum; the thigh: the lateral epicondyle; the leg: the lateral malleolus; the foot: the os tuber calcaneum, and the dorsal surface of the second metatarsophalangeal joint (2MTPJ) (Figure 3).

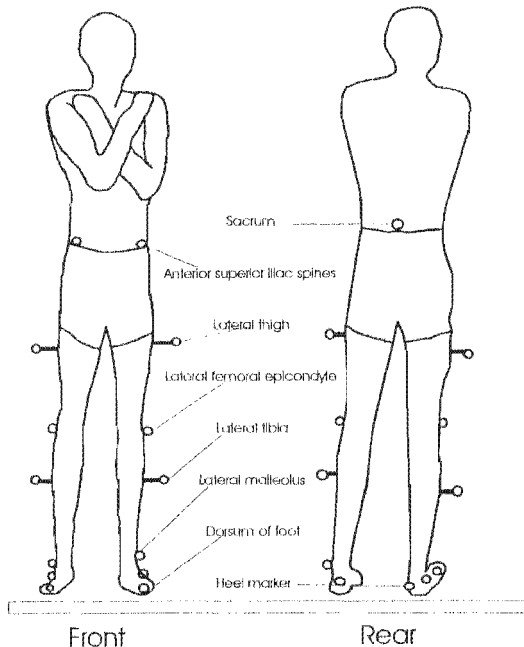


Figure 3. Positions of the retroreflective markers: front and rear view.

In addition, a pair of retro-reflective spheres mounted on 30mm long rigid wands was attached to the mid-point of the lateral aspect of the thigh bilaterally. A similar pair of retro-reflective spheres mounted on 30mm long rigid wands was attached to the mid-point of the lateral aspect of the leg bilaterally.

### 2.6.3. Gait analysis system

A six-camera Vicon 370 Motion Analysis System (Oxford Metrics Ltd, Oxford, England) was used to collect kinematic data at 120Hz. The six digital video cameras were mounted on extendable tripods and arranged in a hexagon at the circumference of the laboratory. The axis of each camera was directed at the force plate at the centre of the room. Each camera emitted red light from a series of red light emitting diodes arranged circumferentially about the lens of the camera. The retro-reflective markers attached to calibration frame placed on the force plate and 500mm dynamic wand reflected the emitted red light. The reflected light was captured by the six cameras, conveyed by underfloor cabling to a data station and converted to digital form for processing. The camera system was calibrated in two stages: the first stage to determine the calibration volume using a fixed calibration frame; and the second stage to refine the calibration process with a dynamic wand. Once calibrated, a “static” trial was completed to identify the positions of each of the attached retro-reflective markers. Thereafter, “dynamic” trials for running data were captured with the motion analysis system.

### 2.6.4. Force plate equipment

The AMTI® force plate was used to capture ground reaction force data at 1000Hz. The force plate measured the three orthogonal force components along the X, Y, and Z-axes, and the moments about the three axes, producing a total of six outputs. A channel recorded each of these outputs.

Each channel of the force plate was manually calibrated prior to the commencement of data capture. Underfloor cabling to a data station for processing conveyed analogue data from the force plate.

## 2.7. Data analysis

The five trials with few if any “gaps” in the data series and that required minimal interpolation were selected for analysis. All gait analysis data collected were processed to a standard binary format that contained 3D data, analogue data and data parameters (C3D files) with the Workstation® program by Oxford Metric (Oxford, England). The C3D files were reconstructed in the Workstation® program to an animation to allow identification of gait events and assist editing of the data (Figure 4).

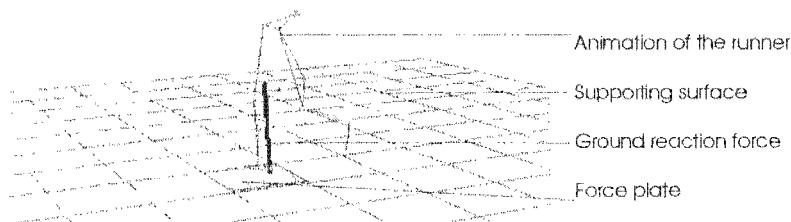


Figure 4. A three-dimensional reconstruction of the C3D data in Workstation®.

The C3D files were further converted to Data Storage and Transfer (DST) files using the Rdata2® program by Motion Lab Systems (Baton Rouge, USA). Processing of the raw data files was accomplished with the Bodybuilder® program by Oxford Metrics and the GaitLab® program by Kiboho Publishers (Cape Town, South Africa). These programs enabled the calculation of three degrees of freedom joint angles and power-time curves for the knee and ankle joints. All data were exported as text files for analysis in Excel® (Microsoft Corporation, Redmond, USA).

## 2.8. Gait analysis variables

The running style gait analysis variables determined with clinical gait analysis techniques for this study were selected on the basis of previously reported studies described in Literature review (Messier et al., 1991; de Wit et al., 2000). The movements of subtalar joint pronation and supination of the foot are traditionally considered important in understanding the aetiology of running injuries. As described earlier (Literature review), these specific movements are difficult to measure in a laboratory without the use of highly invasive surgical techniques (Stacoff et al., 2000). The modified Helen-Hayes marker set and the GaitLab® mathematical model used to analyse the running style data in this study essentially computes the movement of the foot as a single segment about three-axes through the ankle. Flexion-extension and abduction-adduction about the ankle is determined from the rotation of the foot segment about the y-axis and x-axis the through the ankle, respectively. Inversion-eversion rotation at the ankle is determined from the rotation of the leg segment about the long axis of the foot (Vaughan et al., 1999). None of the movements determined with the modified Helen-Hayes marker set and GaitLab® mathematical model represent the clinical movements of subtalar joint pronation and supination. Consequently the clinical movements of pronation and supination were not determined in this study as a result of the limitation of the marker set and mathematical model used. The gait analysis data selected to describe running style were limited to the gross sagittal plane movements and dynamics of the

knee and ankle. Conventional temporal-distance parameters such as stride and step length were selected as determined as described below. Novel temporal-distance variables included the vertical displacement of the sacrum and left heel marker during a gait cycle. The vertical and horizontal components of the ground reaction force were based on those described in the literature, and are detailed below (Messier et al., 1991). The vertical ground reaction force inconsistency is reported by earlier researchers (McCaw et al., 2000). The work and power variables during stance were selected, as they may provide the clinician insight to the activity of the musculoskeletal structures. However, these variables do not explain the contributions of specific tissue types or structures that undertake this activity.

## 2.9. Running speed

The average displacement to time ratio of the sacrum retroreflective marker along the x-axis of the global reference system was used to determine the running speed. The running speed was averaged for the five running trials analysed per runner.

## 2.10. Temporal-distance variables

The average vertical displacement of the sacral marker in the z-axis of the global reference system over five running trials was used to determine the average vertical body displacement (m) (Figure 5). The average horizontal (x-axis) and vertical (z-axis) displacements of the left heel marker over five running trials were used to determine the average stride length (m) and vertical foot displacement (m), respectively (Figure 5). The average vertical body oscillation, stride length and vertical foot displacement were corrected for leg length. This was undertaken by converting the variables to a dimensionless ratio, thereby factoring out the effect leg length may have on the data.

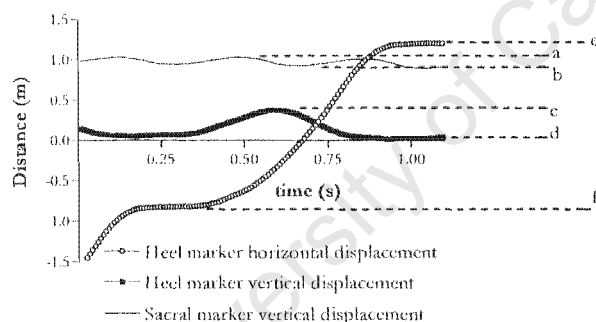


Figure 5. Typical displacement-time graph of the sacral and heel markers

Average vertical displacement of the sacral marker (a-b), Average vertical displacement of the heel marker (c-d), Average horizontal displacement of the heel marker (e-f)

## 2.11. Ground reaction forces

The kinetic data of the five trials per runner were averaged (Clarke et al., 1983; de Wit et al., 2000; McCaw et al., 2000). The ground reaction force variables included: the loading rate and magnitude of the vertical impact force peak, the vertical propulsive force peak, and the horizontal braking and propulsive force peaks (Figure 2.3.1). All ground reaction force variables were expressed in multiples of body weight (BW).

## 2.12. Joint angles

The knee and ankle joint angle variables in this study were limited to those about the y-axis through the knee and ankle joints. The kinematic data for five running trials per runner were averaged and analysed (Figure 2.3.5). Selected data points included both swing and stance phase kinematics. Swing phase data included the peak knee flexion angle in swing phase, and the peak knee extension angle and the accompanying ankle angle during terminal swing phase immediately prior to initial contact with the supporting surface. The stance phase data included the knee and ankle angles at initial contact with the supporting surface and the peak knee flexion and ankle dorsiflexion angles in stance phase.

## 2.13. Joint power

The knee and ankle power (Watts/kg) curves during stance phase were determined with an inverse dynamics method using a three degrees of freedom joint model in GaitLab® (Kiboho Publishers, Cape Town, South Africa). The peak negative and positive knee and ankle power values were determined from the data in an Excel® (Microsoft Corporation, Redmond, USA) spreadsheet (Figure 2.3.7).

## 2.14. Joint work

Negative (eccentric) and positive (concentric) work (J/kg) values were calculated from the trapezoidal integration of the area below the negative and positive portions of the power-time curve, respectively (Figure 2.3.9) (Stefanyshyn and Nigg, 2000).

## 3. Main outcome variables

The biomechanical variables that were compared for the groups were:

1. The temporal-distance variables: vertical oscillation of the sacrum (m) and heel marker (m), and stride (m) and step length (m).
2. Ground reaction forces: loading rate (BW/s) and magnitude (BW) of the vertical impact force at peak value, the magnitude of the propulsive force in the vertical (BW) and horizontal (BW) directions and the horizontal braking force (BW);
3. Joint angles: during mid-swing ( $^{\circ}$ ), terminal swing ( $^{\circ}$ ), initial supporting surface contact ( $^{\circ}$ ) and midstance ( $^{\circ}$ );
4. Joint power and work: the magnitude of the knee and ankle power (Watts/kg) and work (J/kg) during support and propulsive phases of stance.

## 4. Statistical analysis

Statistical tests were undertaken of the gait analysis variables using a commercial statistical programme (StatSoft, Inc. (2000). STATISTICA for Windows [Computer program manual]. Tulsa, OK, USA). Pearson's Moment Correlation Coefficients were used to represent the corresponding components of repeatability of the data collection procedure (Portney and Watkins, 1993). Differences in the data between individual test sessions of the consecutive day component and between individual sessions of the same day test component were determined with dependent t-tests. The level of significance for all tests was set at  $p < 0.05$ .

## 5. Results

### 5.1. History

#### 5.1.1. Personal and training history

The runners all participated in regular running activity with a [mean±SD] running distance of 22.4±6.3 km/week. The [mean±SD] best 10km time for the group was 50.78±15.34 minutes. All participating runners were injury free for at least one year prior to participation in the study. None of the runners had a history of neurological or orthopaedic disease, other medical illnesses or surgical procedures that may influence the gait pattern.

#### 5.1.2. Running shoe and orthoses history

All runners habitually wore running shoes for all running activities with a [mean±SD] shoe size of 7.94±2.38 UK. At least two runners wore semi-rigid orthoses during the running activities. None of the runners regularly participated in barefoot running activities.

### 5.2. Clinical examination

#### 5.2.1. Lower limb alignment evaluation

Ten (10) and seven (7) runners were identified to have neutral and pronated feet, respectively. None of the runners had supinated feet.

### 5.3. Running speed

The [mean±SD] running speed of the trials on the second day (3.9±0.5 m/s) of the consecutive day component of the study was greater than the first (3.8±0.5 m/s) ( $p= 0.031$ ). The [mean±SD] running speed of the same day component were the same (2.8±0.4 m/s).

### 5.4. Temporal-distance variables

The Pearson's Product Moment Correlation Coefficients (r-values) were determined for the test-retest temporal-distance variables of both the consecutive and same day components of the study (Table 1).

Table 1. Repeatability of temporal-distance variables in the consecutive and same day components.

	Consecutive day r- values (n=10)	p- value	Same day r- values (n=7)	p- value
VSDsp	0.89	0.001	0.84	0.027
VHDsp	0.83	0.004	0.96	0.000
StrideLn	0.96	0.000	0.97	0.000
StepLn	0.95	0.000	0.95	0.002

Vertical sacrum marker displacement (m) [VSDsp], Vertical left heel marker displacement (m) [VHDsp], Stride length (m) [StrideLn], Step length (m) [StepLn]

In the consecutive day component, the r- values of the temporal-distance variables ranged from 0.83 ( $p= 0.004$ ) to 0.96 ( $p= 0.000$ ). The r-values of the temporal-distance variables ranged from 0.84 ( $p= 0.027$ ) to 0.97 ( $p= 0.000$ ) for the same day component of the study. There were no differences between the temporal-spatial values in both components of the study (Table 3.2).

Table 2. Comparison of temporal-distance variables between before [Bf] and after [Af] variables of the consecutive<sup>(c)</sup> (n= 10) and same day<sup>(s)</sup> (n= 7) components

	Bf <sup>c</sup>	Af <sup>c</sup>	p- value	Bf <sup>s</sup>	Af <sup>s</sup>	p- value
VSDsp	0.09 ± 0.03	0.10± 0.03	0.484	0.08± 0.02	0.08± 0.02	0.873
VHDsp	0.38 ± 0.11	0.39± 0.14	0.520	0.35± 0.07	0.35± 0.05`	0.924
StrideLn	2.20 ± 0.55	2.22± 0.71	0.373	2.08± 0.40	2.10± 0.39	0.788
StepLn	1.09 ± 0.34	1.12± 0.36	0.432	1.03± 0.20	1.04± 0.15	0.880

Vertical sacrum marker displacement (m) [VSDsp], Vertical left heel marker displacement (m) [VHDsp], Stride length (m) [StrideLn], Step length (m) [StepLn]

### 5.5. Ground reaction forces

In the consecutive day component, the r-values of the ground reaction force variables ranged from 0.75 (p= 0.012) to 0.93 (p= 0.000) (Table 3). The r-values ranged from 0.92 (p= 0.003) to 0.99 (p= 0.000) for the same day component (Table 4).

Table 3. Repeatability of the ground reaction forces in the consecutive and same day components

	Consecutive day r- values (n=10)	p- value	Same day r- values (n=7)	p- value
HBF	0.86	0.001	0.92	0.003
HPF	0.93	0.000	0.96	0.001
VIF	0.75	0.012	0.97	0.000
VLR	0.75	0.012	0.97	0.000
VPF	0.91	0.000	0.99	0.000

Horizontal braking force (BW) [HBF], Horizontal propulsive force (BW) [HPF], Vertical impact force peak (BW) [VIF], Vertical impact force peak loading rate (BW/s) [VLR], Vertical propulsive force peak (BW) [VPF]

There were no differences between the HBF, HPF, VLR and VPF variables of the consecutive day component. The VIF was greater on the second day (VIF: 1.58±0.28 BW) compared with the first day (VIF: 1.45±0.26 BW) (p<0.05) of the consecutive day component. There were no differences in the ground reaction forces of the same day component of the study.

Table 4. Comparison between before [Bf] and after [Af] ground reaction forces in the consecutive<sup>(c)</sup> (n= 10) and same day<sup>(s)</sup> (n= 7) components.

	Bf <sup>c</sup>	Af <sup>c</sup>	p- value	Bf <sup>s</sup>	Af <sup>s</sup>	p- value
HBF	0.30± 0.08	0.32± 0.08	0.073	0.23± 0.05	0.24± 0.07	0.881
HPF	0.20± 0.05	0.20± 0.05	0.832	0.17± 0.02	0.16± 0.02	0.643
VIF	1.45± 0.26	1.58± 0.28	0.020	1.25± 0.18	1.27± 0.22	0.634
VLR	58.2± 10.4	57.9± 10.5	0.784	50.2± 7.3	50.9± 9.0	0.632
VPF	2.48± 0.45	2.48± 0.44	0.931	2.29± 0.20	2.26± 0.21	0.390

Horizontal braking force (BW) [HBF], Horizontal propulsive force (BW) [HPF], Vertical impact force peak (BW) [VIF], Vertical impact force peak loading rate (BW/s) [VLR], Vertical propulsive force peak (BW) [VPF]

### 5.6. Joint angles

The test-retest knee and ankle joint angle variables correlation coefficients of the consecutive day component of the study ranged from 0.81 (p= 0.004) to 0.95 (p= 0.000) (Table 5). The test-retest correlation values for the knee and ankle joint angles ranged from r= 0.81 (p= 0.027) to 0.97 (p= 0.000) for the same day component of the study.

Table 5. Repeatability of the joint angles in consecutive and same day components.

	Consecutive day r- values (n=10)	p- value	Same day r- values (n=7)	p- value
KswF	0.88	0.001	0.81	0.027
KswE	0.81	0.004	0.96	0.000
Kic	0.95	0.000	0.97	0.000
Kst	0.92	0.000	0.93	0.002
Asw	0.93	0.000	0.95	0.001
Aic	0.86	0.001	0.95	0.001
Ast	0.88	0.001	0.88	0.009

Knee swing phase peak flexion angle ( $^{\circ}$ ) [KswF], Knee angle in terminal swing phase ( $^{\circ}$ ) [KswE], Knee angle at initial supporting surface contact ( $^{\circ}$ ) [Kic], Knee angle in midstance ( $^{\circ}$ ) [Kst], Ankle angle in terminal swing phase ( $^{\circ}$ ) [Asw], Ankle angle at initial supporting surface contact ( $^{\circ}$ ) [Aic], Ankle angle in midstance ( $^{\circ}$ ) [Ast]

Significant differences in the knee and ankle joint angles between the first and second days of the consecutive day component were evident (Table 6). The Kst, Asw and Aic variables in the consecutive day component were different between the first day (Kst:  $38.5 \pm 3.3^{\circ}$ , Asw:  $-9.2 \pm 5.3^{\circ}$ , Aic:  $-6.4 \pm 5.3^{\circ}$ ) and second days (Kst:  $39.8 \pm 4.0^{\circ}$ , Asw:  $-5.5 \pm 7.2^{\circ}$ , Aic:  $-3.8 \pm 7.0^{\circ}$ ) ( $p < 0.05$ ). There were no differences in the knee and ankle joint angles between the same day component of the study.

Table 6. Comparison between before [Bf] and after [Af] joint angles in the consecutive ( $^c$ ) (n= 10) and same day ( $^s$ ) (n= 7) components

	Bf <sup>c</sup>	Af <sup>c</sup>	p- value	Bf <sup>s</sup>	Af <sup>s</sup>	p- value
KswF	82.4 $\pm$ 6.2	83.6 $\pm$ 3.6	0.270	83.8 $\pm$ 2.8	83.6 $\pm$ 3.8	0.783
KswE	11.9 $\pm$ 5.7	13.7 $\pm$ 6.2	0.151	19.9 $\pm$ 3.8	19.7 $\pm$ 4.3	0.599
Kic	18.6 $\pm$ 5.1	19.0 $\pm$ 4.5	0.402	24.6 $\pm$ 4.1	25.2 $\pm$ 3.4	0.187
Kst	38.5 $\pm$ 3.3	39.8 $\pm$ 4.0	0.034	43.8 $\pm$ 4.9	43.8 $\pm$ 5.5	0.941
Asw	-9.2 $\pm$ 5.3	-5.5 $\pm$ 7.2	0.004	-9.36 $\pm$ 4.1	-8.79 $\pm$ 4.3	0.310
Aic	-6.4 $\pm$ 5.3	-3.8 $\pm$ 7.0	0.047	-7.93 $\pm$ 4.06	-7.19 $\pm$ 3.76	0.185
Ast	21.6 $\pm$ 3.1	21.4 $\pm$ 2.7	0.753	-24.2 $\pm$ 1.92	-24.0 $\pm$ 1.84	0.535

Knee swing phase peak flexion angle ( $^{\circ}$ ) [KswF], Knee angle in terminal swing phase ( $^{\circ}$ ) [KswE], Knee angle at initial supporting surface contact ( $^{\circ}$ ) [Kic], Knee angle in midstance ( $^{\circ}$ ) [Kst], Ankle angle in terminal swing phase ( $^{\circ}$ ) [Asw], Ankle angle at initial supporting surface contact ( $^{\circ}$ ) [Aic], Ankle angle in midstance ( $^{\circ}$ ) [Ast]

### 5.7. Joint power and work

In the consecutive day component, the r-values ranged from  $r = 0.75$  ( $p = 0.012$ ) to  $0.94$  ( $p = 0.001$ ) (Table 7). The r-values ranged from  $r = 0.82$  ( $p = 0.023$ ) to  $0.96$  ( $p = 0.000$ ) for the same day component of the study.

## 6. Discussion

The main findings of the present study were that the test-retest correlation of the data collected from the runners in the component of the study that was completed in a single day (before and after 1000m run) was significant and there were no differences between the data of the test sessions within this component of the study. In contrast, although the test-retest correlation of the data collected in the component of the study conducted across consecutive days was significant, differences of the data between the test sessions within this component were noted.

Table 7. Repeatability of joint power and work in consecutive and same day components.

	Consecutive day r- values (n=10)	p- value	Same day r- values (n=7)	p- value
KPA	0.88	0.001	0.82	0.023
KPG	0.79	0.006	0.82	0.024
APA	0.87	0.001	0.96	0.000
APG	0.94	0.001	0.91	0.005
EKW	0.84	0.002	0.81	0.028
CKW	0.75	0.012	0.83	0.022
EAW	0.80	0.005	0.93	0.003
CAW	0.94	0.000	0.86	0.013

Knee power absorption (Watt/kg) [KPA], Knee power generation (Watt/kg) [KPG], Ankle power absorption (Watt/kg) [APA], Ankle power generation (Watt/kg) [APG], Eccentric knee work (J/kg) [EKW], Concentric knee work (J/kg) [CKW], Eccentric ankle work (J/kg) [EAW], Concentric ankle work (J/kg) [CAW]

The CAW on the first day ( $0.43 \pm 0.15$  J/kg) was greater than on the second day ( $0.38 \pm 0.14$  J/kg) ( $p = 0.014$ ) (Table 8). There were no differences in the power and work variables between the before-and-after 1000m run component of the study.

Table 8. Comparison of before [Bf] and after [Af] joint power and work in the consecutive (<sup>c</sup>) and same day (<sup>s</sup>) components.

	Bf <sup>c</sup>	Af <sup>c</sup>	p- value	Bf <sup>s</sup>	Af <sup>s</sup>	p- value
KPA	5.98± 1.63	5.89± 1.34	0.756	6.40± 2.36	6.43± 2.02	0.946
KPG	6.41± 2.16	6.44± 2.78	0.602	6.10± 2.14	6.33± 1.70	0.641
APA	6.54± 2.02	6.75± 2.14	0.786	5.69± 1.51	5.74± 1.34	0.801
APG	7.57± 2.16	7.63± 2.49	0.684	7.14± 1.95	7.20± 1.83	0.834
EKW	0.31± 0.11	0.32± 0.12	0.593	0.37± 0.15	0.37± 0.15	0.949
CKW	0.44± 0.11	0.42± 0.11	0.624	0.47± 0.17	0.49± 0.13	0.683
EAW	0.38± 0.13	0.41± 0.10	0.307	0.39± 0.11	0.39± 0.09	0.880
CAW	0.43± 0.15	0.38± 0.14	0.014	0.47± 0.12	0.46± 0.10	0.875

Knee power absorption (Watt/kg) [KPA], Knee power generation (Watt/kg) [KPG], Ankle power absorption (Watt/kg) [APA], Ankle power generation (Watt/kg) [APG], Eccentric knee work (J/kg) [EKW], Concentric knee work (J/kg) [CKW], Eccentric ankle work (J/kg) [EAW], Concentric ankle work (J/kg) [CAW]

This discussion will focus on the similarities and differences between the two components of the study to explain the discrepancy of the results. The two components of the study were similar in that they both used a test-retest protocol, the same marker set and laboratory testing equipment. The same number of running trials were recorded, the raw data collected and saved, and processed in an identical manner. The runners were barefoot in both components. An additional factor common to both components of the study was the use of self-selected running speeds for the collection of data. It appeared that self-selected running speed was primarily responsible for the differences in repeatability between the two components. The self-selected running speeds of the test sessions of the same-day testing component were identical. In the consecutive day testing component, there was a marked increase in the running speed on the second day. An increase in walking and running speed is typically associated with an increase in the magnitude of the ground reaction force components (Vaughan et al., 1987; de Wit et al., 2000). Similarly an increase in running speed is associated with an increased knee flexion and a reduction in ankle dorsiflexion in stance (de Wit et al., 2000; Novacheck, 1995). A decrease in ankle power generation with an increase in running speed is also commonly reported (Novacheck, 1995). The differences in the

gait analysis variables apart from ankle plantarflexion between the test sessions of the consecutive day testing reflect these changes. It therefore appears that the higher running speed selected by the runners on the second day of the consecutive day testing component may account for the differences observed in the ground reaction forces, kinematics and joint dynamics. It is unclear what the reasons were for the increase in self-selected running speed on the second day. However, it appears reasonable to assume that the runners underwent a learning process during the testing procedure and that this familiarity with the test protocol may have resulted in the higher self-selected running speeds. Self-selected running speed may be highly variable and this may be due to its subjective nature. A change in the runners' perception of their self-selected running speed with the successive days testing is not excluded. Control of running speed appears necessary with testing on consecutive days. However, this will result in a change in study design as self-selected will be changed to controlled running speed. A second difference in the test protocol between the same day and consecutive day testing is the attachment of the retroreflective markers. The retroreflective markers remained attached to the runners throughout the same day component, but were replaced on the second day in the consecutive day component. While the investigator charged with attaching the markers was experienced in this regard, it is likely that this may have contributed to the discrepancy in results within the consecutive day component. The retroreflective markers are vital for the determination of joint angles and joint powers as these variables are sensitive to the position of attachment of the retro-reflective markers. However, the ground reaction forces are independent of marker attachment as they represent the acceleration of the centre of mass of the runner only. Since there were differences in the ground reaction force data, as well as the kinematics and joint dynamics, it is unlikely that retro-reflective marker attachment alone may account for the differences observed in the consecutive day component of the study. Differences in running shoe cushioning and running surface consistency have previously been associated with a change in the magnitude and loading rate of the vertical impact force peak (Clarke et al., 1982, 1983; Dixon et al., 2000). However, the barefoot running condition and nature of the running surface was consistent across both test days. A change in running style from heel-toe to midfoot too, is associated with a reduction in the magnitude of the vertical impact force (Cavanagh and Lafortune, 1980). All runners were encouraged to maintain a heel-toe running style in this study. Therefore, running shoes, surfaces and styles did not appear responsible for the difference in the magnitude of vertical ground reaction forces.

## **7. Conclusion**

This study demonstrates that the gait analysis variables commonly used to describe running style are repeatable in recreational runners at self-selected running speed protocols that are completed within a day. Discrepancies of the results in a test-retest protocol may occur if the test protocol extends over more than a day period. Differences in self-selected running speed are likely to influence the results of running style gait analysis. Careful consideration should be given to the use of self-selected running speeds in running style gait analysis, over more than one day, as differences in self-selected running speeds may result in artificial differences of the variables studied.

## **8. Relevance of the findings of this study to the thesis**

As a result of the finding of this study of the study, consistency of the self-selected running speed was encouraged in all studies that compared a single runner population over one or more test conditions, irrespective of whether the testing was completed within a single day or extended over more than one day. The effect of running speed on selected gait analysis variables noted in this study is elaborated in the following chapter (Study Two).

## STUDY TWO

### The effect of foot-type, age and speed on the gait analysis variables descriptive of running style

#### 1. Introduction

The preceding study has demonstrated that running speed has an effect on the gait analysis variables selected to describe running style (Study One). These findings are consistent with the reports that the propulsive forces and dynamic loading of the musculoskeletal system increase linearly with increased running and walking speed (de Wit et al., 2000; Voloshin 2000). It is important to note that the knee and ankle joint excursions increase with running speed (Novacheck, 1995; de Wit et al., 2000; Mann and Hagy, 1980) and that the source of power generation for forward propulsion changes from the ankle to the hip with an increase in running speed (Ounpuu, 1990). The exact effect of running speed on the gait analysis variables selected to describe running speed in this work is not known. Clarification of the effect of running speed on the gait analysis variable is the primary focus of this study as this would be relevant to all subsequent studies in which running speed will be measured. Age is reported to have an effect on the gait analysis variables that describe running style such that older runners have greater loading rates of the vertical impact force than younger runners in trials where running speed was matched (Bus et al., 2001). The effect of age on the knee and ankle joint angles and dynamic variables used to describe running style is not known. As the age of the runner may have an effect on at least some of the gait analysis variables used to describe running style in this work, it appears relevant that the effect of age on these variables be investigated in this study. Foot-type is an alignment factor that is associated with an increased risk of injury (James et al., 1978). Abnormal subtalar joint pronation and internal tibial rotation is one mechanism by which abnormal foot-type is hypothesized to cause injury (Tibero, 1987; Krivickas, 1997). However, as discussed earlier (Literature review), there is no consensus on the mechanisms by which foot-type is associated with injury. A possible explanation for the uncertainty as to the relevance of foot-type to injury is the difficulty with measuring intrinsic foot movement with the non-invasive kinematic techniques. The aim of this thesis is to determine if running style has an association with injury by evaluating the gait analysis variables selected to describe running style. In order to achieve this goal, it would be important to determine if foot-type has an effect on the gait analysis variable selected to describe running style as this relationship is currently not known. The importance of controlling for foot-type in all subsequent studies in this work will be determined in the present study. The aim of this study is to determine the relationship between the gait analysis variables descriptive of running style with foot-type, age, and self-selected running speed in an adult recreational runner population.

#### 2. Methods

##### 2.1. Subjects

Sixty (60) male and female recreational runners, (mean $\pm$ SD, [range]), (mass: 75.7 $\pm$  13.7, [49 to 115] kg; height: 1.76 $\pm$  0.09, [1.54 to 2.01] m; age: 34.9 $\pm$  13.1, [18 to 70] years) free of physical deformity and injury, were recruited. The runners were recruited from local running clubs in Cape Town, South Africa with flyers handed out at the Sports Science Institute of South Africa (SSISA), Cape Town. All testing was completed in the Gait Analysis Laboratory at SSISA.

## 2.2. Informed consent

Detailed information of the nature of the testing procedure was provided. Informed consent as required and approved by the Medical Ethics Committee of the University of Cape Town was obtained from all runners prior to participation in the study.

## 2.3. Procedure

All runners followed the same standard testing procedure described in Study One. A lower limb evaluation (foot-type) and anthropometric measurements were undertaken (Study One). A 1000m barefoot run on the indoor-tartan track at SSISA at a self-selected running speed was then completed (Study One). The runners then completed a series of ten (10) barefoot running trials in the gait analysis laboratory at self-selected running speeds (Study One). Gait analysis data were collected, and five trials per runner were selected for processing and analysis (Study One).

## 3. Main outcome variables

The gait analysis variables that were compared between the three pronated, supinated and neutral foot-types, and correlated with age, height and running speed were:

1. Ground reaction forces: loading rate (BW/s) and magnitude (BW) of the vertical impact force at peak value, the magnitude of the propulsive force in the vertical (BW) and horizontal (BW) directions and the horizontal braking force (BW);
2. Joint angles: during mid-swing ( $^{\circ}$ ), terminal swing ( $^{\circ}$ ), initial supporting surface contact ( $^{\circ}$ ) and midstance ( $^{\circ}$ );
3. Joint power and work: the magnitude of the knee and ankle power (W/kg) and work (J/kg) during support and propulsive phases of stance.

## 4. Statistical analysis

Statistical analysis was undertaken of the gait analysis variables using a commercial statistical program (StatSoft, Inc. (2000). STATISTICA for Windows [Computer program manual]. Tulsa, OK, USA). Detailed descriptive statistics were conducted of the demographic data of the cohort of runners. A one-way ANOVA was used to determine differences in the gait analysis variables between the pronated, neutral and supinated foot-types. A dependent t-test was used to determine differences in the magnitude and loading rate of the vertical impact force at the peak value. The Pearson's Moment Correlation Coefficient and linear regression analysis were used to determine the relationships between age, height and running speed. Relationships between selected gait analysis variables and, age, height and running speed were studied. A statistical significance level of  $p < 0.05$  was selected for all tests.

## 5. Results

### 5.1. Running speed

The mean $\pm$ SD [range] self-selected running speed for the group is 3.1 $\pm$ 0.5 m/s, [range 2.2-4.8 m/s].

### 5.2. Mass, height and age

There are no differences in the age, mass and height between the runners in each of the three foot-type groups (Table 1). The relationships between age, mass, height and running speed are described in Table 2. Mass correlates significantly with age ( $r = 0.357$ ,  $p = 0.004$ ) and height ( $r =$

0.743,  $p=0.000$ ). There are no significant correlations between running speed, and mass, height and age.

Table 1. Comparison of the mass, height, age and running speed by foot-type

	Neutral (n= 35)	Pronated (n= 21)	Supinated (n= 4)	p-value
Mass (kg)	75.2± 13.4	74.5± 12.7	86.3± 9.8	$p=0.451$
Height (m)	1.76± 0.09	1.76± 0.10	1.81± 0.08	$p=0.313$
Age (years)	34.7± 13.6	35.1± 13.5	35.0± 8.2	$p=0.463$
Speed (m/s)	3.08± 0.55	3.20± 0.50	2.64± 0.38	$p=0.363$

No significant differences between the test conditions. [n= 60]

Table 2. Relationship between mass, height, age and running speed [n=60]

	Height	Age	Running speed
Mass	$r=0.743, p=0.000$	$r=0.357, p=0.004$	$r=0.088, p=0.492$
Height		$r=0.112, p=0.377$	$r=0.243, p=0.053$
Age			$r=-0.122, p=0.336$

### 3. Ground reaction forces

There are no significant differences in the ground reaction forces in a comparison of the three foot-types (Table 3).

Table 3. Comparison of the ground reaction forces by foot-type

	Neutral (n= 35)	Pronated (n= 21)	Supinated (n= 4)	p-value
HBF	0.23± 0.07	0.24± 0.06	0.21± 0.05	$p=0.524$
HPF	0.18± 0.04	0.17± 0.04	0.14± 0.04	$p=0.316$
VIF	1.30± 0.24	1.36± 0.21	1.20± 0.16	$p=0.493$
VLR	50.3± 10.6	50.4± 10.4	39.2± 8.7	$p=0.285$
VPF	2.29± 0.29	2.36± 0.24	2.00± 0.23	$p=0.277$

Horizontal braking force (BW) [HBF], Horizontal propulsive force (BW) [HPF], Vertical impact force peak (BW) [VIF], Vertical impact force peak loading rate (BW/s) [VLR], Vertical propulsive force peak (BW) [VPF], No significant differences between the test conditions.

The relationships between ground reaction forces and age, height and running speed are depicted in Table 4. The horizontal braking ( $r=0.677, p=0.000$ ) and propulsive ( $r=0.694, p=0.000$ ) forces increase with running speed. Similarly the vertical impact force peak magnitude ( $r=0.423, p=0.000$ ) and its loading rate ( $r=0.386, p=0.002$ ), and the vertical propulsive force peak ( $r=0.443, p=0.000$ ) increase with running speed. The horizontal braking force ( $r=-0.341, p=0.006$ ), horizontal propulsive force ( $r=-0.261, p=0.037$ ) and vertical propulsive force ( $r=-0.422, p=0.001$ ) decrease with age. There is no correlation between age and the other ground reaction forces. Height does not correlate with any of the ground reaction forces.

Table 4. Relationship between the ground reaction forces, and age, height and running speed (n= 60)

	Age	Height	Running speed
HBF	$r=-0.341, p=0.006$	$r=0.109, p=0.390$	$r=0.677, p=0.000$
HPF	$r=-0.261, p=0.037$	$r=-0.123, p=0.333$	$r=0.694, p=0.000$
VIF	$r=-0.005, p=0.997$	$r=0.075, p=0.555$	$r=0.429, p=0.000$
VLR	$r=0.056, p=0.659$	$r=-0.004, p=0.974$	$r=0.386, p=0.002$
VPF	$r=-0.422, p=0.001$	$r=-0.214, p=0.089$	$r=0.443, p=0.000$

Horizontal braking force (BW) [HBF], Horizontal propulsive force (BW) [HPF], Vertical impact force peak (BW) [VIF], Vertical impact force peak loading rate (BW/s) [VLR], Vertical propulsive force peak (BW) [VPF]

### 5.4. Joint angles

There were no significant differences in the selected swing and stance phase knee and ankle joint angles between the foot-type groups (Table 5).

Table 5. Comparison of the joint angles by foot-type.

	Neutral	Pronated	Supinated	p-value
KswF	84.3± 3.8	84.6± 3.4	84.1± 4.6	p=0.204
KswE	18.4± 6.8	17.1± 6.0	21.9± 5.3	p=0.406
Kic	23.5± 5.8	23.0± 5.1	25.4± 5.2	p=0.309
Kst	43.7± 4.7	42.9± 6.1	46.5± 6.9	p=0.412
Asw	-10.2± 5.8	-6.5± 8.2	-11.9± 4.8	p=0.515
Aic	-8.4± 5.4	-5.4± 6.9	-10.1± 3.9	p=0.418
Ast	-23.7± 3.3	-21.9± 2.9	-24.8± 3.4	p=0.421

Knee swing phase peak flexion angle ( $^{\circ}$ ) [KswF], Knee angle in terminal swing phase ( $^{\circ}$ ) [KswE], Knee angle at initial supporting surface contact ( $^{\circ}$ ) [Kic], Knee angle in midstance ( $^{\circ}$ ) [Kst], Ankle angle in terminal swing phase ( $^{\circ}$ ) [Asw], Ankle angle at initial supporting surface contact ( $^{\circ}$ ) [Aic], Ankle angle in midstance ( $^{\circ}$ ) [Ast]  
No significant differences between the test conditions.

The relationship between knee and ankle joint angle variables and age, height and running speed is depicted in Table 6. The ankle is more plantarflexed at initial supporting surface contact ( $r=0.270$ ,  $p=0.032$ ) and during stance phase ( $r=0.319$ ,  $p=0.011$ ) with an increase in running speed. The knee is more extended in stance ( $r=-0.252$ ,  $p=0.046$ ) with greater running speed. There are no other associations between the knee and ankle angles and running speed. Ankle plantarflexion in stance increases with age ( $r=0.283$ ,  $p=0.025$ ). There are no other associations between age and any of the other knee and ankle joint angle variables. Taller runners are associated with a greater knee flexion in terminal swing ( $r=0.257$ ,  $p=0.042$ ) and at initial contact with the supporting surface ( $r=0.257$ ,  $p=0.042$ ). There are no associations between height and any other knee and ankle joint angle variables studied.

Table 6. Relationship between age, height and running speed, and joint angles

	Age	Height	Running speed
KswF	$r=0.121$ , $p=0.344$	$r=0.222$ , $p=0.081$	$r=0.022$ , $p=0.864$
KswE	$r=0.213$ , $p=0.094$	$r=0.257$ , $p=0.042$	$r=-0.176$ , $p=0.168$
Kic	$r=0.208$ , $p=0.102$	$r=0.257$ , $p=0.042$	$r=-0.125$ , $p=0.330$
Kst	$r=-0.077$ , $p=0.549$	$r=0.212$ , $p=0.095$	$r=-0.252$ , $p=0.046$
Asw	$r=0.104$ , $p=0.417$	$r=-0.012$ , $p=0.925$	$r=0.213$ , $p=0.094$
Aic	$r=0.103$ , $p=0.421$	$r=-0.080$ , $p=0.531$	$r=0.270$ , $p=0.032$
Ast	$r=0.283$ , $p=0.025$	$r=0.095$ , $p=0.459$	$r=0.319$ , $p=0.011$

Knee swing phase peak flexion angle ( $^{\circ}$ ) [KswF], Knee angle in terminal swing phase ( $^{\circ}$ ) [KswE], Knee angle at initial supporting surface contact ( $^{\circ}$ ) [Kic], Knee angle in midstance ( $^{\circ}$ ) [Kst], Ankle angle in terminal swing phase ( $^{\circ}$ ) [Asw], Ankle angle at initial supporting surface contact ( $^{\circ}$ ) [Aic], Ankle angle in midstance ( $^{\circ}$ ) [Ast]

### 5.5. Joint power and work

There were no differences in the knee and ankle dynamic variables of the sixty (60) runners between the foot-type groups (Table 7).

Table 7. Comparison of joint power and work by foot-type (n= 60)

	Neutral	Pronated	Supinated	p-values
KPA	6.79± 1.68	6.08± 2.15	6.69± 1.47	p=0.483
KPG	6.58± 1.62	6.75± 2.50	4.71± 0.27	p=0.296
APA	5.89± 1.76	6.22± 1.84	4.83± 0.98	p=0.510
APG	7.45± 1.35	7.23± 1.86	5.92± 1.45	p=0.323
EKW	0.39± 0.12	0.34± 0.14	0.42± 0.14	p=0.237
CKW	0.51± 0.11	0.50± 0.16	0.43± 0.10	p=0.551
EAW	0.37± 0.12	0.41± 0.15	0.34± 0.06	p=0.564
CAW	0.47± 0.07	0.46± 0.13	0.42± 0.09	p=0.675

Knee power absorption (Watt/kg) [KPA], Knee power generation (Watt/kg) [KPG], Ankle power absorption (Watt/kg) [APA], Ankle power generation (Watt/kg) [APG], Eccentric knee work (J/kg) [EKW], Concentric knee work (J/kg) [CKW], Eccentric ankle work (J/kg) [EAW], Concentric ankle work (J/kg) [CAW]

No significant differences between the test conditions.

The relationships between age, height and running speed, and selected ankle and knee and ankle dynamic variables are depicted in Table 8. Peak ankle power absorption ( $r= 0.582$ ,  $p= 0.000$ ) and ankle eccentric work ( $r= 0.291$ ,  $p= 0.025$ ) increases with running speed. Eccentric knee work ( $r= -0.363$ ,  $p= 0.005$ ) decreases with running speed. Peak knee power generation ( $r= 0.387$ ,  $p= 0.002$ ) and ankle power generation ( $r= 0.380$ ,  $p= 0.003$ ) increases with running speed. Knee power absorption ( $r= -0.344$ ,  $p= 0.008$ ), ankle power absorption ( $r= -0.370$ ,  $p= 0.004$ ), knee power generation ( $r= -0.263$ ,  $p= 0.044$ ) and ankle power generation ( $r= -0.266$ ,  $p= 0.042$ ) decreases with age. Ankle eccentric load decreases with age ( $r= -0.286$ ,  $p= 0.028$ ) and knee eccentric load following a similar trend ( $r= -0.243$ ,  $p= 0.064$ ). No other knee and ankle work and power variables correlate significantly with age. None of the ankle and knee and ankle dynamic variables have an association with height.

Table 8. Relationship between age, height and running speed and joint power and work (n= 60)

	Age	Height	Running speed
KPA	$r= -0.344$ , $p= 0.008$	$r= 0.184$ , $p= 0.164$	$r= -0.080$ , $p= 0.546$
APA	$r= -0.370$ , $p= 0.004$	$r= 0.059$ , $p= 0.658$	$r= 0.582$ , $p= 0.000$
KPG	$r= -0.263$ , $p= 0.044$	$r= 0.030$ , $p= 0.820$	$r= 0.387$ , $p= 0.002$
APG	$r= -0.266$ , $p= 0.042$	$r= 0.058$ , $p= 0.665$	$r= 0.380$ , $p= 0.003$
EKW	$r= -0.243$ , $p= 0.064$	$r= 0.190$ , $p= 0.150$	$r= -0.363$ , $p= 0.005$
EAW	$r= -0.286$ , $p= 0.028$	$r= 0.076$ , $p= 0.568$	$r= 0.291$ , $p= 0.025$
CKW	$r= -0.190$ , $p= 0.150$	$r= 0.115$ , $p= 0.386$	$r= 0.058$ , $p= 0.664$
CAW	$r= -0.136$ , $p= 0.305$	$r= 0.119$ , $p= 0.368$	$r= -0.100$ , $p= 0.451$

Knee power absorption (Watt/kg) [KPA], Knee power generation (Watt/kg) [KPG], Ankle power absorption (Watt/kg) [APA], Ankle power generation (Watt/kg) [APG], Eccentric knee work (J/kg) [EKW], Concentric knee work (J/kg) [CKW], Eccentric ankle work (J/kg) [EAW], Concentric ankle work (J/kg) [CAW]

## 6. Discussion

The main finding of this study is that an increase in self-selected running speed is associated with an increase in the magnitude of the ground reaction forces, a change in knee and ankle geometry in stance, and an increase in the power and work at the knee and ankle. Age is associated with a reduction in the ground reaction forces, a plantarflexed ankle in stance, and a reduction in the

power and work at the knee and ankle. Foot-type does not have an effect on the running style gait analysis variables.

### 6.1. Running speed and running style

Running speed is a measure of the distance a runner completes within a known time interval. The transition from walking to running is occurs at approximately 2m/s (Voloshin, 2000). At the other extreme of the spectrum of running speed, elite 10km runners are reported to maintain a running speed of 5.08 m/s for the duration of the race (Weston et al., 1999). The running speeds selected in this study [2.2-4.8 m/s] represents the range of running speeds that most recreational runners will achieve during training and participating in long distance races. An important factor to evaluate is whether running speed has a relationship with the demographic descriptors of age, height, and mass. Mass is strongly associated with age and height, and considered not to be an independent variable. In addition all kinetic and knee and ankle dynamic variables are corrected for either body mass or body weight. Running speed does not have a relationship with age and height. Neither is there a relationship between age and height. Running speed, age and height are therefore independent variables (Table 2). The mean values for the HBF, VIF and VLR (weight acceptance phase variables) (Table 4.3) are consistent with that reported in the literature (de Wit et al., 2000; McCaw et al., 2000). The increase in the HBF, VIF, and VLR (Table 4) with running speed is similar to that reported previously (de Wit et al., 2000). The GRF variables that represent the propulsive component of stance include the horizontal propulsive force (HPF) and the vertical propulsive force (VPF). The latter two GRF components represent the force required to achieve forward propulsion. In this study, the mean VPF is approximately 13.4 times the magnitude of the HPF, and similar to that reported earlier (Vaughan et al., 1992). An increase in the magnitude of the HPF and VPF with a higher self-selected running speed is consistent with that in the literature (de Wit et al., 2000). It may be obvious to the casual observer that people running at different speeds often differ in lower limb geometry during both stance and swing phases. The difference in lower limb geometry with increasing running speeds is due to the greater excursions that may be undertaken by the joints to achieve greater displacement (Mann and Hagy, 1980). Greater running speed may be achieved with increases in the stride length and frequency (Novacheck, 1995). In this study, increased knee flexion in stance but not in swing was found with an increase in running speed. This contrasts earlier studies that have demonstrated an increase in the knee flexion angle during swing and stance phase with an increase in running speed (Mann and Hagy, 1980; Novacheck, 1995). Similarly the increased knee flexion at initial contact with an increase in running speed previously reported (Novacheck, 1995) was not found in this study. Rather greater knee flexion during stance phase with an increase in running speed was found. Some of the differences between the results of this study and earlier studies may be due to study design. In this study, a cross-sectional descriptive study of a large population with a range of abilities was used. This is in contrast to the repeated measured design of the earlier researchers that studied the evolution of the limb kinematics with an increase in running speed within a single small population (Mann and Hagy, 1980; Novacheck, 1995). With a greater self-selected running speed, ankle plantarflexion increased at initial foot contact and was maintained in stance phase (Table 6). Initial foot contact with the ball of the foot rather than the heel at greater running speeds, and being characteristic of sprinters rather than long distance runners, is reported (Novacheck, 1995; de Wit et al., 2000). The peak power absorption and generation at the ankle during stance phase increases with running speed. The peak power quantifies the dynamics within the musculotendinous structures crossing the ankle in stance. This suggests dynamics within the musculotendinous structures crossing the ankle to control the forward rotation of the shank (leg) over the ankle during weight acceptance, and to extend the ankle in propulsion, increase with running speed and is consistent with that reported by Ounpuu, 1990 and contrasts that by Novacheck, 1995, despite similar methodology. This is consistent with the finding that electrical activity in the posterior calf

musculature increased from walking to running to sprinting (Reber et al., 1993). Similar increases in ankle eccentric work to that of ankle power with running speed are noted. Knee power generation but not power absorption increase with running speed. The concentric work of the musculotendinous structures at the knee does not increase to account for the increase in power production. Rather the eccentric work within the musculotendinous structures crossing the knee joint decreased with an increase in running speed. These findings are consistent with the report that stance quadriceps electrical activity does not increase with walking to running to sprinting (Mann and Hagy, 1980). Storage of energy during the loading phase of stance in the ligaments and tendons may occur, with the energy returned during propulsion from the supporting surface (Komi, 1984; Novacheck, 1998). It appears likely that with an increase in running speed, increasing energy is stored in tendon and ligament structures at the knee (quantified as eccentric load) rather than muscular (there is no change in electrical activity). With propulsion, the stored energy is released and measured as knee power generation. This does not explain why the work values do not mirror the power values, and is an area of gait research biomechanics that requires further investigation.

## 6.2. Age and running style

The stress applied to the musculotendinous system is reduced with an increase in age of the runner as evidenced by the reduced power and work values at the knee and ankle, and a smaller force applied to the ground. This is associated with a change in running style, with increased plantarflexion in stance with age. The greater plantarflexion with age may be related to the progressive heel-fat-pad atrophy with age (Jørgensen and Ekstrand, 1988). The loss of cushioning at the heel may encourage runners to adopt a running style that protects the calcaneus. The need to reduce stress to the musculotendinous system and protect the calcaneus may account for the change in running style with age.

## 6.3. Foot-type and running style

The relationship between foot-type and running style gait analysis variables is evaluated in this study. The runners were distinguished by foot-type. The distribution of runners per foot-type group is consistent with that described by previous authors (James et al., 1978; Subotnick, 1985). Similar ages, heights, masses and running speeds between the three foot-type groups give credibility to the comparison of the running style gait analysis variables by foot-type. The similarity of kinetic, kinematic and integrated gait analysis variables between the foot-type groups is surprising. This is inconsistent with the accepted clinical explanation of running biomechanics. Two explanations for this finding are suggested. Clinically relevant movements occur between individual segments of the foot (Donatelli, 1985, 1987). The modified Helen-Hayes marker set used to evaluate the gait analysis variables in this study does not recognize individual segments of the foot. Rather, the foot is modeled as a single segment. Therefore, any movement within the foot that may be of clinical relevance is not necessarily measured with this method of imaging. The similarity of gait analysis variables between different foot-types may be due to limitations of the methods employed for gait analysis. Abnormal foot movement is hypothesized to be propagated to the proximal portions of the lower limb (James et al., 1978; Subotnick, 1985; Tiberio, 1987). However, no differences in lower limb mechanics were detected between the foot-type groups. This is consistent with one recent report that suggested that the propagation of movement from the foot to the lower limb is inconsistent between runners (Stacoff et al., 2000). In addition, the power that determines the rotational movement of the lower limb originates from segments proximal to the tibia rather than from the foot (Bellchamber and van den Bogert, 2000). Foot-type therefore may not necessarily have an effect on the gait analysis variables descriptive of running style when measured with this specific method.

Runner height correlates with greater terminal swing phase and initial contact phase knee flexion. This may reflect a technical limitation of the study as the runway was limited to eleven-meters (11m) in length. The taller runners in the study group may have adjusted their knee angle to achieve their self-selected running speed. The kinematic data of tall runners under these conditions should be interpreted with caution.

## **7. Conclusion**

In the study of this uninjured recreational runner's population age, height and self-selected running speed were independent variables. Foot-type did not have a relationship with the running style gait analysis variables selected when evaluated with the modified Helen-Hayes marker set. Self-selected running speed has a strong relationship with gait analysis variables descriptive of running style, with age and height a lesser relationship. Evaluation of the gait analysis variables of running style, are unlikely to be influenced by the foot-type, but by the self-selected running speed and age and to a lesser degree, the height of the runner.

## **8. Relevance of foot-type, age and speed to the thesis**

The results of the current study emphasize the importance of encouraging the runners to maintain consistency of the self-selected running speed in a repeated measure design study. Maintenance of a consistent running speed is specifically applied in the studies of the effect of running shoes (Study Four), soft orthoses (Study Five), semi-rigid orthoses (Study Six) and running style (Study Seven) on the gait analysis variables. In a comparison of two runner populations, the runners were closely matched to encourage similar running speeds, so that the effects of gender (Study Three) and injury (Study Eight) on the gait analysis variables may be determined. Similarly the age of the runner in the latter study was matched between the runner populations. The importance of controlling for foot-type was not emphasized in any of the subsequent studies.

## STUDY THREE

### The effect of gender on the gait analysis variables descriptive of running style

#### 1. Introduction

The accuracy of an assessment of the differences between two or more runner populations is dependent on commitment to control of confounding variables. Age, running speed and to a lesser extent, height are variables that are important in this regard. Clarification of the relationship of gender to the running style gait analysis variables is intuitive. Recent epidemiological evidence suggests that “females undertaking strenuous exercise alongside males are at increased risk of injury” (Bergman and Miller, 2001) is strong motivation to include female runners in any study that has the aim of understanding running injuries. The identification of running style gait analysis variables that may be related to a risk for injury in female runners is vital so that appropriate preventative interventions may be formulated. The aim of this study is to compare the running style gait analysis variables of female and male runners with a view to determine the merits of matching two or more runner populations for gender. The gender comparison will be scrutinized to identify running style gait analysis variables that may assist in the understanding of the greater risk of injury in female runners.

#### 2. Method

##### 2.1. Subjects

The runners in this study were selected from the group of sixty (60) described in the previous study. All runners were recruited from local running clubs in Cape Town, South Africa by means of flyers handed out at the Sports Science Institute of South Africa (SSISA), Cape Town. Ten (10) uninjured male and ten (10) female recreational runners matched for age (male:  $36.4 \pm 14.2$  years, female:  $31.9 \pm 10.5$  years,  $p = 0.430$ ) height (male:  $1.71 \pm 0.03$  m, female:  $1.70 \pm 0.05$  m,  $p = 0.348$ ) and self-selected running speed (male:  $3.00 \pm 0.59$  m/s, female:  $2.68 \pm 0.25$  m/s,  $p = 0.129$ ) were selected. The male runners recruited were greater in mass ( $73.65 \pm 8.50$  kg) than the female runners ( $64.56 \pm 8.97$  kg), ( $p = 0.032$ ). All runners trained a minimum of three times weekly with a similar weekly running distance between the gender groups (male:  $36.62 \pm 19.09$  km/week, female:  $39.57 \pm 18.92$  km/week,  $p = 0.287$ ). The best 10km race times were similar between the gender groups (male:  $48.43 \pm 4.86$  minutes, female:  $51.71 \pm 6.45$  minutes,  $p = 0.439$ ).

##### 2.2. Informed consent

All runners were informed as to the nature of the testing procedure and their relevant concerns appropriately addressed. Informed signed consent as prescribed and approved by the Research Ethics Committee of the University of Cape Town, South Africa was obtained from all runners.

##### 2.3. Test procedure

All runners completed a standard testing procedure (Study One). The runners completed a 1000m barefoot run on the indoor-tartan track at SSISA at a self-selected running speed (Study One). This

was immediately followed by running trials in the gait analysis laboratory at self-selected running speed (Study One). Gait analysis data were collected with a Vicon 370-motion analysis system at 120Hz and force plate data at 1000Hz (Study One). Temporal-distance, ground reaction forces, kinematic and integrated kinetic data were processed in GaitLab® and analysed (Study One).

### 3. Main outcome variables

The gait analysis variables that were compared between the male and female runners were:

1. The temporal-distance variables: vertical oscillation of the sacrum (m) and heel marker (m), and stride (m) and step length (m).
2. Ground reaction forces: loading rate (BW/s) and magnitude (BW) of the vertical impact force at peak value, the magnitude of the propulsive force in the vertical (BW) and horizontal (BW) directions and the horizontal braking force (BW);
3. Joint angles: during mid-swing ( $^{\circ}$ ), terminal swing ( $^{\circ}$ ), initial supporting surface contact ( $^{\circ}$ ) and midstance ( $^{\circ}$ );
4. Joint power and work: the magnitude of the knee and ankle power (Watts) and work (J) during support and propulsive phases of stance.

### 4. Statistical analysis

Statistical tests were undertaken of the gait analysis variables using a commercial statistical programme (StatSoft, Inc. (2000). STATISTICA for Windows [Computer program manual]. Tulsa, OK). Independent t-tests were used to determine difference of the means of the demographic and selected gait analysis variables between male and female runners. The statistical level of significance was set at  $p < 0.05$ .

## 5. Results

### 5.1. Temporal-distance variables

There were no differences in stride, foot vertical oscillation and vertical body oscillation between male and female runners (Table 1). Neither were there any differences in the temporal-distance parameters after correction for leg length. There was a non-significant trend for female than male runners to have greater vertical body oscillation corrected for leg length (female:  $0.13 \pm 0.03$ ; male:  $0.11 \pm 0.02$ ,  $p = 0.057$ ).

Table 1. Comparison of temporal-distance variables between male and female runners.

	Female (n=10)	Male (n=10)	p-values
StrideLn	$2.11 \pm 0.18$	$2.29 \pm 0.27$	$p = 0.102$
VHDsp	$0.41 \pm 0.07$	$0.45 \pm 0.08$	$p = 0.257$
VSDsp	$0.11 \pm 0.02$	$0.10 \pm 0.02$	$p = 0.102$
StrideLn/LL	$2.42 \pm 0.28$	$2.53 \pm 0.36$	$p = 0.474$
VHDsp/LL	$0.47 \pm 0.08$	$0.50 \pm 0.09$	$p = 0.533$
VSDsp/LL	$0.13 \pm 0.03$	$0.11 \pm 0.02$	$p = 0.057$

Stride length (m) [StrideLn], Vertical left heel marker displacement (m) [VHDsp], Vertical sacrum marker displacement (m) [VSDsp], Stride length/ leg length [StrideLn/ LL], Vertical left heel marker displacement/ leg length [VHDsp/ LL], Vertical sacrum marker displacement/ leg length [VSDsp/ LL]

No significant differences between male and female runners

## 5.2. Ground reaction forces

There were no GRF differences in the ground reaction forces between male and female runners (Table 2).

Table 2. Comparison of the ground reaction forces between male and female runners.

	Female (n=10)	Male (n=10)	p-values
HBF	0.23± 0.05	0.22 ± 0.05	p= 0.739
HPF	0.18± 0.04	0.15± 0.04	p= 0.165
VIF	1.21± 0.23	1.27± 0.17	p= 0.521
VLR	43.4± 7.2	50.6± 10.4	p= 0.088
VPF	2.29± 0.23	2.25± 0.25	p= 0.652

\* Significant difference between male and female runner ground reaction forces

Horizontal braking force (BW) [HBF], Horizontal propulsive force (BW) [HPF], Vertical impact force peak (BW) [VIF], Vertical impact force peak loading rate (BW/s) [VLR], Vertical propulsive force peak (BW) [VPF]

## 5.3. Joint angles

The knee assumes a more flexed position in the terminal swing phase in male (23.2±4.1 degrees) than female runners (16.2±3.6) (p= 0.001) (Figure 1). The knee maintains a greater flexed position at initial foot contact in male (27.0±3.7 degrees) than female runners (22.5±4.2 degrees) (p= 0.020) (Table 3). All other knee and ankle joint angles were similar between male and female runners.

## 5.4. Joint power and work

There were no other differences in knee and ankle work and power variables between male and

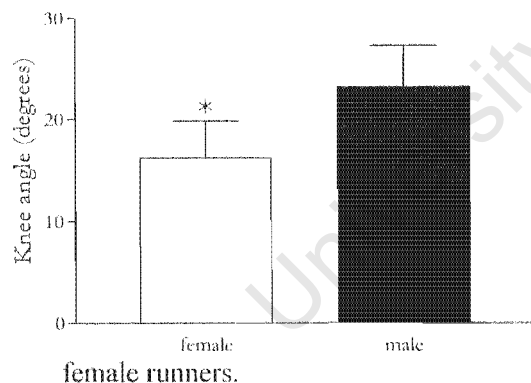


Figure 1. Comparison of knee angle in terminal swing between male and female runners

\* Significant difference between male and female runners, p= 0.001.

Table 3. Comparison of joint angles between male and female runners.

	Female (n=10)	Male (n=10)	p-values
KswF	85.1± 2.6	85.6± 1.5	p= 0.597
Kic	22.5± 4.2	27.0± 3.7	p= 0.020*
Kst	44.9± 6.1	46.6± 5.2	p= 0.527
Asw	-8.1± 9.8	-9.9± 5.6	p= 0.614
Aic	-6.8± 8.3	-8.2± 5.4	p= 0.650
Ast	-25.6± 2.2	-24.4± 3.4	p= 0.355

\* Significant difference between male and female runner joint angles

Knee swing phase peak flexion angle (<sup>0</sup>) [KswF], Knee angle at initial contact (<sup>0</sup>) [Kic], Knee angle in midstance (<sup>0</sup>) [Kst], Ankle angle in terminal swing phase (<sup>0</sup>) [Asw], Ankle angle at initial supporting surface contact (<sup>0</sup>) [Aic], Ankle angle in midstance (<sup>0</sup>) [Ast]

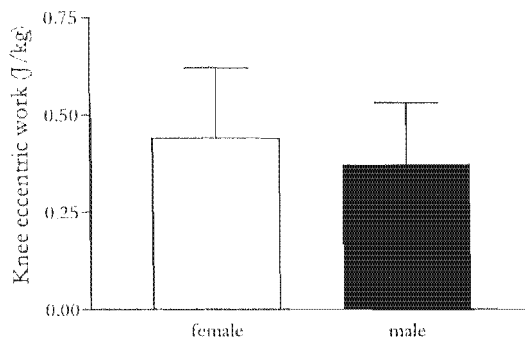


Figure 2. Comparison of knee eccentric work between male and female runners. No significant difference between male and female runners, p= 0.381

Table 4. Comparison of joint power and work between male and female runners.

	Female (n=10)	Male (n=10)	p-values
KPA	7.12± 2.45	6.47± 2.03	p= 0.116
APA	5.94± 2.00	5.81± 1.74	p= 0.874
KPG	7.56± 2.57	6.13± 1.36	p= 0.137
APG	7.46± 0.90	7.07± 2.54	p= 0.658
EAW	0.42± 0.17	0.39± 0.13	p= 0.607
CKW	0.59± 0.14	0.50± 0.10	p= 0.116
CAW	0.51± 0.07	0.46± 0.15	p= 0.338

Knee power absorption (Watt/kg) [KPA], Ankle power absorption (Watt/kg) [APA], Knee power generation (Watt/kg) [KPG], Ankle power generation (Watt/kg) [APG], Eccentric ankle work (J/kg) [EAW], Concentric knee work (J/kg) [CKW], Concentric ankle work (J/kg) [CAW]

No significant difference between male and female runners

## 6. Discussion

The main finding of this study was that female runners have lower vertical impact forces and loading rates, with a more extended knee position in terminal swing and at initial contact than male runners. These findings suggest that gender is an important variable to control in the

comparison of two or more runner populations. The greater knee extension in terminal swing and at initial contact and low loading rates in female compared with male runners is consistent with the lower limb kinematic and ground reaction force changes that occur with a change of shod to barefoot running (de Wit et al., 2000). Shod running is associated with an extended knee and dorsiflexed ankle immediately before and at initial supporting surface contact compared with barefoot running (de Wit et al., 2000). The mechanical work and power at the knee and ankle are estimations of the mechanical work undertaken by the structures that cross the joints. The amount of eccentric work estimated at the knee and ankle may have a relationship with lower limb geometry adopted. In this study, despite a high loading rate and a flexed knee at the beginning of stance, an equivalent amount knee work was found between the sexes. The running style of the female running population is characterized by low impact forces and an extended knee in stance. Although the female runner population is reported to be at risk for injury if exposed to an equivalent training load, no association between specific running style gait analysis variables and a risk for injury is apparent from the results of the present study. The inclusion of injury-free runners in the study may be relevant in this regard.

## **7. Conclusion**

Female runners have lower vertical impact forces and loading rates, with a more extended knee position in terminal swing and at initial contact. There is a non-significant trend for female runners to have greater vertical oscillation of the body and, work and power magnitudes at the knee and ankle. These findings suggest that gender is an important variable to control in the comparison of two or more runner populations.

## **8. Relevance of gender to the aims of the thesis**

The importance of controlling for gender is applied in the comparison of injured and injury-free runners (Study Eight), in which the effect of injury on the gait variables descriptive of running style is evaluated.

## STUDY FOUR

### Effect of running shoes on running gait analysis variables

#### 1. Introduction

Running shoes are essential items of sporting equipment for recreational runners and are designed to provide cushioning from impact forces (James et al., 1978), control abnormal movement of the foot (Adidas Research and Innovation Labs, 1998), assist in the treatment of common running injuries if appropriately prescribed (Pretorius et al., 1986) and provide the vessel in which orthoses and cushioned inserts may be placed for the treatment and prevention of injury (Gross et al., 1991). Running shoes encourage the runner to extend the knee and dorsiflex the ankle in preparation for contact with the supporting surface when compared with barefoot running (de Wit et al., 2000). The protection of the heel fat-pad and consequent reduction in foot discomfort afforded by running shoes appears to be the stimulus for the change in running style as described by the alteration in lower limb geometry (de Wit et al., 2000). The ability of the runner to change the style of running in response to perceived “impact hardness” of the running condition is reported (Hennig et al., 1996; Milani et al., 1997). The latter report is relevant with regards the report of an association between injury and selected gait analysis variables descriptive of running style, particularly the knee eccentric work (Study Eight). A study of the effect of running shoes on the gait analysis variables selected to describe running style will assist in the understanding of the role played by running shoes in the treatment of running injuries. The aim of this study is therefore to determine the effect of running shoes on the gait analysis variables descriptive of running style by comparing running with different shoes to barefoot running.

#### 2. Method

##### 2.1. Subjects

Thirty-five (35) ( $39.3 \pm 13.2$  years;  $1.80 \pm 0.08$  m;  $84.0 \pm 11.6$  kg) injury-free male recreational runners were recruited from a well runner clinic at the Sports Science Institute of South Africa (SSISA), Cape Town, for the study.

##### 2.2. Informed consent

The Research Ethics Committee of the University of Cape Town granted ethical approval for the study, and informed consent was obtained from all recruited runners.

##### 2.3. Test procedure

The runners followed the standard testing procedure described in Study One. A lower limb evaluation (foot-type) and anthropometric measurements were completed (Study One). The runners then completed a 1000m familiarisation run on the indoor tartan track at SSISA, followed by a series of overground running trials in the gait analysis laboratory in each of three randomly administered test conditions at self-selected running speeds (Study One). The test conditions included a barefoot, “neutral” running shoe (LSh1) and “anti-pronation” running shoe conditions (LSh2). Gait analysis data were collected, and five trials per runner were selected for processing and analysis (Study One).

## 2.4. Shoe types

The investigators supplied the running shoes used in this study. The running shoes were unused prior to being worn in the study. The running shoes ranged in size from UK 9 to UK 11. Two types of running shoes were used in the study. Although the two types of running shoes were of different brands, within the brand, all running shoes were of the same model and origin of manufacture, differing only in size. One of the running shoes (LSh1) was commercially marketed as a “neutral”-type running shoe for runners with “neutral gait” (<http://www.newbalance.com>). The midsole was constructed of a single density Ethylene Vinyl Acetate (EVA) material (Figure 2.4). No specific motion control (anti-pronation) features were incorporated into the structure of the midsole. In contrast, the second of the two running shoes (LSh2) was commercially marketed as an “anti-pronation” running shoe for the “runner with pronation issues” (<http://productaj.asicstiger.com>). The main “anti-pronation” feature of this running shoe was the “Extended DuoMax® Medial Post” of the midsole. The medial component of the midsole was constructed of a high-density EVA, and the lateral component, of a low-density EVA to provide “static stability” (Figure 2.4).

### 7.3.4.1. Foot-type and shoe-type matching

The design of the study required that the foot-type of each of the thirty-five (35) runners be determined (Dahle et al., 1991; Chapter Three). All runners then wore each of the two types of running shoes (LSh1 and LSh2). Assuming that not all runners had the same foot-type, some runners would then wear running shoes that were considered “appropriate” and “inappropriate” according to the manufacturer guidelines (above) and general guidelines for running shoe prescription in the literature (McKenzie et al., 1985; Gross, 1995; Literature review [Table 2.2.11]) (Figure 1).

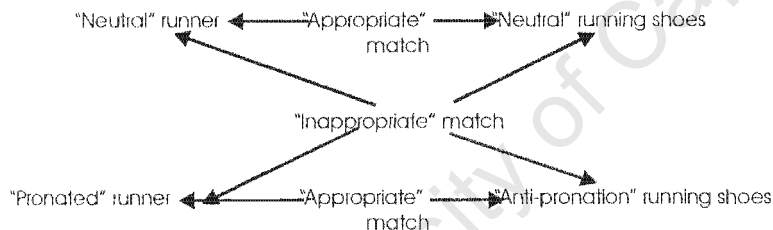


Figure 7.1. Matching foot-type and running shoe type

## 2.5. Rating of perceived impact (RPI)

A ten-point linear rating scale, similar to that modified by other researchers (Henning et al., 1996; Milani et al., 1997; McCaw et al., 2000) from the Borg’s Rating of Perceived Effort (Borg, 1982), was used to rate the impact experienced by the runners in each of the running conditions. The lowest and the highest score on the scale were representative of the least and the most amount of force imaginable, respectively (Table 1). Whole numbers and fractions within the limits of the scale were recorded in the RPI.

Table 1. A ten-(10) point Rating of Perceived Impact Scale (RPI)

Rating	Perception	Rating	Perception
0	No impact at all	6	
0.5	Just noticeable impact	7	Very strong impact
1	Very slight impact	8	
2	Slight impact	9	
3	Impact noticeable	10	Almost maximum impact
4	Impact somewhat strong	*	Maximal amount of impact imaginable
5	Strong impact		

The runners were asked to rate the perceived impact that they experienced after both the familiarisation and laboratory components of that test condition were completed. The runners were offered the opportunity to edit the scores of the initial test conditions on completion of successive test conditions.

## 7. Main outcome variables

The gait analysis variables that were compared for the group across the barefoot and running shoe conditions were:

1. Ground reaction forces: loading rate (BW/s) and magnitude (BW) of the vertical impact force at peak value, the magnitude of the propulsive force in the vertical (BW) and horizontal (BW) directions and the horizontal braking force (BW);
2. Joint angles: in mid-swing ( $^{\circ}$ ), terminal swing ( $^{\circ}$ ), initial supporting surface contact ( $^{\circ}$ ) and midstance ( $^{\circ}$ );
3. Joint power and work: the magnitude of the knee and ankle power (Watts) and work (J) during support and propulsive phases of stance.
4. The rating of perceived impact.

## 4. Statistical analysis

Statistical tests of the main outcome variables were undertaken using a commercial statistical program (StatSoft, Inc. (2000). STATISTICA for Windows [Computer program manual]. Tulsa, OK, USA). Detailed descriptive statistics of the age, height and mass were completed. Repeated measures analysis of variance was conducted of the running speed, gait analysis variables and rating of perceived impact between the three test conditions. The Schéffe post hoc analysis test was used to determine relationships alerted to by significant F-ratios in the repeated measures analysis of variance tests. A dependent t-test was undertaken to identify differences in the running speed, gait analysis variables and rating of perceived impact between the “appropriate” and “inappropriate” foot-type/ running shoe-type combinations.

## 5. Results

### 5.1. Running speed

There were no significant differences in the mean running speed between the barefoot ( $3.03 \pm 0.39$  m/s), LSh1 ( $3.03 \pm 0.37$  m/s) and LSh2 ( $3.03 \pm 0.37$  m/s) running conditions ( $p= 0.941$ ). There

were also similar running speeds between the “appropriate” ( $3.00 \pm 0.37$  m/s) and “inappropriate” ( $3.04 \pm 0.37$  m/s) foot-type/ running shoe-type combinations ( $p= 0.068$ ).

## 5.2. Ground reaction forces

The horizontal propulsive force peak (HPF) was greater in the barefoot ( $0.17 \pm 0.04$  BW), than LSh1 ( $0.15 \pm 0.04$  BW) and LSh2 ( $0.15 \pm 0.04$  BW) conditions (F-ratio = 21.82,  $p= 0.000$ ) (Table 7.2). The peak magnitude of the vertical impact force (VIF) was less in the barefoot ( $1.31 \pm 0.20$  BW), than LSh1 ( $1.53 \pm 0.22$  BW) and LSh2 ( $1.52 \pm 0.34$  BW) conditions (F-ratio = 18.13,  $p= 0.000$ ). The loading rate of the vertical impact force at the peak magnitude (VLR) was greater in the barefoot ( $49.7 \pm 10.6$  BW), than LSh1 ( $36.7 \pm 6.9$  BW) and LSh2 ( $35.4 \pm 9.7$  BW) conditions (F-ratio = 79.35,  $p= 0.000$ ) (Figure 7.2). There were no other differences between the ground reaction force variables of either the LSh1 or LSh2 running conditions. Neither were there differences between the ground reaction force variables of the “appropriate” and “inappropriate” foot-type/ running shoe-type combinations (Table 3).

Table 2. Comparison of the ground reaction forces between barefoot and running shoes

	Barefoot	LSh1	LSh2	F-ratio	p-values
HBF	$0.22 \pm 0.05$	$0.22 \pm 0.05$	$0.22 \pm 0.05$	0.30	0.741
HPF	$0.17 \pm 0.04$	$0.15 \pm 0.04$	$0.15 \pm 0.04$	21.82	0.000*
VIF	$1.31 \pm 0.20$	$1.53 \pm 0.22$	$1.52 \pm 0.34$	18.13	0.000*
VPF	$2.25 \pm 0.23$	$2.27 \pm 0.22$	$2.28 \pm 0.23$	1.84	0.176

\* Significantly different from LSh1 and LSh2 [n= 35]

Horizontal braking force (BW) [HBF], Horizontal propulsive force (BW) [HPF], Vertical impact force at 25ms (BW) [VIF25], Vertical impact force at 25ms loading rate (BW/s) [VLR25], Vertical impact force peak (BW) [VIF], Vertical propulsive force peak (BW) [VPF]

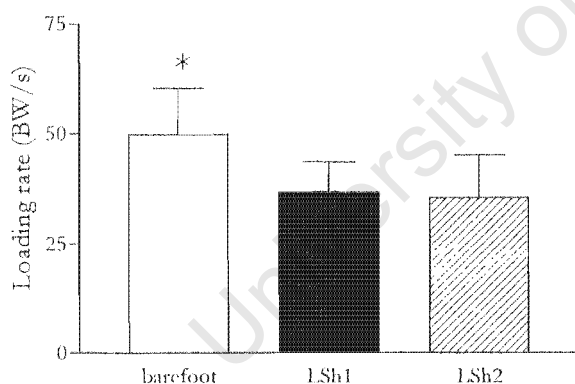


Figure 2. Comparison of the loading rate of the vertical impact force between the barefoot and running shoes

\* Significantly different from LSh1 and LSh2,  $p= 0.000$  [n=35]

Table 3. Comparison of the ground reaction forces between “appropriately” and “inappropriately” matched foot-running shoe combinations

	Appropriate	Inappropriate	p- value
HBF	0.22± 0.04	0.21± 0.06	0.494
HPF	0.14± 0.03	0.15± 0.04	0.750
VIF	1.51± 0.33	1.50± 0.35	0.939
VLR	35.6± 9.2	35.6± 9.6	0.977
VPF	2.27± 0.22	2.21± 0.45	0.334

Horizontal braking force (BW) [HBF], Horizontal propulsive force (BW) [HPF], Vertical impact force at 25ms (BW) [VIF25], Vertical impact force at 25ms loading rate (BW/s) [VLR25], Vertical impact force peak (BW) [VIF], Vertical impact force peak loading rate (BW/s) [VLR], Vertical propulsive force peak (BW) [VPF]

No significant difference between LSh1 and LSh2 [n=35]

### 5.3. Joint angles

There were no differences in the peak swing knee flexion angle (KswF) and knee angle in the terminal portion of swing (KswE), between the barefoot, LSh1 and LSh2 conditions (Table 4). A greater knee flexion angle was achieved at initial foot contact (Kic) in the barefoot (24.8± 5.1<sup>0</sup>) compared with LSh1 (22.1± 6.4<sup>0</sup>) and LSh2 (21.4± 8.3<sup>0</sup>) (F-ratio = 3.433, p= 0.038) (Figure 3). There was no difference in the peak stance knee flexion angle (Kstl<sup>0</sup>) between the three test conditions.

The ankle was more plantarflexed in the barefoot (-10.8± 4.4<sup>0</sup>) compared with LSh1 (-19.0± 5.2<sup>0</sup>) and LSh2 (-18.6± 3.7<sup>0</sup>) prior to initial contact with the supporting surface (F-ratio = 47.637, p= 0.000). The greater ankle plantarflexion was maintained at initial contact with the supporting surface in the barefoot (-9.0± 4.0<sup>0</sup>) compare with LSh1 (-17.5± 5.0<sup>0</sup>) and LSh2 (-17.3± 4.2<sup>0</sup>) (F-ratio = 53.908, p= 0.000). The peak ankle dorsiflexion angle in midstance achieved were greater in the LSh1 (-28.4± 2.5<sup>0</sup>) and LSh2 (-25.5± 3.6<sup>0</sup>) compared with barefoot (-22.4± 3.1<sup>0</sup>) (F-ratio = 38.850, p= 0.000). There were no differences in any of the knee and ankle joint angles variables between the LSh1 and LSh2 running conditions.

Table 4. Comparison of joint angles between barefoot and running shoes

	Barefoot	LSh1	LSh2	F-ratio	p-value
KswF	85.4± 2.4	85.6± 2.7	85.4± 4.5	0.022	0.979
KswE	19.9± 5.9	18.7± 7.0	18.0± 6.8	1.403	0.253
Kst	44.4± 4.5	45.2± 5.2	42.7± 7.8	2.489	0.091
Asw	-10.8± 4.4	-19.0± 5.2	-18.6± 3.7	47.637	0.000*
Aic	-9.0± 4.0	-17.5± 5.0	-17.3± 4.2	53.908	0.000*
Ast	-22.4± 3.1	-28.4± 2.5	-25.5± 3.6	38.850	0.000*

\* Significantly different from LSh1 and LSh2 [n=35]

Knee swing phase peak flexion angle (<sup>0</sup>) [KswF], Knee angle in terminal swing phase (<sup>0</sup>) [KswE], Knee angle in midstance (<sup>0</sup>) [Kst], Ankle angle in terminal swing phase (<sup>0</sup>) [Asw], Ankle angle at initial supporting surface contact (<sup>0</sup>) [Aic], Ankle angle in midstance (<sup>0</sup>) [Ast]

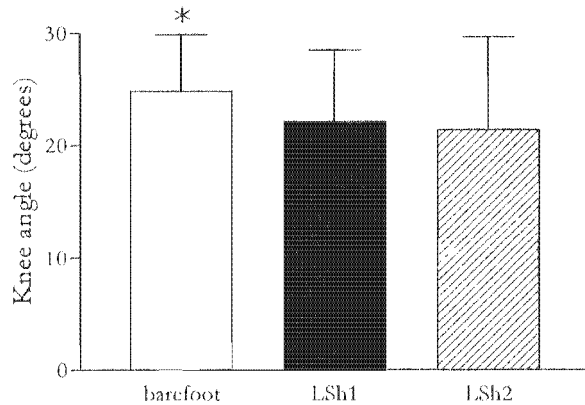


Figure 3. Comparison of the knee angle at initial contact between barefoot and running shoes  
\* Significantly different from LSh1 and LSh2,  $p=0.038$ , [n= 35]

There were no differences between the knee and ankle joint angles between either the “appropriate” and “inappropriate” foot-type/ running shoe-type combinations (Table 5).

Table 5. Comparison of joint angles between “appropriately” and “inappropriately” matched foot-running shoes combinations

	Appropriate	Inappropriate	p- value
KswF	85.3± 4.5	85.7± 2.8	0.716
KswE	18.0± 7.7	18.7± 6.0	0.633
Kic	21.6± 8.8	21.9± 5.7	0.816
Kst	43.7± 8.0	44.3± 5.1	0.672
Asw	-19.0± 4.8	-18.6± 4.3	0.743
Aic	-17.6± 5.0	-17.2± 4.2	0.654
Ast	-26.5± 3.9	-27.4± 2.8	0.352

Knee swing phase peak flexion angle ( $^{\circ}$ ) [KswF], Knee angle in terminal swing phase ( $^{\circ}$ ) [KswE], Knee angle at initial supporting surface contact ( $^{\circ}$ ) [Kic], Knee angle in midstance ( $^{\circ}$ ) [Kst], Ankle angle in terminal swing phase ( $^{\circ}$ ) [Asw], Ankle angle at initial supporting surface contact ( $^{\circ}$ ) [Aic], Ankle angle in midstance ( $^{\circ}$ ) [Ast]  
No significant differences between LSh1 and LSh2,  $p=0.038$ , [n= 35]

#### 5.4. Joint power and work

The peak knee power absorption values were greater in the LSh1 ( $7.98 \pm 1.96$  Watts/kg) and LSh2 ( $8.02 \pm 1.85$ ) compared with barefoot ( $6.41 \pm 1.96$ ) (F-ratio = 18.06,  $p=0.000$ ) (Table 7.6). The ankle power absorption was not different between the three test conditions. Greater knee power generation was achieved in the LSh1 ( $6.73 \pm 1.96$  Watts/kg) and LSh2 ( $6.90 \pm 1.92$  Watts/kg) compared with barefoot ( $6.08 \pm 1.97$  Watts/kg) (F-ratio = 5.47,  $p=0.006$ ). Greater ankle power generation was achieved in the barefoot ( $6.80 \pm 1.87$  Watts/kg) than LSh1 ( $5.09 \pm 1.23$  Watts/kg); there was no difference between LSh2 ( $5.61 \pm 1.35$  Watts/kg) and either barefoot and LSh1 conditions (F-ratio = 22.06,  $p=0.000$ ). The knee eccentric work was greater in the LSh1 ( $0.48 \pm 0.13$  J/kg) and LSh2 ( $0.49 \pm 0.13$  J/kg) compared with barefoot ( $0.37 \pm 0.13$  J/kg) (F-ratio = 19.98,  $p=0.000$ ) (Figure 4).

Table 6. Comparison of joint power and work between barefoot and running shoes

	Barefoot	LSh1	LSh2	F-ratio	p-value
KPA	6.41±1.96	7.98±1.96	8.02±1.85	18.06	0.000*
APA	5.49±1.81	5.00±1.15	5.23±1.23	2.61	0.080
KPG	6.08± 1.97	6.73±1.96	6.90±1.92	5.47	0.006*
APG	6.80±1.87	5.09±1.23	5.61±1.35	22.06	0.000*
EAW	0.36± 0.13	0.33± 0.07	0.34± 0.07	1.19	0.312
CKW	0.48± 0.14	0.50± 0.10	0.52± 0.11	1.81	0.171
CAW	0.44± 0.11	0.34± 0.07	0.38± 0.08	14.73	0.000*

\* Significantly different from LSh1 and LSh2 [n=35]

Knee power absorption (Watt/kg) [KPA], Ankle power absorption (Watt/kg) [APA], Knee power generation (Watt/kg) [KPG], Ankle power generation (Watt/kg) [APG], Eccentric ankle work (J/kg) [EAW], Concentric knee work (J/kg) [CKW], Concentric ankle work (J/kg) [CAW]

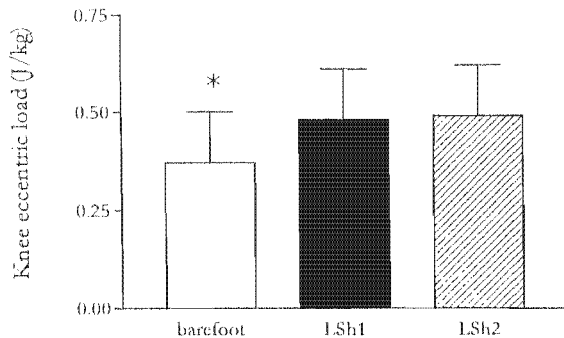


Figure 4. Comparison of knee eccentric work between barefoot and running shoes

\* Significantly different from LSh1 and LSh2, p= 0.000, [n= 35]

There were no differences in the eccentric ankle and concentric knee work between the three test conditions. The ankle concentric work was greater in the barefoot ( $0.44 \pm 0.11$  J/kg) compared with LSh1 ( $0.34 \pm 0.07$  J/kg) and LSh2 ( $0.38 \pm 0.08$  J/kg) (F-ratio = 14.73, p= 0.000). There were no knee and ankle power and work variables differences between the LSh1 and LSh2 conditions. The power and work variables at the knee and ankle were compared between the “appropriate” and “inappropriate” foot-type/ running shoe-type combinations (Table 7). The “inappropriate” combination ankle power generation ( $5.53 \pm 1.37$  Watts/kg) and concentric work ( $0.37 \pm 0.08$  J/kg) were greater than the “appropriate” combination ankle power generation ( $5.17 \pm 1.24$  Watts/kg, p= 0.006) and concentric work ( $0.35 \pm 0.07$  J/kg, p= 0.018). There were no other significant ankle and knee, power and work differences between the “appropriate” and “inappropriate” combinations.

### 5.5. Rating of perceived impact

The RPI was greater in the barefoot ( $4.50 \pm 1.86$ ) compared with LSh1 ( $1.56 \pm 0.90$ ) and LSh2 ( $2.07 \pm 1.06$ ) (F-ratio = 71.41, p= 0.000). The RPI was similar between the “appropriate” ( $1.70 \pm 0.98$ ) and “inappropriate” ( $1.94 \pm 1.03$ ) combinations (p= 0.141).

## 6. Discussion

The main findings of this study are greater magnitudes and loading rates of the vertical impact force peak, more knee flexion and ankle plantarflexion at initial ground contact, lower knee

eccentric work and power absorption and a higher rating of perceived impact (RPI) in the barefoot compared with the two running shoe conditions.

Table 7. Comparison of joint power and work between “appropriately” and “inappropriately” matched foot-running shoe combinations

	Appropriate	Inappropriate	p-values
KPA	7.98± 1.86	8.03± 1.95	0.785
APA	5.08± 1.16	5.15± 1.22	0.502
KPG	6.75± 1.88	6.88± 2.00	0.405
APG	5.17± 1.24	5.53± 1.37	0.006*
EKW	0.48± 0.13	0.49± 0.13	0.847
EAW	0.34± 0.07	0.34± 0.07	0.661
CKW	0.51± 0.10	0.51± 0.11	0.495
CAW	0.35± 0.07	0.37± 0.08	0.018*

\* Significantly greater in the “inappropriate” than “appropriate” group [n=35]

Knee power absorption (Watt/kg) [KPA], Ankle power absorption (Watt/kg) [APA], Knee power generation (Watt/kg) [KPG], Ankle power generation (Watt/kg) [APG], Eccentric knee work (J/kg) [EKW], Eccentric ankle work (J/kg) [EAW], Concentric knee work (J/kg) [CKW], Concentric ankle work (J/kg) [CAW]

There were no differences in the variables reported between the two running shoe conditions. The ankle power generation and concentric work were higher in the “inappropriate” than “appropriate” prescribed foot-type/running shoe-type combinations. Runners are able to perceive subtle differences in the stiffness of the midsole of otherwise identical running shoes as indicated by a negative correlation between the passive impact force peak and the rating of perceived impact [ $r = -0.73$ ] (Milani et al., 1997). This is consistent with an earlier study that reported that runners are able to reduce the magnitude of the impact force peak in response to an increase in the hardness of the midsole of the running shoe (Hennig et al., 1996). The results of the present study are supportive of the latter report and demonstrate that an increase in the peak magnitude of the vertical impact force and a decrease in the rating of perceived impact occur with a change from barefoot to running with shoes (Table 2). The reduction in impact force magnitudes in response to a higher rating of perceived impact is proposed to be due to a change in lower limb geometry. The greater knee flexion and ankle plantarflexion at initial contact reported in the present study (Table 3) appears to support the latter proposal and is consistent with the running style adaptations reported in an earlier barefoot-shod comparison (de Wit et al., 2000). The flexed knee and plantarflexed ankle geometry appears to reduce contact of the heel with the supporting surface in favour of flat foot contact with the supporting surface which is aimed at reducing distortion of the heel fat pad (de Wit et al., 2000). The observation that the kinematic changes are initiated in swing has led to the suggestion that running style modifications are due to active central nervous system control and are in response to the perception of the degree of “contact-hardness” of the running condition (de Wit et al., 2000). The lower limb geometry prepared in swing and executed at the initiation of stance for either barefoot or shod running, is accompanied by a corresponding amount of power and work undertaken by the musculotendinous structures that support the knee and ankle in stance, specific for the running condition. Greater peak power absorption and generation, and eccentric work at the knee are reported with the use of running shoes compared with barefoot running (Table 5). The lever arms at the knee and ankle are the most important determinants of the magnitudes of the joint torques, power and work at the concerned joints (Vaughan, 1996). The magnitude of the lever arm is in turn determined by the distance of the resultant ground reaction force vector from the joint centre (Figure 2.3.6; Chapter Two) (Vaughan, 1996). The resultant ground reaction force in turn is a reflection of the acceleration of the total

body's centre of mass (Lake, 2000). It appears plausible that a change in the position of the centre of mass, due to a change in the orientation of the trunk, upper limbs and head, may influence the direction of the ground reaction force and consequently the magnitude of the lever arms at the knee and ankle. The mathematical model used to obtain gait analysis data in the present study is not designed to provide centre of mass data or data related to the orientation of the trunk in stance. A hypothetical model of the relationship between the gait analysis and perceptual variables of this study is proposed below in the context of related data in the literature. Runners with a pronated foot are described to contact the supporting surface in a pronated position and are unable to employ the natural impact attenuating benefits offered by "normal" pronation (Subotnick, 1985). In contrast, a foot that is inflexible and not able to employ the natural impact attenuating benefits offered by "normal" pronation exposes the runner with a supinated foot to excessive impact forces. Therefore running shoes that are appropriately prescribed are suggested to reduce excessive pronation in the runner with the pronated foot, and on the other hand provide optimal cushioning for the supinated foot (McPoil, 2000). "Appropriate" and "inappropriate" foot-type/ running shoe-type combinations as described in Figure 7.1 were reported to have similar ground reaction forces and lower limb kinematics. The ground reaction force, which is a measure of acceleration of the centre of mass of the runner and not of the impact force dynamics at the periphery of the limbs (Lake, 2000), does not appear appropriate to the study of the effect of running shoes on the stress applied to the runner. Accelerometry and the estimation of regional joint stress by inverse dynamics may hold merit in determining the peripheral effect of the impact attenuation and anti-pronation properties of running shoes with specific prescriptions (Literature review). The knee and ankle joint angles, and work and power data are obtained from the markers attached to the running shoe and lower limb. An earlier study has demonstrated that markers attached to the running shoe do not necessarily indicate the movement of the foot within the running shoe (Stacoff et al., 1992). Considerable care was taken in this study to replicate the marker positions of the foot on the surface of the running shoe. This limitation has been addressed with the use of "windows" in the upper of the shoes (Stacoff et al., 1992) and intracortical bone pins in previous studies (Stacoff et al., 2000). The latter technique has significant limitations with regard functional impairment of the subjects during running and technical errors associated with the stability of the intracortical bone pins (Stacoff et al., 2000). The focus of the present study is to obtain information in a functional and clinical setting and does not support the use of the described invasive kinematic techniques. However, the use of "windows" in the uppers of the running shoes is an area that may be considered for future studies in this regard.

## **7. Conclusion**

The results of the present study support the view that running shoes have characteristic effects on the gait analysis variables descriptive of running style that are distinct from that of barefoot running. The effect of running shoes on the gait variables appears to be related to the rating of perceived impact, which decreases from barefoot to shod running conditions. A model that integrates the gait analysis and perceptual variables suggests control by the central nervous system. Further research in this regard is encouraged.

## **8. Relevance of the use of running shoes to the aims of the thesis**

In the present chapter, running shoes are associated with greater peak power absorption and eccentric work at the knee compared with barefoot running. In this context, the effect of using running shoes on "normal" runners is described, with the effect on "injured" runners unknown. Therefore it would be premature to assume that running shoes are a risk for injury and disregard the epidemiological evidence of the clinical benefit of the prescription of running shoes for injury (James et al., 1978; Pretorius et al., 1986). Therefore, the merits of barefoot running in the

treatment, rehabilitation and prevention of running injuries should be evaluated in future controlled clinical trials, with specific reference to the lower eccentric load at the knee with the barefoot state. A hypothetical model of the effect of barefoot running in the context of the relevant data in the literature is described below. Active kinematic adaptation displayed by alteration in lower limb geometry in swing occurs with the apparent aim to reduce the discomfort to the heel in the barefoot condition and thereby causes a reduction of the magnitude of the impact component of the ground reaction forces (de Wit et al., 2000). The specific running style adopted in barefoot running, recognized from the lower limb geometry observed, is associated with lower quantities of work and power absorption within the musculotendinous structures at the knee and ankle joint that are required to support the lower limb in stance. Additional to the lower limb geometry, the position of the whole body centre of mass, which is influenced by the orientation of the trunk, arms and head, may contribute to the smaller magnitudes of the power and work at the knee and ankle in the barefoot than shod conditions. It appears that barefoot running is associated with a specific running style as demonstrated by characteristic lower limb geometry and possibly upper body orientation, which is adopted with the aim of reducing distortion of the heel fat pad and therefore causes a reduction in the magnitudes of the vertical impact forces and power and work at the knee and ankle. The effect of running shoes is that the running style is changed in a manner that increases the vertical impact forces and the power and work at the knee and ankle. Central Nervous control appears necessary to effect these running style adaptations to the barefoot and shod running conditions. This model is integrated with that of injured runners (Study Eight), semi-rigid orthoses (Study Six) and running style modification (Study Seven) in a global model of running injury management (Discussion and conclusion).

## STUDY FIVE

### The effect of soft orthoses on running style gait analysis variables

#### 1. Introduction

Soft orthoses provide protection from injury during repetitive impact activities (Schwellnus et al., 1990; Fauno et al., 1993). The exact mechanism by which soft orthoses afford protection from injury is not known, but it has been suggested that injury protection is afforded by the attenuation of impact forces (deMoya, 1982), a concept that originates from the impact-injury relationship described in sub-primate animals (Simon, 1972). The results of the preceding study (Study Four) suggest that the running shoes may have a centrally mediated effect on the running style of the runner as implied by the changes in the descriptive gait analysis variables. In the context of a central role of running shoes on the gait analysis variables descriptive of running style, a suggestion has been made that the comfort provided by soft orthoses may be protective and not necessarily the mechanical changes that the soft orthoses have on the runner (Mundermann et al., 2001). Evidence in this regard stems from the observation that comfort offered by soft orthoses is associated with a reduction in the incidence of stress fractures in military personnel (Mundermann et al., 2001). The aim of this study is to determine the relationship between the “hardness” of soft orthoses and selected gait analysis variables that describe running style and what effect this has on the subjective rating of perceived impact.

#### 2. Methods

##### 2.1. Subjects and informed consent

Ten (10) injury-free male recreational runners (age:  $31.80 \pm 13.31$  years; height:  $1.74 \pm 0.04$  m; mass:  $70.21 \pm 10.30$  kg) were recruited for the study. Testing was undertaken in the Gait Analysis Laboratory, University of Cape Town, South Africa. Informed consent as required and approved by the University of Cape Town Research Ethics Committee was obtained from all runners.

##### 2.3. Soft orthoses

Custom-made “soft orthoses” (insoles/ sockliners) were constructed from 4mm thick Ethylene Vinyl Acetate (EVA). The “soft orthoses” varied in the “hardness” and ranged from (soft) 25 Shore A [25SA], to (hard) 50 Shore A [50SA] and (hard) 55 Shore A [55SA], manufactured by (Woodheads, Cape Town, South Africa). The test conditions included barefoot (Bf), running shoes with manufacturer-supplied insole (LSh1), and three custom-made “soft orthoses” (25SA, 50SA, 55SA) (Figure 1). The investigators supplied the running shoes. The custom-made “soft-orthoses” were each placed inside the running shoe for testing, so that apart from the specific “soft orthoses” all other footwear components were similar between the test conditions. The running shoe (LSh1) was commercially marketed as a “neutral”-type of running shoe for runners with a “neutral gait” (<http://www.newbalance.com>). The midsole was constructed of a single density Ethylene Vinyl Acetate (EVA) material. No specific motion control (anti-pronation) features were incorporated into the structure of the midsole. The manufacturer-supplied “insole” was considered an intervention in the various “soft orthoses” test conditions.

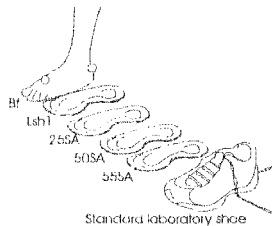


Figure 1 Test conditions to evaluate the effect of soft orthoses on gait analysis and perceptual variables  
Barefoot condition (Bf), Standard insoles (Lsh1), 25 Shore A soft orthoses (25SA), 50 Shore A soft orthoses (50SA), 55 Shore A EVA soft orthoses (55SA)

## 2.4. Test procedure

All runners followed the same standard testing procedure described in Study One. A lower limb evaluation (foot-type) and anthropometric measurements were undertaken (Study One). All runners completed a series of 10 overground running trials in each of the test conditions in a randomised manner, at self-selected running speed in the gait analysis laboratory (Study One). Gait analysis data were collected, and five trials per runner were selected for processing and analysis (Study One). The runners were blinded to the hardness of the customised “soft orthoses” and the manufacturer-supplied insole used in the running shoe. The rating of perceived impact (RPI) in each of the five test conditions was recorded with a ten-point scale on completion of both the familiarisation and gait analysis components of the procedure (Study Four).

## 3. Main outcome variables

The gait analysis variables that were compared for the group across the barefoot and soft orthoses conditions were:

1. Ground reaction forces: loading rate (BW/s) and magnitude (BW) of the vertical impact force at peak value, the magnitude of the propulsive force in the vertical (BW) and horizontal (BW) directions and the horizontal braking force (BW);
2. Joint angles: during mid-swing ( $^{\circ}$ ), terminal swing ( $^{\circ}$ ), initial supporting surface contact ( $^{\circ}$ ) and midstance ( $^{\circ}$ );
3. Joint power and work: the magnitude of the knee and ankle power (Watts/kg) and work (J/kg) during support and propulsive phases of stance.
4. The rating of perceived impact.

## 4. Statistical analysis

Statistical tests were undertaken of the running speed, gait analysis and perceptual variables using a commercial statistical programme (StatSoft, Inc. (2000). STATISTICA for Windows [Computer program manual]. Tulsa, OK, USA). A repeated measure ANOVA was used to determine differences between the test conditions. The Shêffe post hoc test was used to identify relationships of variables with significant F-ratios. A significance level of  $p < 0.05$  was used for all tests.

## 5. Results

### 5.1. Running speed

The mean running speeds were similar between the barefoot ( $3.00 \pm 0.44$  m/s), LSh1 ( $3.01 \pm 0.54$  m/s), 25SA ( $3.05 \pm 0.46$  m/s), 50SA ( $3.03 \pm 0.43$  m/s) and 55SA ( $3.02 \pm 0.46$  m/s) running conditions (F-ratio: 0.218,  $p=0.927$ ).

### 5.2. Ground reaction forces

The HPF barefoot ( $0.16 \pm 0.05$  BW), 25SA ( $0.16 \pm 0.03$  BW), 50SA ( $0.16 \pm 0.03$  BW) and 55SA ( $0.16 \pm 0.03$  BW) were greater than the LSh1 ( $0.14 \pm 0.03$  BW) conditions (F-ratio= 3.136,  $p=0.026$ ) (Table 8.1). The loading rate of the vertical impact force at peak magnitude (VLR: F-ratio= 9.532,  $p=0.000$ ) was significantly greater in the barefoot than all soft orthoses conditions. The VFP was greater in the soft orthoses than the barefoot conditions (F-ratio= 4.115,  $p=0.008$ ). No other differences in ground reaction forces between the individual soft orthoses were reported.

Table 1. Comparison of the ground reaction forces by soft orthoses

	BF	LSh1	25SA	50SA	55SA	F-ratio	p-level
HBF	$0.21 \pm 0.04$	$0.21 \pm 0.05$	$0.21 \pm 0.05$	$0.22 \pm 0.05$	$0.22 \pm 0.04$	0.436	0.782
HPF	$0.16 \pm 0.05$	$0.14 \pm 0.03^*$	$0.16 \pm 0.03$	$0.16 \pm 0.03$	$0.16 \pm 0.03$	3.136	0.026
VIF	$1.32 \pm 0.19$	$1.43 \pm 0.19$	$1.47 \pm 0.22$	$1.48 \pm 0.21$	$1.45 \pm 0.19$	2.615	0.051
VLR	$47.8 \pm 9.30^*$	$37.4 \pm 7.2$	$36.29 \pm 3.6$	$37.7 \pm 6.7$	$36.7 \pm 6.7$	9.532	0.000
VFP	$2.26 \pm 0.25^*$	$2.31 \pm 0.22$	$2.36 \pm 0.17$	$2.37 \pm 0.16$	$2.38 \pm 0.20$	4.115	0.008

\* Significantly different from the other conditions [ $n=10$ ]

Horizontal braking force (BW) [HBF], Horizontal propulsive force (BW) [HPF], Vertical impact force at 25ms (BW) [VIF25], Vertical impact force at 25ms loading rate (BW/s) [VLR25], Vertical impact force peak (BW) [VIF], Vertical impact force peak loading rate (BW/s) [VLR], Vertical propulsive force peak (BW) [VFP]

### 5.3. Joint angles

The knee at initial contact was more flexed in the barefoot than the soft orthoses conditions (F-ratio = 6.746,  $p=0.000$ ), there being no differences between the individual soft orthoses condition (Table 8.2). The ankle was more plantarflexed in the barefoot than any of the individual soft orthoses conditions during terminal swing (Asw: F-ratio = 23.243,  $p=0.000$ ), initial supporting surface contact (Aic: F-ratio = 3.481,  $p=0.016$ ) and in stance (Ast: F-ratio = 6.732,  $p=0.000$ ), there being no differences between the individual soft orthoses conditions. There were no other significant differences at the knee and ankle.

### 5.4. Joint work and power

The knee power absorption (F-ratio = 2.826,  $p=0.039$ ) and eccentric work (F-ratio = 3.289,  $p=0.021$ ) were less in the barefoot than the “soft orthoses” conditions, there not being any differences between the individual “soft orthoses”, (Table 3). The ankle power absorption (F-ratio = 3.802,  $p=0.011$ ) and production (F-ratio = 12.924,  $p=0.000$ ) were greater in the barefoot than the “soft orthoses” conditions there not being any differences between the individual “soft orthoses” conditions. The ankle eccentric (F-ratio = 2.725,  $p=0.044$ ) and concentric work (F-ratio = 5.801,  $p=0.001$ ) were greater in the barefoot than “soft orthoses” condition, there not being any difference between the individual “soft orthoses” conditions.

Table 2. Comparison of knee and ankle angles by soft orthoses

	BF	LSh1	25SA	50SA	55SA	F-ratio	p-value
KswF	85.6± 2.1	86.5± 2.3	86.9± 1.9	87.5± 1.2	87.3± 1.1	2.136	0.099
KswE	18.4± 8.6	18.0± 8.9	18.0± 9.7	19.9± 7.2	18.2± 10.3	0.541	0.707
Kic	23.7± 7.3*	20.4± 7.9	21.9± 8.2	21.3± 7.9	20.6± 9.0	6.746	0.000
Kst	43.2± 4.8	43.4± 5.5	44.0± 4.6	43.7± 5.0	43.8± 4.7	0.357	0.838
Asw	-9.1± 5.0*	-16.6± 6.6	-16.0± 6.5	-14.9± 4.7	-16.5± 6.3	23.243	0.000
Aic	-7.9± 4.4*	-12.1± 10.9	-13.9± 5.8	-13.6± 5.3	-15.4± 5.7	3.481	0.016
Ast	-24.6± 4.7*	-28.5± 6.0	-28.2± 5.6	-27.3± 4.9	-28.5± 5.4	6.732	0.000

\* Significantly different from the other conditions [n= 10]

Knee swing phase peak flexion angle (<sup>0</sup>) [KswF], Knee angle in terminal swing phase (<sup>0</sup>) [KswE], Knee angle at initial supporting surface contact (<sup>0</sup>) [Kic], Knee angle in midstance (<sup>0</sup>) [Kst], Ankle angle in terminal swing phase (<sup>0</sup>) [Asw], Ankle angle at initial supporting surface contact (<sup>0</sup>) [Aic], Ankle angle in midstance (<sup>0</sup>) [Ast]

Table 3. Comparison of joint power and work by soft orthoses

	BF	LSh1	25SA	50SA	55SA	F-ratio	p-value
KPA	5.92± 1.92*	6.90± 1.49	6.99± 1.59	7.08± 2.04	7.17± 2.10	2.826	0.039
APA	5.94± 1.72*	4.93± 1.02	5.26± 1.08	4.82± 0.82	5.16± 0.94	3.802	0.011
KPG	5.88± 1.28	6.26± 1.95	6.45± 1.87	6.46± 2.42	6.66± 2.34	1.332	0.277
APG	7.23± 1.34*	5.34± 1.35	5.54± 1.40	5.52± 1.54	5.72± 1.56	12.924	0.000
EKW	0.32± 0.13*	0.39± 0.09	0.40± 0.10	0.41± 0.14	0.42± 0.14	3.289	0.021
EAW	0.39± 0.13*	0.33± 0.05	0.35± 0.05	0.32± 0.04	0.34± 0.05	2.725	0.044
CKW	0.46± 0.10	0.48± 0.10	0.48± 0.10	0.49± 0.14	0.50± 0.14	0.419	0.793
CAW	0.45± 0.09*	0.36± 0.07	0.37± 0.06	0.37± 0.08	0.38± 0.07	5.801	0.001

\* Significantly different from the other conditions [n= 10]

Knee power absorption (Watt/kg) [KPA], Ankle power absorption (Watt/kg) [APA], Knee power generation (Watt/kg) [KPG], Ankle power generation (Watt/kg) [APG], Eccentric knee work (J/kg) [EKW], Eccentric ankle work (J/kg) [EAW], Concentric knee work (J/kg) [CKW], Concentric ankle work (J/kg) [CAW]

## 5.5. Rating of perceived impact (RPI)

The rating of perceived impact was greater in the barefoot ( $4.30 \pm 2.67$ ) than all individual soft orthoses conditions (F-ratio = 6.846, p= 0.000). Although there were no differences between the individual soft orthoses, the RPI mirrored the manufacturer specification hardness of the orthoses (Figure 8.2).

## 6. Discussion

The main finding of this study is that the “hardness” of the soft orthoses conditions does not have a graded effect on the running style gait analysis variables as determined with clinical gait analysis. However, the subjective rating of the impact perceived by the runner resembles the manufacturer specification of the hardness of the soft orthoses. There is evidence of a relationship between high magnitudes and loading rates of the vertical impact force peak and common running injuries (Duncan et al., 2000). Impact attenuation is postulated to be the mechanism by which protection from injury is afforded by footwear (James et al., 1978). This has been supported by controlled laboratory studies in which Saran soft orthoses (insoles) in military boots were found to have a protective effect (deMoya, 1982). Epidemiological studies in military (Schwellnus et al., 1990) and soccer referee populations (Fauno et al., 1993) have also found the use of soft orthoses in

“hard” midsole military boots or soccer boots to provide protection from injury. The results of the present study contrast the results of previous studies in that there was no difference in the magnitude or loading rate of the vertical impact component of the ground reaction force between “soft” and “hard” soft orthoses.

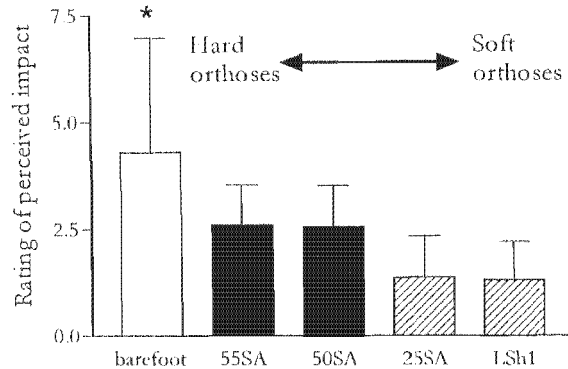


Figure 2. Comparison of the rating of perceived impact by soft orthoses condition

\* Significant difference between barefoot and all orthoses conditions  
 Barefoot condition (Bf), Standard insoles (LSh1), 25 Shore A soft orthoses (25SA), 50 Shore A soft orthoses (50SA), 55 Shore A EVA soft orthoses (55SA)

In view of the current re-evaluation of the merits of “cushioning” (in the biomechanics literature), it appears that soft orthoses may not necessarily provide protection by attenuating the ground reaction forces. Technical limitations of this study that may account for the current ground reaction force findings and alternative mechanisms by which soft orthoses may provide protection are discussed below. One technical limitation in the present study that may account for the similar impact forces in the “soft” and “hard” soft orthoses conditions may be the running shoe. The running shoe has a soft midsole with excellent cushioning properties. This contrasts the military boots in the previous studies that have “hard” or “firm” midsoles. The soft midsole of the running shoes used in this study may mask the differences in the ground reaction forces between “soft” and “hard” soft orthoses. These differences may be apparent with running shoes that have a midsole consistency similar to that of military boots. A second technical limitation of this study is that the ground reaction force measured is representative of the acceleration of the centre of mass and does not necessarily represent loading at the periphery of the body (Lake, 2000). It is possible that the ground reaction force measurement is not sensitive enough to determine the subtle differences in cushioning with soft orthoses that vary in “hardness”, at the peripheries. Alternative mechanical measurement techniques such as accelerometry (Lake, 2000) and the estimation of joint power and work that represent a regional load may be of merit. In a search for explanations alternative to the attenuation of ground reaction forces, for the protection offered by soft orthoses, the concept of footwear comfort was explored (Mundermann et al., 2001). In a controlled clinical trial of the effect of soft orthoses on the incidence of injuries in 206 military personnel, soft orthoses were randomly prescribed to half of the study group. The group prescribed the soft orthoses reported a comfort rating of at least 2.3 points higher on a visual analogue scale, than the no orthoses group. The incidence of stress fractures to the foot, knee and lower back, and pain at different locations was reduced by 1.5 to 13.4% in the soft orthoses group compared with the no orthoses group. The investigators of the study proposed that the comfort provided by the soft orthoses is important in injury prevention (Mundermann et al., 2001). The importance of comfort in running shoes is not new, but its relationship to injury prevention is a long way from being understood. There is data to suggest that a “low” comfort running shoe condition has running style characteristics different to

that of a “high” comfort running shoe condition (Hennig et al., 1996). The alteration in running style by the runner with a change from “high” to “low” running shoe comfort is thought to be necessary to protect the body from injury, with the risk of injury potentially greater in the “low” comfort condition (Hennig et al., 1996; Milani et al., 1997). In this regard, an association between the comfort of soft orthoses and a reduced risk of injury is proposed based on a controlled clinical trial (Mundermann et al., 2001). However a specific cause-effect mechanism between “low” comfort and injury, and “high” comfort and injury protection is not well explained. It is suggested that the rating of perceived impact may provide insight to the comfort experienced in a pair of sports shoes (Hennig et al., 1996; Milani et al., 1997; McCaw et al., 2000). In this regard the condition that provides the most cushioning (impact attenuation) has been considered the most comfortable (Hennig et al., 1996; Milani et al., 1997; McCaw et al., 2000). In the present study, the changes in RPI occurred independently of changes in the ground reaction forces. This suggests that the RPI may be dependent on the stimulation of the dermal sensory receptors by the materials in contact with the sole of the foot. The high correlation between the local heel pressure and the rating of perceived impact previously reported may be evidence for this suggestion (Milani et al., 1997). Soft orthoses are meant to provide cushioning rather than motion control (Gross and Napoli, 1993). The effect of orthoses on motion control has previously been examined with kinematic analysis of the rearfoot and leg segments (Bates et al., 1979; Moss et al., 1990; McCulloch et al., 1993; Eng and Pierrynowski, 1994; Brown et al., 1995; Genova and Gross, 2000). In the present study, the kinematic variables are limited to knee and ankle movement in the sagittal plane. In the preceding study (Study Four), a cushioned running condition (shod condition) caused significant changes in the knee and ankle joint angles compared with barefoot running. The absence of a kinematic response and knee and ankle work and power changes with the hardness of the soft orthoses, does not assist in the understanding explanation of how soft orthoses protect the runner from injury.

## 7. Conclusion

Soft orthoses are commonly prescribed to runners to assist in reducing the risk associated with excessive impact forces and to provide comfort. A comparison of soft orthoses of differing “hardness” did not demonstrate a relationship between the hardness of the soft orthoses and any of the selected running style gait analysis variables. However, the subjective rating of perceived impact was higher in the “hard” versus “soft” soft orthoses. The results of this study suggest that the use of soft orthoses may be important in providing a sensation of comfort rather than addressing the gait analysis variables and the concept of comfort in protection from injury should receive attention in future related research.

## 8. Relevance of soft orthoses to the thesis

The use of soft orthoses appears to have an association with the subjective reporting of the “hardness” of the “soft insole” rather than any of the gait analysis variables descriptive of running style. Although the loading rate of the vertical impact force has a relationship with the gross perception of running barefoot or shod (Study Four), the ground reaction force variables do not appear helpful in determining subtle differences between the “soft orthoses”. The measurement of plantar pressures that may give insight to the subtle stimulation of the sole of the foot may be valuable in this regard. The observation that runners are able to perceive subtle differences between soft orthoses condition suggests that there may be scope for the manipulation of the texture or hardness of the soft orthoses to mimic a variety of supporting surface condition, including that of an abrasive texture similar to barefoot running. The study of the response of runners to a replicated barefoot condition is encouraged as this may be an alternative intervention that may be applied in the management of the injured runner (Discussion and conclusion).

## STUDY SIX

### Effect of semi-rigid orthoses on running gait analysis variables

#### 1. Introduction

Running shoe semi-rigid orthoses are a popular treatment option for runners with common running injuries with more than three-quarters of injured runners successfully treated with appropriately prescribed semi-rigid orthoses (James et al, 1978; Gross et al, 1991; Gross, 1995). Despite the reported success of the treatment of running injuries with semi-rigid orthoses, clinicians have been cautioned “running shoe orthoses do not necessarily control the injury pattern of most runners” (McKenzie et al, 1985). The word of caution originates perhaps not from a contradiction of the results of clinical trials in which running shoe semi-rigid orthoses have proved successful, but rather from the concern that the mechanism by which this clinical tool acts is still relatively unknown. As discussed in earlier portions of this thesis (Literature review), research that originates from the late 1970’s suggests that semi-rigid orthoses may have an effect on the subtalar joint mechanics (Bates et al., 1979) and by limiting abnormal intrinsic foot movement (abnormal subtalar joint pronation) assist in the treatment and prevention of injury. The result of a recent research study in this regard suggests that the kinematic effect of semi-rigid orthoses response on individual runners is variable and that a group response is not apparent (Stacoff et al., 2000), prompting the need for an alternative hypothesis by which semi-rigid orthoses may function. One such hypothesis is that semi-rigid orthoses may have an effect on the work undertaken by individual structures at a joint by changing the moment arm at the concerned joint (Arendse, 2004). This hypothesis would suggest that semi-rigid orthoses may have an effect on joint mechanics and the mechanism by which semi-rigid orthoses function, differ from that of soft orthoses, which appear to have a predominant effect on the runners perception of the “impact hardness” (or comfort) of the running condition (Study Five). The aim of this study is therefore to determine whether semi-rigid orthoses have an effect on the joint mechanics as described by the running style gait analysis variables in adult recreational runners who are accustomed to the use of custom-made semi-rigid running shoe orthoses at self-selected running speed.

#### 2. Method

##### 2.1. Subjects

The runners in this study were selected from the group of sixty (60) uninjured, recreational runners described in an earlier portion of this thesis (Study Two). The primary selection criterion was that they had previously used semi-rigid orthoses as part of routine training and racing activity. All the runners were recruited from local running clubs in Cape Town, South Africa by means of flyers handed out at the Sports Science Institute of South Africa (SSISA), Cape Town. Twelve (12) uninjured male and female recreational runners (age:  $35.6 \pm 13.0$  years; height:  $175.4 \pm 5.7$  m; mass:  $74.0 \pm 10.0$  kg) were selected for the study. All runners trained a minimum of three times weekly for a period of one year prior to participation in the study.

## 2.2. Informed consent

All runners were informed as to the nature of the testing procedure and their relevant concerns addressed. Informed signed consent as prescribed and approved by the Research and Ethics Committee of the University of Cape Town, South Africa was obtained from all runners.

## 2.3. Test procedure

All runners followed the standard testing procedure described in Study One. A lower limb evaluation (foot-type) and anthropometric measurements were undertaken (Study One). The runners completed a 1000m familiarisation run and a series of running trials in the gait analysis laboratory, in standard laboratory running shoes (lightweight racing shoe) with- and without- semi-rigid orthoses in randomised order at self-selected running speeds (Study One). Gait analysis data were collected, and five trials per runner were selected for processing and analysis (Study One). All runners were requested to rate the amount of impact they perceived during the running trials with and without orthoses with a 10-point rating scale (Study Four).

## 2.4. Running shoes

The researchers provided the running shoes in this study. The running shoes (LSh1) were commercially marketed as a “neutral”-type of running shoe for runners with a “neutral gait” (<http://www.newbalance.com/>). The midsole was constructed of a single density Ethylene Vinyl Acetate (EVA) material. No specific motion control (anti-pronation) features were incorporated into the structure of the midsole.

## 2.5. Semi-rigid orthoses

The orthoses used in this study were the runners’ property. The orthoses were specifically prescribed by each runners’ personal orthotist or podiatrist. All orthoses used in this study were of a semi-rigid construction and custom built for each runner (Figure 1). The orthoses were prescribed to correct “imbalances” of the rearfoot rather than the forefoot. None of the orthoses extended for the full length of the plantar surface of the foot.

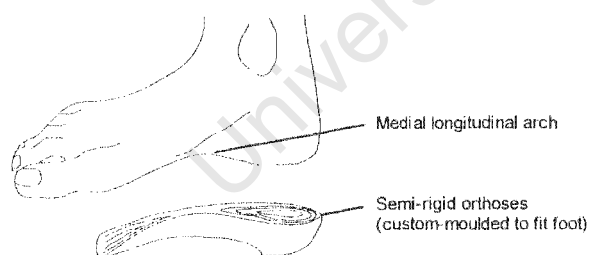


Figure 1. Custom-made semi-rigid orthoses

## 3. Main outcome variables

The gait analysis variables that were compared for the group across the with- and without semi-rigid orthoses running conditions were:

1. Ground reaction forces: loading rate (BW/s) and magnitude (BW) of the vertical impact force at peak value, the magnitude of the propulsive force in the vertical (BW) and horizontal (BW) directions and the horizontal braking force (BW);
2. Joint angles: during mid-swing ( $^{\circ}$ ), terminal swing ( $^{\circ}$ ), initial supporting surface contact ( $^{\circ}$ ) and midstance ( $^{\circ}$ );
3. Joint power and work: the magnitude of the knee and ankle power (Watts/kg) and work (J/kg) during support and propulsive phases of stance.
4. The rating of perceived impact.

#### 4. Statistical analysis

Statistical tests were undertaken of the gait analysis variables using a commercial statistical programme (StatSoft, Inc. (2000). STATISTICA for Windows [Computer program manual]. Tulsa, OK, USA). Dependent t-tests were used to determine differences of the group means of the running speed, gait analysis and perceptual variables between the with- and without- semi-rigid orthoses running shoe conditions, the level of significance at  $p < 0.05$ .

## 5. Results

### 5.1. Running speed

The mean running speed of the trials with orthoses ( $2.89 \pm 0.28$  m/s) was similar to those without orthoses ( $2.93 \pm 0.33$  m/s) ( $p = 0.422$ ).

### 9.5.2. Ground reaction forces

There were no other differences in the ground reaction forces of the recreational runners with and without semi-rigid orthoses.

Table 1. Effect of semi-rigid orthoses on the ground reaction forces

	Without-orthoses	With -orthoses	p-value
HBF	$0.23 \pm 0.06$	$0.33 \pm 0.35$	0.358
HPF	$0.15 \pm 0.04$	$0.15 \pm 0.04$	0.351
VIF	$1.52 \pm 0.33$	$1.53 \pm 0.35$	0.893
VLR	$32.0 \pm 6.6$	$31.6 \pm 4.9$	0.744
VPF	$2.35 \pm 0.39$	$2.36 \pm 0.39$	0.848

\* Significant difference between groups [n=12]

Horizontal braking force (BW) [HBF], Horizontal propulsive force (BW) [HPF], Vertical impact force peak (BW) [VIF], Vertical impact force peak loading rate (BW/s) [VLR], Vertical propulsive force peak (BW) [VPF]

### 5.3. Joint angles

There were no differences in any of the sagittal plane kinematics of the knee and ankle joint angles between the with- and without-orthoses conditions (Table 2).

### 5.4. Joint power and work

The ankle eccentric work (EAW) was significantly reduced with the use of semi-rigid orthoses (EAW:  $0.34 \pm 0.08$  J/kg) in comparison with the without-orthoses condition (EAW:  $0.38 \pm 0.11$  J/kg, [ $p = 0.046$ ]) (Figure 2). The ankle power absorption (APA) was significantly reduced with the use of semi-rigid orthoses (APA:  $4.86 \pm 1.41$  Watts/kg) in comparison with the without-orthoses condition (APA:  $5.51 \pm 1.72$  Watts/kg, [ $p = 0.012$ ]). There were no other findings of the work and

power variables of the knee and ankle between the with- and without-orthoses conditions (Table 3).

Table 2. Effect of semi-rigid orthoses on joint angles

	Without-orthoses	With -orthoses	p-value
KswF	85.6± 3.8	85.2± 3.5	0.751
KswE	18.2± 3.6	19.2± 4.3	0.113
Kic	21.2± 4.1	21.9± 3.9	0.263
Kst	45.2± 4.9	45.7± 4.5	0.263
Asw	19.4± 4.5	20.7± 4.9	0.149
Aic	17.5± 4.6	18.3± 5.9	0.464
Ast	26.3± 3.7	25.8± 3.5	0.497

No significant difference between groups [n=12]

Knee swing phase peak flexion angle ( $^{\circ}$ ) [KswF], Knee angle in terminal swing phase ( $^{\circ}$ ) [KswE], Knee angle at initial supporting surface contact ( $^{\circ}$ ) [Kic], Knee angle in midstance ( $^{\circ}$ ) [Kst], Ankle angle in terminal swing phase ( $^{\circ}$ ) [Asw], Ankle angle at initial supporting surface contact ( $^{\circ}$ ) [Aic], Ankle angle in midstance ( $^{\circ}$ ) [Ast]

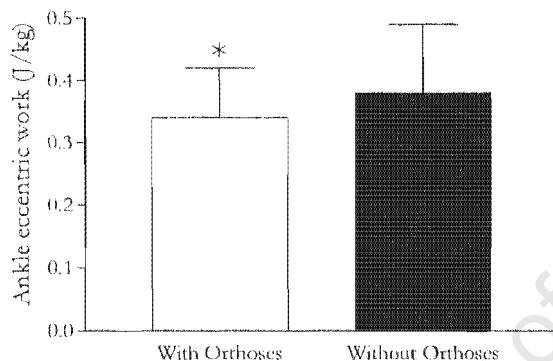


Figure 2. Comparison of the ankle eccentric work between with- and without semi-rigid orthoses

\* Significant difference,  $p=0.046$ , [n= 12]

Table 3. Effect of semi-rigid orthoses on joint power and work

	Without-orthoses	With -orthoses	p-value
KPA	8.85± 2.84	9.05± 3.61	0.562
APA	5.51± 1.72	4.86± 1.41	0.012*
KPG	7.28± 2.50	7.93± 3.40	0.228
APG	6.07± 1.85	5.78± 2.02	0.288
EKW	0.55± 0.21	0.55± 0.23	0.996
CKW	0.55± 0.14	0.61± 0.25	0.206
CAW	0.43± 0.12	0.41± 0.13	0.372

\* Significant difference between the groups [n= 12]

Knee power absorption (Watt/kg) [KPA], Knee power generation (Watt/kg) [KPG], Ankle power absorption (Watt/kg) [APA], Ankle power generation (Watt/kg) [APG], Eccentric knee work (J/kg) [EKW], Concentric knee work (J/kg) [CKW], Concentric ankle work (J/kg) [CAW]

### 5.5. Rating of perceived impact

The runners' rated the perceived impact at  $1.41 \pm 1.04$  for the without-orthoses compared with  $2.05 \pm 1.44$  for the with-orthoses condition ( $p = 0.243$ ).

## 6. Discussion

The main findings of this study were that semi-rigid orthoses significantly reduced the power absorption and eccentric work at the ankle compared with the without orthoses condition at matched running speeds. Running injuries are commonly assumed to occur as a result of overload of the musculoskeletal structures of the lower limb, due to the accumulation of excessive impact force or excessive torque from abnormal foot movement (James et al., 1978; Subotnick, 1985). Semi-rigid orthoses are proposed to benefit the long distance runner by providing control of abnormal motion of the foot and leg, and assist impact force attenuation (Gross and Napoli, 1993) and contrasts soft orthoses which have a primary function of impact attenuation (deMoya, 1982). The results of the present study support the assumption that semi-rigid orthoses do offer attenuation of the impact forces. In this regard there is a significant reduction in the magnitude and the loading rate of the vertical impact force at 25 ms of stance with the use of orthoses (Figure 2; Table 1). No differences in the peak impact force magnitude and loading rate were evident between the with- and without-orthoses conditions (Table 1). A reason for the latter finding is that the ground reaction force essentially measures the acceleration of the centre of mass of the whole body. If the mass of the semi-rigid orthoses is negligible and provided all other variables (running speed, style, and running shoe conditions) are similar, the acceleration of the centre of mass will be constant. Therefore the peak magnitude of the force with which the runner impacts the supporting surface will be similar. The effect of semi-rigid orthoses has been almost exclusively studied with regard to the rearfoot and lower limb transverse plane kinematics during running (Bates et al., 1979). There is no consensus on either exactly which variables are important in determining the effect of the semi-rigid orthoses or whether there is a consistent group effect (Stacoff et al., 2000). Alignment errors and movement of the skin markers over the bony skeleton are factors that contribute to the uncertainty of the effect of semi-rigid orthoses on lower limb kinematics (Areblad et al., 1990). In the current study, the sagittal plane kinematics of the knee and ankle were determined. Semi-rigid running shoe orthoses may range in thickness from a few millimetres to several centimetres. One of the consequences of the thick semi-rigid orthoses is that the ankle is plantarflexed within the running shoe (McCulloch et al., 1993). The plantarflexed ankle is able to undergo a greater range of dorsiflexion ( $11.53 \pm 2.03^\circ$ ) than the neutral position ankle without an orthotic ( $10.56 \pm 1.94^\circ$ ), ( $p < 0.01$ ) (McCulloch et al., 1993). However, no effect of the semi-rigid orthoses on the sagittal plane kinematics of the ankle and knee is observed. The large 25mm retro-reflective spheres may have minimised subtle kinematic changes that occurred with repositioning of the foot with the use of semi-rigid orthoses. Future researchers of effect of semi-rigid orthoses should consider alternative kinematic techniques including the use of smaller retro-reflective markers with high resolution cameras. The estimation of the mechanical power at the knee and ankle is obtained from the product of the resultant moment of force at and the angular velocity about the knee and ankle joints (Vaughan et al., 1999). The strongest determinant of the magnitude of the mechanical work and power at the knee and ankle joints is the moment arm (Vaughan, 1996). Therefore, the reduction of the eccentric load at the ankle with the use of semi-rigid orthoses may be due to a change in the magnitude of the moment arm. It appears likely that the magnitude of the moment arm may have changed with re-positioning of the foot within the running shoe with the orthoses. Semi-rigid orthoses are associated with a reduction in the loading rate of the impact force, and a reduction in the ankle eccentric joint load, despite ankle movement

patterns similar to that of that of the without-orthoses condition. A limitation of the current mathematical model used to determine the mechanical work and power at a joint is that this quantity does not give an indication of the activity within any specific structures at the joint of interest. The assumption that changes in the eccentric load and power at the ankle as may occur with semi-rigid orthoses may be beneficial for selected anatomical structures is purely hypothetical as we do not currently know what the effect of eccentric load is at the ankle (Arendse, 2004). While a higher eccentric load at the knee is associated with knee injury (Study Eight), this may not necessarily apply to injuries at the ankle. Controlled progressive eccentric loading of the Achilles' tendon is reported to have clinical benefit in the treatment of Achilles' tendon injuries (Alfredson et al., 1998). This infers that an initial reduction in Achilles' tendon load may be necessary initially in this treatment method. Semi-rigid orthoses in this regard may have a role in the treatment of Achilles' tendinopathy by reducing the eccentric load at the initiation of treatment and set the conditions that allow the Achilles' tendon to be progressively loaded. In contrast, Medial Tibial Stress Syndrome (MTSS) is associated with a traction-type injury to the posterior aspect of the tibia (Sommer and Valentyne, 1995). A reduction in the eccentric load with semi-rigid orthoses may be beneficial in the treatment of MTSS. It is recommended that intervention and prospective clinical trials with the determination of the knee and ankle eccentric load of runners with and without semi-rigid orthoses are undertaken to understand the clinical merits of semi-rigid orthoses prescription.

## **7. Conclusion**

Injury-free adult recreational runners accustomed to the use of semi-rigid orthoses display an absence of changes in sagittal plane knee and ankle kinematics, and a reduction in ankle but not knee eccentric load. Controlled clinical trials in which the latter running style gait analysis variables are monitored may assist in the understanding of the clinical implications of the use of semi-rigid orthoses.

## **8. Relevance of the effect of semi-rigid orthoses to the aim of the thesis**

Semi-rigid orthoses do not have any effect on the eccentric work at the knee. There is evidence that the semi-rigid orthoses reduce the eccentric work at the ankle. In the final chapter of this work, a hypothetical model is proposed which includes the possible role of semi-rigid orthoses in the treatment of running injuries (Discussion and conclusion).

## STUDY SEVEN

### Effect of running style modification on running gait analysis variables

#### 1. Introduction

Running style, as defined as the gross movement pattern of the whole body of the runner, is not well described in the literature in relation to injury. This is despite the suggestion that a dramatic, although perhaps impractical change in running style, such as running in a backward rather than forward direction, may have application in the management of knee injuries (Morton, 1986). If backward running has a role in injury management, an argument may be made that the style of running in a forward direction may be related to common running injuries. Relevant in this regard is the relationship between running style (as described with selected clinical gait analysis variables) and injury described in this thesis (Study Eight). The gait analysis variables selected to describe running style are described to change in what may be argued as a “centrally mediated reflex manner” to a change from barefoot to shod running in a controlled repeated measures designed study (Study Four). Furthermore, a mechanical intervention such as the introduction of a semi-rigid orthoses appears to cause additional changes in the variables selected to describe running style in a controlled trial (Study Six). A voluntary change in running style in the forward direction by instruction of the runner is reported for the change from heel-toe to midfoot running (Williams et al., 2000), and heel-toe to “Groucho” running. A novel running style that has a midfoot strike pattern has been developed and is called Pose running. The main feature of this running style is that the shoulder, hip and the heel at the point of contact with the supporting surface are aligned throughout the stance. The gait analysis characteristics of this running style are not reported. The aim of this study is to determine the effect of voluntary modification of running style from heel-toe to midfoot and Pose running with the aid of clinical gait analysis.

#### 2. Methods

##### 2.1. Subjects

Twenty (20) male and female natural heel-toe recreational runners (height:  $1.62 \pm 0.29$  m, mass  $75.9 \pm 16.6$  kg, age:  $33.2 \pm 12.7$  years) free of physical deformity or neurological abnormality were recruited from running clubs in Cape Town, South Africa. The mean  $\pm$  SD 10km time for the group was  $54.26 \pm 22.51$  minutes (11.06 km/h).

##### 2.2. Informed consent

Informed consent was sought from the runners prior to their participation in the study. Ethical approval for the study was obtained from the Research Ethics Committee of the University of Cape Town.

##### 2.3. Test procedure

All runners followed the standard testing procedure described in Study One. A lower limb evaluation (foot-type) and anthropometric measurements were undertaken (Study One). A

repeated measures experimental design (within-subjects) was employed. The runners were tested in each of three running styles. Initial gait analysis data were collected with the runners in the heel-toe running style. The runners were then instructed in midfoot and Pose running. The runners then completed a series of ten (10) barefoot running trials in the gait analysis laboratory at self-selected running speeds (Study One). Gait analysis data were collected, and five trials per runner were selected for processing and analysis (Study One).

## 2.4. Running styles

All runners naturally employed a heel-toe running style in which initial contact with the supporting surface was made with the heel followed by the mid- and anterior portions of the foot (Figure 2.3.12) (Cavanagh and Lafortune, 1980). The runners were instructed in midfoot and Pose running (Figure 2.3.12).

### 2.4.1. Midfoot running

Midfoot running instruction consisted of practical demonstration and verbal instruction to the runners to alter the point of first contact of the foot with the supporting surface from the heel to the midfoot area. The runners were instructed to avoid contact with the heel of the foot with the supporting surface in stance. The runners were allowed to practice midfoot running until they volunteered that they were confident with the novel running style and the investigators were satisfied that there was no contact of the heel with the supporting surface in stance. None of the runners required more than fifteen-(15) minutes to become confident in the midfoot running technique.

### 2.4.2. Pose running

Pose running instruction consisted of a maximum of 7.5 hours and comprised 1.5-hour sessions daily on five consecutive days. The runners were encouraged to achieve the postural changes and actions described in Literature Review (Figure 2.3.12).

## 3. Main outcome variables

The gait analysis variables that were compared for the group across the three running styles were:

1. The temporal-distance variables: vertical oscillation of the sacrum (m) and heel marker (m), and stride (m) and step length (m).
2. Ground reaction forces: loading rate (BW/s) and magnitude (BW) of the vertical impact force at peak value, the magnitude of the propulsive force in the vertical (BW) and horizontal (BW) directions and the horizontal braking force (BW);
3. Joint angles: during mid-swing ( $^{\circ}$ ), terminal swing ( $^{\circ}$ ), initial supporting surface contact ( $^{\circ}$ ) and midstance ( $^{\circ}$ );
4. Joint power and work: the magnitude of the knee and ankle power (Watts/kg) and work (J/kg) during support and propulsive phases of stance.

## 4. Statistical analysis

Statistical tests were undertaken of the gait analysis variables using a commercial statistical programme (StatSoft, Inc. (2000). STATISTICA for Windows [Computer program manual]. Tulsa, OK, USA). Detailed descriptive statistical analysis was undertaken of the demographic and training variables. The means of the running speed and gait analysis variables in each test

condition were compared with the Repeated Measures ANOVA, the level of significance posted at  $p < 0.05$ . Significant relationships between the means as indicated by significant F-ratios were explored with the Schéffe Post Hoc analysis test.

## 5. Results

### 5.1. Running speed

The running speed of the heel-toe running style ( $2.98 \pm 0.42$  m/s) was similar to that of midfoot ( $p = 0.066$ ) and Pose running ( $p = 0.089$ ). The running speed of the midfoot running ( $3.06 \pm 0.42$  m/s) was greater than Pose running ( $2.90 \pm 0.37$  m/s), ( $p = 0.001$ ).

### 5.2. Temporal distance variables

Pose running was characterized by shorter mean stride (F-ratio = 11.478,  $p = 0.000$ ) and step lengths (F-ratio = 4.417,  $p = 0.017$ ) and smaller vertical oscillations of the sacrum (F-ratio = 22.421,  $p = 0.000$ ) and left heel marker (F-ratio = 6.491,  $p = 0.003$ ), compared with both heel-toe and midfoot running (Table 1).

**Table 1. Comparison of the temporal-distance variables between running styles**

	Heel-toe	Midfoot	Pose	F-ratio:	p-value
VSDsp	$0.09 \pm 0.03$	$0.08 \pm 0.03$	$0.05 \pm 0.04^*$	22.421	$p = 0.000$
VHDsp	$0.38 \pm 0.11$	$0.36 \pm 0.14$	$0.28 \pm 0.21^*$	6.491	$p = 0.003$
StrideLn	$2.20 \pm 0.56$	$2.17 \pm 0.71$	$1.48 \pm 1.04^*$	11.478	$p = 0.000$
StepLn	$1.09 \pm 0.33$	$1.09 \pm 0.36$	$0.83 \pm 0.60^*$	4.417	$p = 0.017$

\* Significantly different from heel-toe and midfoot running [n=20]

Vertical sacrum marker displacement (m) [VSDsp], Vertical left heel marker displacement (m) [VHDsp], Stride length (m) [StrideLn], Step length (m) [StepLn]

### 5.3. Ground reaction forces

Heel-toe running caused greater magnitudes (F-ratio: 28.191,  $p = 0.000$ ) of the vertical impact force at peak magnitude compared with midfoot and Pose running (Table 2). Heel-toe running was also associated with greater loading rates (F-ratio: 35.131,  $p = 0.000$ ) of the vertical impact force at peak magnitude compared with midfoot and Pose running (Figure 1). The vertical propulsive force was similar between the heel-toe, midfoot and Pose running. The horizontal braking (F-ratio = 18.045,  $r = 0.000$ ) and propulsive forces (F-ratio = 3.588,  $r = 0.035$ ) were less in Pose than heel-toe and midfoot running.

**Table 2. Comparison of the ground reaction forces between running style**

	Heel-toe	Midfoot	Pose	F-ratio:	p-value
HBF	$0.22 \pm 0.05$	$0.22 \pm 0.07$	$0.15 \pm 0.07^*$	18.045	$p = 0.000$
HPF	$0.18 \pm 0.04$	$0.18 \pm 0.05$	$0.15 \pm 0.07^*$	3.588	$p = 0.035$
VIF	$1.21 \pm 0.24^\ddagger$	$0.87 \pm 0.25$	$0.78 \pm 0.39$	28.907	$p = 0.000$
VPF	$2.22 \pm 0.17$	$2.25 \pm 0.51$	$1.97 \pm 0.78$	2.426	$p = 0.099$

\* Significantly different from heel-toe and midfoot running [n=20] † Significantly different from midfoot and Pose running Horizontal braking force (BW) [HBF], Horizontal propulsive force (BW) [HPF], Vertical impact force peak (BW) [VIF], Vertical propulsive force peak (BW) [VPF]

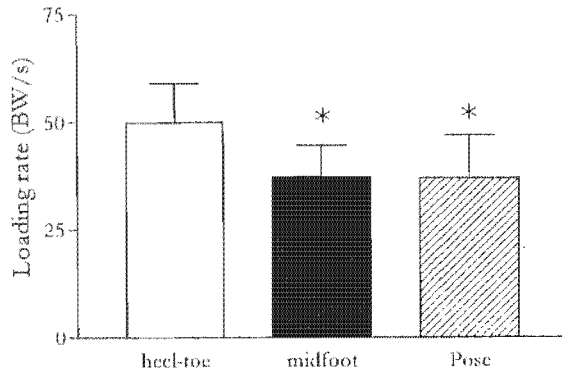


Figure 1. Comparison of the loading rate of the vertical impact force peak between heel-toe, midfoot and Pose running

\* Significantly different from heel-toe running,  $p=0.000$ , [n=20]

#### 5.4. Joint angles

The peak knee flexion in swing was the same in all three running styles (Table 3). The knee flexed more in preparation for initial foot contact in Pose ( $29.5 \pm 7.8^{\circ}$ ) compared with heel-toe ( $23.3 \pm 6.5^{\circ}$ ) and midfoot ( $23.6 \pm 6.1^{\circ}$ ) running (F-ratio: 10.460,  $p=0.000$ ) (Figure 2). The ankle in terminal swing was neutral in Pose ( $-0.4 \pm 4.9^{\circ}$ ) compared with a dorsiflexed ( $-18.3 \pm 19.8^{\circ}$ ) and plantarflexed ( $11.00 \pm 5.9^{\circ}$ ) position in heel-toe and midfoot running, respectively (F-ratio: 29.899,  $p=0.000$ ).

The knee and ankle geometries in terminal swing of the respective running styles were maintained at initial foot contact (knee: F-ratio: 4.304,  $p=0.020$ ; ankle: F-ratio: 138.548,  $p=0.000$ ). The peak knee flexion in stance was greater in the heel-toe ( $49.4 \pm 3.8^{\circ}$ ) and midfoot ( $47.6 \pm 6.9^{\circ}$ ) compared with Pose running ( $43.9 \pm 6.5^{\circ}$ ) (F-ratio: 5.819,  $p=0.006$ ). The peak ankle dorsiflexion in stance was greater in the heel-toe ( $-26.1 \pm 2.0^{\circ}$ ) than midfoot ( $-19.7 \pm 3.2^{\circ}$ ) and Pose running ( $-20.6 \pm 3.1^{\circ}$ ) (F-ratio: 32.594,  $p=0.000$ ).

Table 3. Comparison of joint angles between running styles

	Heel-toe	Midfoot	Pose	F-ratio:	p-value
KswF	$85.6 \pm 2.4$	$85.0 \pm 5.6$	$83.1 \pm 6.2$	1.274	$p=0.291$
Kic	$27.3 \pm 5.3$	$27.2 \pm 6.4$	$31.5 \pm 8.1^*$	4.304	$p=0.020$
Kst	$49.4 \pm 3.8$	$47.6 \pm 6.9$	$43.9 \pm 6.5^*$	5.819	$p=0.006$
Asw	$-18.3 \pm 9.8^{\ddagger}$	$11.00 \pm 5.9$	$-0.4 \pm 4.9^*$	29.899	$p=0.000$
Aic	$-13.2 \pm 4.5^{\ddagger}$	$11.5 \pm 5.8$	$-0.2 \pm 6.4^*$	138.548	$p=0.000$
Ast	$-26.1 \pm 2.0^{\ddagger}$	$-19.7 \pm 3.2$	$-20.6 \pm 3.1$	32.594	$p=0.000$

\* Significantly different from heel-toe and midfoot running [n=20]

$\ddagger$  Significantly different from midfoot and Pose running

Knee swing phase peak flexion angle ( $^{\circ}$ ) [KswF], Knee angle at initial supporting surface contact ( $^{\circ}$ ) [Kic], Knee angle in midstance ( $^{\circ}$ ) [Kst], Ankle angle in terminal swing phase ( $^{\circ}$ ) [Asw], Ankle angle at initial supporting surface contact ( $^{\circ}$ ) [Aic], Ankle angle in midstance ( $^{\circ}$ ) [Ast]

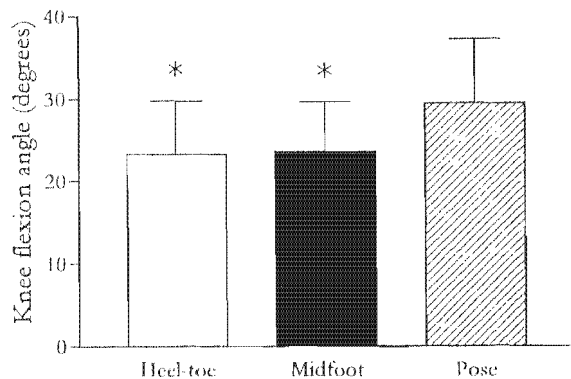


Figure 2. Comparison of the knee flexion angle in terminal swing between heel-toe, midfoot and Pose running

\* Significantly different from Pose running,  $p= 0.000$ , [n= 20]

### 5.5. Joint power and work

The knee eccentric work was less in Pose ( $0.16 \pm 0.08$  J/kg) compared with both heel-toe ( $0.46 \pm 0.15$  J/kg) and midfoot running ( $0.47 \pm 0.16$  J/kg) (work: F-ratio: 67.026,  $p= 0.000$ ) (Figure 10.3). The eccentric work at the ankle in Pose ( $0.44 \pm 0.13$  J/kg) was greater compared with heel-toe ( $0.35 \pm 0.08$  J/kg) and midfoot running ( $0.36 \pm 0.09$  J/kg) (work: F-ratio: 4.737,  $p= 0.015$ ) (Figure 4). The knee power absorption was less in Pose ( $3.70 \pm 1.40$  Watts/kg) compared with both heel-toe ( $7.01 \pm 1.75$  Watts/kg) and midfoot running ( $7.40 \pm 1.93$  Watts/kg) (power: F-ratio: 64.320,  $p= 0.000$ ) (Table 4). The power absorption at the ankle in Pose ( $6.91 \pm 1.93$  Watts/kg) was greater compared with heel-toe ( $5.85 \pm 1.39$  Watts/kg) and midfoot running ( $5.87 \pm 1.40$  Watts/kg) (power: F-ratio: 4.629,  $p= 0.016$ ) (Table 4).

Table 4. Comparison of joint power and work between running styles

	Heel-toe	Midfoot	Pose	F-ratio:	p-value
KPA	$7.01 \pm 1.75$	$7.40 \pm 1.93$	$3.70 \pm 1.40^*$	64.320	$p=0.000$
APA	$5.85 \pm 1.39$	$5.87 \pm 1.40$	$6.91 \pm 1.93^*$	4.629	$p=0.016$
KPG	$6.27 \pm 1.44$	$6.34 \pm 1.55$	$5.01 \pm 2.49^*$	7.089	$p=0.003$
APG	$8.49 \pm 1.54$	$8.57 \pm 1.56$	$8.29 \pm 1.94$	0.405	$p=0.669$
CKW	$0.48 \pm 0.13$	$0.49 \pm 0.13$	$0.30 \pm 0.16^*$	25.198	$p=0.000$
CAW	$0.53 \pm 0.11$	$0.54 \pm 0.11$	$0.50 \pm 0.13$	1.711	$p=0.195$

\* Significantly different from heel-toe and midfoot running [n=20]

Knee power absorption (Watt/kg) [KPA], Ankle power absorption (Watt/kg) [APA], Knee power generation (Watt/kg) [KPG], Ankle power generation (Watt/kg) [APG], Concentric knee work (J/kg) [CKW], Concentric ankle work (J/kg) [CAW]

The knee power generation and concentric work were less in Pose ( $5.01 \pm 2.49$  Watts/kg,  $0.30 \pm 0.16$  J/kg) than either heel-toe ( $6.27 \pm 1.44$  Watts/kg,  $0.48 \pm 0.13$  J/kg) or midfoot running ( $6.34 \pm 1.55$  Watts/kg,  $0.49 \pm 0.13$  J/kg) (power F-ratio: 7.089,  $p= 0.003$ ; work F-ratio: 25.198,  $p= 0.000$ ). There were no differences in ankle power generation and concentric work between the three running styles.

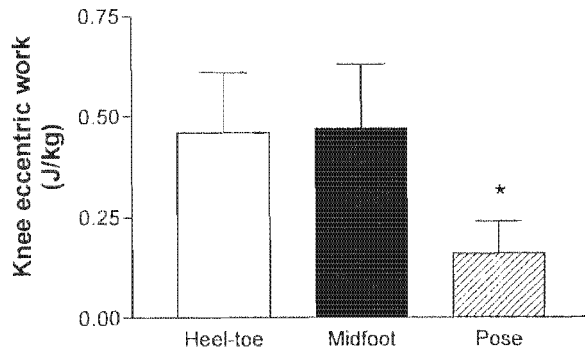


Figure 3. Comparison of the knee eccentric work between heel-toe, midfoot and Pose running  
\* Significantly different from heel-toe and midfoot running [n=20]

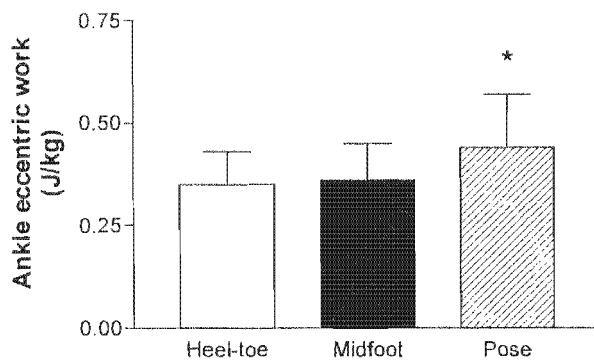


Figure 4. Comparison of the ankle eccentric work between heel-toe, midfoot and Pose running  
\* Significantly different from heel-toe and midfoot running [n=20]

## 6. Discussion

The first relevant finding of this study was that clinical gait analysis was able to identify the gait analysis differences in midfoot and Pose running in natural heel-toe runners. Thus, it was found that Pose running is characterised by shorter stride lengths, lower magnitudes of the vertical impact forces, greater knee flexion in preparation for and at initial contact, and less eccentric work at the knee and more eccentric work at the ankle compared with midfoot and heel-toe running. Previous attempts to modify running style have measured the efforts of changing stride length (Williams et al., 1991) vertical displacement of the body (Petray and Krahenbuhl, 1985), trunk inclination, arm swing and leg mechanics (Messier and Cirillo, 1989). Although each of these studies has demonstrated changes in individual kinematic variables, these changes have been inconsistent, showing the resistance of the naturally chosen running style to change. In contrast, marked changes in running biomechanics have been measured with changes in running speed (Novacheck, 1995), gradient of the supporting surface (Swanson and Caldwell, 2000) and the use of running shoes (de Wit et al., 2000). The results of the present study show that Pose running can produce marked changes in gait analysis variables. Pose running produced significantly smaller vertical displacement of the body, the feet are kept close to the supporting surface and the stride and step lengths are shorter, compared with heel-toe and midfoot running (Table 10.1). Like midfoot running, but in contrast to heel-toe running, Pose running reduced the magnitudes and loading rates of the vertical impact force at peak value (Table 2). However, Pose and midfoot running cause different lower limb geometry during the running stride (Table 3). The horizontal

braking and propulsive forces appeared to be the only components of the ground reaction force that may distinguish between Pose and midfoot running. This suggests that the ground reaction forces may not be the most valuable measurements for evaluating modification of running style and that the other gait analysis variables need also to be considered. A change in knee and ankle geometry with the transition from barefoot to shod running (de Wit et al., 2000), and between running at different speeds on treadmills (Mann and Hagy, 1980; Kivi et al., 2001) and overground (Novacheck, 1995), are well described. The results of the present study indicate the knee is more flexed in preparation for and at initial contact in Pose compared with heel-toe and midfoot running (Table 3). This may be a function of the short stride length characteristic of Pose running (Table 1). Ankle position also distinguished between the three running styles in terminal swing and at initial contact, with the ankle dorsiflexed in heel-toe, plantarflexed in midfoot and neutral in Pose running. Ankle dorsiflexion in heel-toe running appears to be associated with the greater magnitude of the vertical impact force compared with midfoot and Pose running. The difference in ankle angles between Pose and midfoot running does not appear to have any association with any other variable measured. Downhill running has been shown to increase knee eccentric work (Buczek and Cavanagh, 1990). This study shows that knee power absorption and eccentric work were significantly reduced with Pose compared with heel-toe and midfoot running (Figure 3). In contrast, ankle power absorption and eccentric work were increased with Pose compared with heel-toe and midfoot running (Figure 4). This suggests that there is redistribution of the work activity between the knee and ankle joints with different running styles. However, the effects of a different running style on the hip dynamics were not studied. Hip power is of greater importance for forward propulsion during running than during walking (Ounpuu, 1990; Novacheck, 1995). In contrast, the contribution of the knee and ankle power is minimised as running speed increases. The reduction in knee power generation and concentric work with Pose running was not accompanied by a complementary increase in the ankle power generation and concentric work. Presumably this was provided by changes in the hip as a source of power and work for forward propulsion, which was likely increased in Pose running. This would explain the constant ankle dynamics in propulsion in all three running styles. To clarify this relationship, the hip biomechanics should be evaluated in future studies of running style modification. The magnitude of the moment arm at the joint of interest is an important determinant of the magnitude of the mechanical joint work calculated with the inverse dynamics approach is (Vaughan, 1991). The low work values at the knee and high work values at the ankle in Pose running suggest that the magnitude of the moment arm at the knee is least, but is greatest at the ankle. This observation may be due to a combination of the lower limb geometry and the position of the torso in stance. The similarity of knee and ankle work and power between the heel-toe and midfoot running suggests that the different ankle joint positions do not change the moment arms. Positioning of the torso over the supporting limb may influence the direction of the ground reaction force in relation to the lower limb joint centres. The posture of the whole body throughout the gait cycle should be included in future studies to fully understand the reasons for the changes in knee and ankle joint power and work. In this study the runners were evaluated in the barefoot condition, to which they were not habituated. Although standard to all three test conditions, it is possible that the barefoot condition may prevent the adoption a conventional heel-toe running style. Runners protect the heel during barefoot running and reduce distortion of the heel fat pad (de Wit et al., 2000). Subsequently, initial contact occurs predominantly with the anterior portion of the foot. This may explain the similar gait analysis variables between heel-toe and midfoot running in the barefoot condition. The runners in this study naturally employed a heel-toe running style. The duration of instruction in midfoot running was no greater than 15 minutes. In contrast, Pose running was instructed over a total of 7.5 hours. The prolonged time to teach Pose running was devoted mainly to achieving the desired alignment of the trunk and supporting limb in stance. It is unlikely that a longer duration of instruction in midfoot running may have elicited differences in the gait analysis variables between midfoot and heel-toe running. This opinion is based on the results of a study in

which six male and three female heel-toe runners readily changed to midfoot contact with verbal instruction by the investigators with similar instruction time to the present study (Williams et al., 2000). More importantly the gait analysis variables of the natural heel-toe runners with the changed landing technique, were similar to that of natural midfoot runners (Williams et al., 2000). Accordingly, since the kinetics and kinematics of Pose running were different from those of midfoot running, and it appears reasonable to conclude that the gait analysis characteristics of midfoot running were faithfully reproduced in this study and were not an artifact of too- short familiarization period. An increase in walking and running speed is known to significantly increase the magnitude of the ground reaction forces (Vaughan et al., 1987; de Wit et al., 2000). Although the running speed in midfoot running was significantly greater than that of Pose, the ground reaction forces were similar. Kinematic adaptations may produce similar ground reaction forces with different running conditions (Fredrickson, 1986). In this regard, the differences in ankle kinematics between midfoot and Pose running may have minimised any differences in the ground reaction forces between the two, despite a difference in running speed. A limitations imposed upon this study is the absence of a verification of foot-strike pattern. Consequently ensuring that the runners achieved each of the foot-strike movements or patterns is not possible and the limits that depth to which the data may be interpreted.

## **7. Conclusion**

The results of the current study suggest that runners can be taught to run with the novel running style of Pose running which has gait analysis characteristics different to that of midfoot and heel-toe running. Pose running is characterised by a shorter stride length, lower vertical impact forces, 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 midfoot and 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 the heel-toe and midfoot running styles. The position of the torso and the centre of mass should be included in future studies of running style modification.

## **8. Relevance of running style modification to the aim of the thesis**

The clinical or performance consequences of the gait analysis differences between heel-toe, midfoot and Pose running were not evaluated. Nevertheless, the possibility that the reduced knee eccentric work and increased ankle eccentric work in Pose running may be associated with or have a role in the treatment and rehabilitation of different types and frequencies of running injuries should be evaluated in controlled trials. The role of running style modification in the treatment of running injuries is proposed in a hypothetical model in the final chapter of this work (Discussion and conclusion).

## STUDY EIGHT

### The effect of injury on running style gait analysis variables

#### 1. Introduction

The relationship between injury and the gait analysis variables chosen to describe running style is explored in this study. This case-control study is designed with consideration of the findings of the preceding studies of the thesis. The relevant findings of the preceding chapters are that the gait analysis variables selected to describe running style are repeatable (Study One) and that age, running speed (Study Two) and gender (Study Three) are factors that must receive close attention in the comparison of two or more groups of runners. In this study the gait analysis variables descriptive of running style of runners with Anterior Knee Pain Syndrome (AKPS) and injury-free (IF) runners are compared. Running injuries occur in at least two-thirds of all recreational runners that train regularly and participate in long distance races (van Mechelen, 1992). AKPS is among the most common of the running injuries (Taunton et al., 2002) and is associated with abnormalities in the volume and intensity of training (training errors), personal characteristics of the runner (lower limb alignment abnormalities) (Caylor et al., 1993; Neely 1998; Rudzki, 1997; Wen et al., 1998; Witvrouw et al., 2000) and the running environment (unyielding surfaces) (Satterthwaite et al., 1999; Wen et al., 1997; Yeung and Yeung, 2001). The concerned health professional is required to identify and correct all possible aetiologic factors in the treatment of runners diagnosed with AKPS. Abnormal impact forces and movement patterns of the lower limb associated with training errors, lower limb alignment abnormalities and unyielding surfaces are thought to result in the accumulation of sub-threshold stress within the musculoskeletal system, exceed the regenerative capacity of the knee musculotendinous tissues and cause injury (Stannish, 1984, Nigg, 1985, Krivickas, 1997; McPoil, 2000). The prediction of this hypothesis is that impact force and movement patterns are representative of the stress that accumulates within the musculoskeletal structures in which injury manifests in runners. Abnormal impact forces are traditionally associated with musculoskeletal injury largely on the basis of studies from early sub-primate animal impact force models (Simon et al., 1976; Radin et al, 1982). The repetitive nature of long distance running makes it reasonable to assume that runners accumulate a significant amount of sub-threshold impact force. Indeed, unattenuated impact force has been associated with running injuries (James et al., 1978). Consensus has not however been reached on the relationship between excessive impact forces and running injuries. This is reflected in the difference of opinion regarding the association between the impact force variables and common running injuries (Duffey et al., 2000; Hreljac et al., 2000; Messier et al., 1991; 1995). The relationship between lower limb movement patterns and running injuries has its origins in the clinical practice of associating "abnormal" foot morphology with injury (James et al., 1978). Thus, subtle but abnormal movements of the knee and ankle in runners with abnormal foot morphology have been associated with injury. Early study of foot movement with 2D kinematic techniques substantiated the clinical opinion that "abnormal" feet had movements different to that of "normal" feet (Bates et al., 1979). In addition, foot orthoses appeared to correct the abnormal movements (Bates et al., 1979) and produced encouraging clinical results (Gross, 1995). Several studies to duplicate the initial findings with both 2D (Moss et al., 1990; Genova and Gross, 2000; Brown et al., 1995) and 3D techniques, with surface markers (McCulloch et al., 1993; Eng and Pierrynowski, 1994) and markers mounted on intracortical bone pins (Stacoff et al., 2000) were undertaken. The rotatory movements were found to be subtle and vary considerably between runners. In addition, the listed

measurement techniques acknowledged significant limitations which included alignment errors with the 2D techniques (Areblad et al., 1990) and excessive movement of skin markers over the underlying skeletal structures (Stacoff et al., 2000). As a result, it appears that the measurement of abnormal movement of the foot (abnormal subtalar pronation) and the correction thereof (with semi-rigid orthoses) does not contribute to the explanation of how common running injuries occur or the reported recovery from injury. While substantial scientific effort has been devoted to studying the relationship of subtle lower limb movements with injury, the same is not true for the gross sagittal plane movements of the lower limb, this despite the ease of measurement and low sensitivity of sagittal plane joint movement to the technical limitations described above (Vaughan et al., 1999). The study of sagittal plane knee and ankle joint angles has been conducted with regard to the effect of athletic performance (Cavanagh et al., 1977), running speed (Novacheck, 1995), treadmill surfaces (Wank et al., 1998) and running surface inclination (Smith, 1980; Buczek and Cavanagh, 1990). However, the sagittal plane joint movement is perhaps most relevant to running injuries as a result of its contribution to the estimation of joint mechanical work and power during walking and running activities (Vaughan, 1996). The integration of ground reaction forces and lower limb movement patterns by the mathematical process of inverse dynamics has allowed the estimation of mechanical work and power at a joint by the computation of joint torque (Williams et al., 2003), power (Stefanyshyn and Nigg, 2000) and work (Winter, 1983). In stance, negative mechanical joint work is performed by the musculotendinous structures that cross the knee and control flexion of the knee. The negative mechanical joint work is considered representative of eccentric work at a joint (Buczek and Cavanagh, 1990). The term "eccentric work" is borrowed from the muscle activity described to occur when there is lengthening of the muscle opposite to the direction of the force the muscle generates (Albert, 1991). The estimated eccentric joint work is representative of the net activity of the muscles and other musculoskeletal structures at the affected joint. Similarly, positive mechanical work is synonymous with concentric joint work, with similar assumptions. In a related application, excessive eccentric work (negative mechanical work) is associated with medial epicondylopathy in tennis players (Wu et al., 2001). To date, the relationship between eccentric work and injury in runners, particularly knee eccentric work and AKPS, is unknown. The aim of this case-control study is therefore to compare the impact forces, lower limb movement patterns and eccentric joint work as determined with standard clinical gait analysis methods, between runners diagnosed with Anterior Knee Pain Syndrome and injury-free runners.

## 2. Methods

### 2.1. Subjects

Seventeen (17) recreational runners that fulfilled the diagnostic criteria for Anterior Knee Pain Syndrome (AKPS) of the right lower limb were recruited from the sports medicine and physiotherapy practices at the Sports Science Institute of South Africa (SSISA), Cape Town, South Africa. The AKPS runners were compared with forty-three (43) injury-free (IF) runners matched for age, gender and self-selected running speed as defined previously (Table 6.1). IF runners were recruited at a well-runner clinic at SSISA. All of the AKPS runners were asymptomatic at the time of the assessment and complied with the relevant inclusion and exclusion criteria for the study (Table 6.2).

Table 1. Comparison of the demographic variables between injured and injury-free runners.

	<b>Injured (n=17)</b>	<b>Uninjured (n=43)</b>
Age (years)	31.9± 6.1	33.4± 11.8
Height (m)	1.74± 0.08	1.73± 0.09
Mass (kg)	73.3± 11.7	71.4± 13.2
Speed (m/s)	2.89± 0.37	2.96± 0.40

## 2.2. Informed consent

All runners signed an informed consent prior to their participation in the study. Ethical approval for the study was obtained from the Research Ethics Committee of the Faculty of Health Sciences of the University of Cape Town.

## 2.3. Clinical assessment

As the runners were asymptomatic at the time of assessment, the appropriate clinical records were reviewed to ensure that the diagnostic criteria were fulfilled.

The diagnostic criteria for Anterior Knee Pain Syndrome were as follows:

- The pain is localised to the peri-patellar tissues of the knee and infero-medial border of the patellar (Krivickas, 1997).
- The pain is not associated with a current or previous traumatic episode (Duffey et al., 2000).
- The pain is worse after either a physically demanding run, running downhill, walking up or down stairs, sitting with the knee flexed for a long time (Thomee et al., 2002).
- Other knee pathology is excluded on clinical examination.

## 2.4. Test procedure

The runners followed the standard testing procedure described in Study One. A lower limb evaluation (foot-type) and anthropometric measurements were undertaken (Study One). The runners completed a 1000m warm-up run and a series of ten (10) barefoot running trials in the gait analysis laboratory at self-selected running speeds (Study One). Gait analysis data were collected, and five trials per runner were selected for processing and analysis (Study One).

## 3. Main outcome variables

The gait analysis variables compared between the AKPS and injury-free groups were:

1. Ground reaction forces: loading rate (BW/s) and magnitude (BW) of the vertical impact force at peak value, the magnitude of the propulsive force in the vertical (BW) and horizontal (BW) planes and the horizontal braking force (BW);
2. Joint angles: during mid-swing ( $^{\circ}$ ), terminal swing ( $^{\circ}$ ), initial supporting surface contact ( $^{\circ}$ ) and midstance ( $^{\circ}$ );
3. Joint power and work: the magnitude of the knee and ankle power (Watts) and work (J) during working and propulsive phases of stance.

Table 2. Inclusion and exclusion criteria for the injured and injury-free runners

<b>Injured runners</b>	<b>Injury-free runners</b>
<p><b>Inclusion criteria</b></p> <ul style="list-style-type: none"> <li>• At least 18 years of age at the time of assessment.</li> <li>• Must have participated regularly in recreational running or jogging activity for at least one year prior to participation in the study.</li> <li>• Running injury sustained must have been of a sufficient severity to preclude regular running activity for at least one week at the time of injury.</li> <li>• At least one running injury must be localised to the right lower limb.</li> <li>• Running injury must be asymptomatic at the time of assessment, so that running activity at a self-selected training pace for at least 1000m is pain-free.</li> <li>• Diagnostic criteria for the running injury must be fulfilled.</li> </ul> <p><b>Exclusion criteria</b></p> <ul style="list-style-type: none"> <li>• Persistent pain associated with the running injury.</li> <li>• Uncertain of the diagnosis of the running injury.</li> <li>• Surgical intervention that has been instituted for the injury.</li> <li>• Accompanying neurological or orthopaedic abnormality that may interfere with the normal running style.</li> </ul>	<p><b>Inclusion criteria</b></p> <ul style="list-style-type: none"> <li>• At least 18 years of age at the time of assessment.</li> <li>• Runners should regularly participate in recreational running or jogging activities for a period not less than one-year.</li> <li>• No history of running injuries in the year prior to the assessment.</li> <li>• Freedom from neurological disease or orthopaedic deformity that may interfere with the normal running style.</li> </ul> <p><b>Exclusion criteria</b></p> <ul style="list-style-type: none"> <li>• The runner will be excluded from the study if any of the inclusion criteria are not met.</li> </ul>

#### 4. Statistical analysis

Statistical analysis of the gait analysis variables was completed with a statistical program (StatSoft, Inc. (2000). STATISTICA for Windows [Computer program manual] Tulsa, OK, USA). The running speed, ground reaction forces, and knee and ankle joint angles and load (work) and power were compared with an independent t-test between the AKPS and IF groups. A statistical significance level was accepted when  $p < 0.05$ .

## 5. Results

### 5.1. History

None of the runners in both the AKPS and injury-free groups reported a past medical or surgical history that interfered with the normal gait pattern. All runners regularly participated in running for at least one year with a minimum weekly training distance of 15 km and were habituated to running in shoes. There were equivalent percentages of pronated, neutral and supinated foot-types of the runners between the injury-free (IF) and AKPS groups.

### 5.2. Running speed

The running speeds were similar between AKPS ( $2.89 \pm 0.27$  m/s) and IF ( $2.96 \pm 0.40$  m/s [ $p=0.276$ ]).

### 5.3. Ground reaction forces

The loading rate of the vertical impact force at the peak magnitude (VLR) was greater in IF (VLR:  $44.5 \pm 9.5$  BW/s) than AKPS (VLR:  $38.1 \pm 7.3$  BW/s [ $p=0.020$ ]) (Figure 1). The horizontal propulsive force was greater in IF ( $0.18 \pm 0.04$  BW) than AKPS ( $0.15 \pm 0.03$  BW [ $p=0.025$ ]) (Table 3). No other GRF differences were apparent.

Table 3. Comparison of the ground reaction forces between Anterior Knee Pain Syndrome and injury-free runners

	AKPS runners (n= 17)	IF runners (n=43)	p-values
HBf	$0.23 \pm 0.06$	$0.21 \pm 0.05$	$p=0.384$
HPf	$0.15 \pm 0.03$	$0.18 \pm 0.04$	$p=0.025^*$
VIf	$1.21 \pm 0.14$	$1.23 \pm 0.21$	$p=0.643$
VPf	$2.25 \pm 0.20$	$2.24 \pm 0.22$	$p=0.721$

\* Significant difference between Anterior Knee Pain Syndrome (AKPS) and injury-free (IF) runners  
 HBf: Horizontal braking force [BW], HPf: Horizontal propulsive force [BW], VIf: Vertical impact force peak [BW], VPf: Vertical propulsive force peak [BW]

### 5.4. Joint angles

There were no differences in the knee and ankle joint angles between AKPS and IF runners

Table 4. Comparison of joint angles of the Anterior Knee Pain Syndrome and injury-free runners

	AKPS runners (n= 17)	IF runners (n=43)	p-values
KswF	$85.2 \pm 2.7$	$84.6 \pm 3.3$	$p=0.232$
KswE	$19.4 \pm 6.1$	$18.6 \pm 5.0$	$p=0.640$
Kic	$24.5 \pm 5.1$	$22.5 \pm 4.2$	$p=0.478$
Kst	$45.2 \pm 5.3$	$44.8 \pm 2.9$	$p=0.592$
Asw	$10.4 \pm 4.3$	$12.7 \pm 4.7$	$p=0.321$
Aic	$9.2 \pm 4.1$	$11.5 \pm 4.1$	$p=0.228$
Ast	$24.1 \pm 3.3$	$24.9 \pm 3.2$	$p=0.804$

Knee swing phase peak flexion angle ( $^{\circ}$ ) [KswF], Knee angle in terminal swing phase ( $^{\circ}$ ) [KswE], Knee angle at initial supporting surface contact ( $^{\circ}$ ) [Kic], Knee angle in midstance ( $^{\circ}$ ) [Kst], Ankle angle in terminal swing phase ( $^{\circ}$ ) [Asw], Ankle angle at initial supporting surface contact ( $^{\circ}$ ) [Aic], Ankle angle in midstance ( $^{\circ}$ ) [Ast] No difference between Anterior Knee Pain Syndrome (AKPS) and injury-free (IF) joint angles

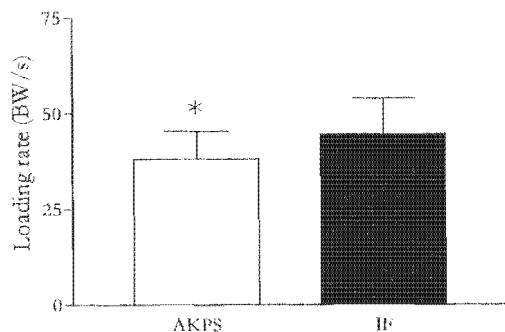


Figure 1. Comparison of loading rate of the vertical impact force between injury-free and Anterior Knee Pain Syndrome runners \* Significant difference between injury-free (IF) and Anterior Knee Pain Syndrome (AKPS) runners,  $p=0.020$

### 5.5. Joint power and work

The eccentric knee work and power absorption were greater in AKPS (EKW:  $0.49 \pm 0.12$  J/kg; KPA:  $7.74 \pm 1.78$  Watts/kg) than IF (EKW:  $0.40 \pm 0.16$  J/kg [ $p=0.022$ ] (Figure 6.2); KPA:  $6.34 \pm 2.06$  Watts/kg [ $p=0.010$ ] (Table 6.5)). There were no other differences in the joint power and work variables between AKPS and IF runners.

Table 5. Comparison of joint power and work between Anterior Knee Pain Syndrome and injury-free runners

	AKPS runners (n= 17)	IF runners (n=43)	p-values
KPA	$7.74 \pm 1.78$	$6.34 \pm 2.06$	$P=0.010^*$
KPG	$5.80 \pm 1.41$	$5.82 \pm 1.75$	$P=0.968$
APA	$6.25 \pm 1.87$	$6.17 \pm 1.90$	$P=0.420$
APG	$7.83 \pm 2.31$	$7.40 \pm 1.51$	$P=0.273$
CKW	$0.38 \pm 0.08$	$0.38 \pm 0.13$	$P=0.922$
EAW	$0.49 \pm 0.17$	$0.49 \pm 0.13$	$P=0.781$
CAW	$0.53 \pm 0.15$	$0.48 \pm 0.10$	$P=0.150$

\* Significant difference between Anterior Knee Pain Syndrome (AKPS) and injury-free (IF) runners  
 Knee power absorption (Watt/kg) [KPA], Knee power generation (Watt/kg) [KPG], Ankle power absorption (Watt/kg) [APA], Ankle power generation (Watt/kg) [APG], Concentric knee work (J/kg) [CKW], Eccentric ankle work (J/kg) [EAW], Concentric ankle work (J/kg) [CAW]

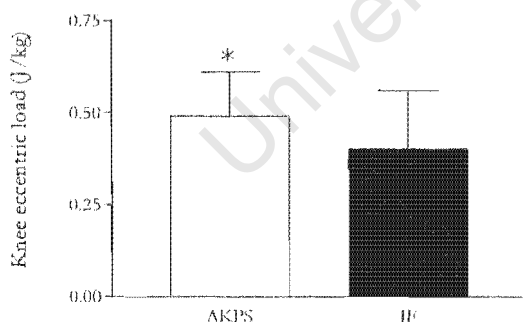


Figure 2. Comparison of the knee eccentric work between Anterior Knee Pain Syndrome and injury-free runners \* Significant difference between Anterior Knee Pain Syndrome (AKPS) and injury-free (IF) runners,  $p=0.022$

## 6. Discussion

The main findings of the study were that the rate of force application against the supporting surface (vertical loading rate) was decreased and the work undertaken by the musculotendinous structures at the knee (eccentric work) was greater in the runners diagnosed with Anterior Knee Pain Syndrome (AKPS) compared with the injury-free (IF) runners despite similar lower limb movement patterns (joint angles). At least two hypotheses may be formulated from the results of this study. One hypothesis is that the characteristics observed are a true representation of the gait analysis variables descriptive of the running style of runners diagnosed with AKPS and that a low loading rate and a high eccentric work represents the stress generated within the structures that support the knee in stance. The assumption that the medial and lateral retinaculae assist in the support of the knee in stance may contribute to the association of knee eccentric work with injury of these structures and the clinical presentation of the AKPS as is suggested in the literature (Krivickas, 1997). This hypothesis is strengthened by the recruitment of pain-free injured runners so that the running style observed is true to those characteristics that may be associated with injury. An alternative hypothesis is that the observed low loading rate and a high eccentric work are an adaptation to the injury, in which the vertical impact force loading rate is reduced in the expectation of protection from further injury. Support for this hypothesis emerges from the observation that injury-runners adopt a "protective" running style that is characterized by lower impact forces in a "high impact" running conditions as occurs with barefoot running (de Wit et al., 2000) and running in shoes with a hard midsole (Hennig et al., 1996). Currently the eccentric knee load change of the injury-free runner to a "high impact" running condition is not known. However, it appears plausible that a high eccentric load generation within the structures that support the knee may be protective response to recent injury as is evident from the results of this study. The report of a role of controlled progressive eccentric work exercises in the rehabilitation of Achilles' Tendonosis (Alfredson et al., 1998) supports the hypothesis that a running style characterized by high eccentric work at the injured joint is beneficial. Studies with designs appropriate to determining a cause-effect relationship between a low loading rate of the impact force and a high eccentric work at the knee with Anterior Knee Pain Syndrome are encouraged. Prospective and clinical trials that take cognizance of the multifactorial aetiology of running injuries (Satterthwaite et al., 1999; Wen et al., 1997; Yeung and Yeung, 2001) and in which the other known aetiological factors for these injuries are controlled, are recommended. The difference in impact forces and knee eccentric work between AKPS and IF runners, despite similar lower limb movement patterns, is surprising. However, the whole body centre of mass and moment arm at the knee, which were not specifically measured in this study, are gait analysis variables that may assist in an explanation of this unexpected observation (Figure 2.3.6; Literature Review). The whole body centre of mass represents a point about which the mass of the entire body is evenly distributed. In this regard, the resultant ground reaction force represents the acceleration of the whole body centre of mass. The direction of the ground reaction force and its path past the involved lower limb joints is therefore determined by the whole body centre of mass position with respect to the centre of application of the body to the supporting surface (Lake, 2000). The orientation of the trunk and upper limbs may have a role in determining the position of the whole body centre of mass and hence the path of the ground reaction force within the supporting limb(s). The perpendicular distance between the centre of a joint and the resultant ground reaction force is termed the moment arm at the same joint. Furthermore, the magnitude of the moment arm at the knee is essential to estimating eccentric work (Vaughan, 1996). Therefore, in a situation in which the lower limb geometry is similar between AKPS and IF runners, the orientation of the trunk and upper limbs may cause a difference in the magnitude of the moment arms at the knee between the two groups. Consequently, the orientation of the trunk and upper limbs may have a role in determining the magnitude of the eccentric work estimated at the knee independently of the knee geometry. Whole body centre of mass and trunk kinematic data are not presented in this analysis and consequently,

these hypotheses were not examined. Future investigations of the relationship between injury and running style gait analysis variables should include whole body centre of mass and trunk kinematic data. A model that integrates whole body repositioning in response to or as a cause of injury, thereby causing greater eccentric loading of the structures that support the knee and a reduction in impact force application to the runner, would require central nervous control, the sensory stimulus as yet unknown. However, it is hoped the results of this study will encourage research to complete the puzzle of the aetiology of running injuries. All runners were studied in the barefoot condition. The runners were however not habitual barefoot runners. Therefore the runners were familiarised with barefoot running prior to testing, to minimise the effect of the barefoot condition described previously (de Wit et al., 2000). It would be more realistic and true to the racing and training conditions to which the runners are accustomed, to test them under shod conditions. The mechanical power in this study was determined with a three-degrees of freedom joint model (Vaughan et al., 1999). Technical limitations of the comparison between the injured and injury-free groups may be due to the choice of the three degrees of freedom joint model, which may over- or underestimate power by as much as 40%, compared with a six-degrees of freedom joint model (Duncan et al., 1997). Future studies in this regard should use a mechanical joint model that may give a more precise estimation of the mechanical power and work at the lower limb joints.

## 7. Conclusion

In conclusion, the ground reaction forces and work and power at the knee joint required to effect a similar lower limb movement pattern in runners with Anterior Knee Pain Syndrome and injury-free runners are different. A high eccentric knee work and low rate of application of impact force is required to effect the observed movement patterns in runners with anterior knee pain. Future studies of running injury aetiology should include gait analysis variables such as joint work and power as these novel gait analysis descriptors of the stress within commonly injured structures may give insight to the aetiology of common running injuries.

## 8. Relevance of the effect of injury on running style descriptive gait analysis

The results of the present study demonstrate an association between injury and the gait analysis variables that describe running style. As discussed above, the design of the study precludes the formulation of a cause-effect relationship between the injury and the concerned gait analysis variables. However, the results of this study encourage the design and implementation of future studies for the exploration of a cause-effect relationship between injury and the gait analysis variables descriptive of running style. The preliminary results of a heterogeneous group of running injuries that in addition to AKPS, include Ilio-Tibial Band Friction Syndrome, Medial Tibial Stress Syndrome and Achilles' Tendinosis are compared with injury-free runners with methodology similar to that of the present study are presented in Appendix 1. This represents the effort that is being made to expand the investigation of the relationship between the various common running injuries and the gait analysis variables descriptive of running style. The current study is conducted on the recommendations of the preceding studies that suggest the chosen gait analysis variables are repeatable (Study One) and that the age, running speed (Study Two) and gender (Study Three) should receive attention to reduce bias. The effects of traditional (Studies Four, Five and Six) and novel (Study Seven) intervention methods on the gait analysis variables descriptive of running style are studied in the later portions of this work. A working model that proposes a central nervous system role in determining the position of the whole body centre of mass and hence the estimated mechanical joint work at the concerned lower limb joints, and relevant injury management guidelines are presented in the final portion of this work (Discussion and Conclusion).

## Discussion and Conclusion

Running injuries are of concern to health professions as they occur in almost two-thirds of all recreational runners annually (van Mechelen, 1992). The multifactorial aetiology of running injuries is relevant in this regard, as this makes running injuries extremely difficult to treat. The health professional is charged with identifying and correcting all possible implicated factors in the treatment of injured runners. In this regard, it is important for the health professional to be aware of the relationship between running style and injury and have guidelines as to how to address aspects of running style that may have an association with injury.

### **Aims and objectives of the series of studies**

The first aim of this thesis was to determine the relationship between gait analysis variables descriptive of running style and common running injuries with a view to establishing the merit of running style analysis in the evaluation and treatment of running injuries. The second aim was to determine the effect of commonly prescribed clinical interventions such as running shoes, semi-rigid orthoses and soft orthoses on the running style gait analysis variables found to be associated with running injuries. The third aim was to determine the effect of changing running style through a systematic method of running style modification on the gait analysis variables descriptive of running style, and particularly those associated with injury. To explore these aims, fundamental work with regard the gait analysis variables descriptive of running style was completed initially. In this regard, an acceptable test-retest repeatability of the selected gait analysis variables was determined. In addition, the relationships between the gait analysis variables descriptive of running style and age, gender, foot-type and self-selected running speed were determined and the need for control of the latter variables in all relevant studies to be controlled. The objectives undertaken to achieve the aims of the thesis are described below with regard to the research milestones achieved.

### **Research milestones**

#### **1. Repeatability of the gait analysis variables to describe running style**

The swing and stance phase gait analysis variables based on those described in the literature were selected and determined to be statistically repeatable in a test-retest design study of 17 recreational runners at self-selected running speeds. The strength of the gait analysis correlation coefficients was related to the consistency of the self-selected running speed in the test-retest design.

#### **2. Effect of foot-type, age and running speed on running style**

A more extended knee position in stance was associated with greater self-selected running speed. This was accompanied by a reduction in the knee eccentric work required to support the runner in stance with greater self-selected running speed. The power at the knee and ankle required to propel the runner increased with running speed. Older runners minimised the power absorption and generation at the knee and ankle compared with younger runners. Foot-type did not have an association with the gait analysis variables descriptive of running style. Age and running speed were factors that were considered in the selection of runners in all subsequent studies.

### **3. Effect of gender on running style**

Male runners flexed the knee significantly more during the approach to, and at initial contact with the supporting surface, than female runners. The consequent vertical impact force was greater on the male than on the female runners. The knee and ankle mechanical joint work required to support and propel the runners during stance phase were similar between the sexes. Gender was therefore controlled in all subsequent studies.

### **4. Effect of running shoes on running style**

The use of running shoes lead to changes in running style that included extending the knee and dorsiflexing the ankle in terminal swing and at initial contact compared with the barefoot condition. The loading rate of the impact force was reduced with the introduction of running shoes over the barefoot condition. The change in running style with the use of running shoes included an increase of the peak knee power absorption and eccentric work. Greater perceived impact was reported in the barefoot than shod condition.

### **5. Effect of soft orthoses on running style**

Soft orthoses, irrespective of the objective hardness, did not have an effect on any of the gait analysis variables descriptive of running style. The runners appeared able to perceive the “impact hardness” of the soft orthoses by rating them similar to the objective hardness score.

### **6. Effect of semi-rigid orthoses on running style**

The loading rate of the impact forces and ankle joint eccentric work were reduced with the use of semi-rigid orthoses. However, no change in the lower limb geometry, knee eccentric work or perception of impact rating was found with the use of semi-rigid orthoses.

### **7. Effect of learning a novel style of running**

A novel running style characterised by the alignment of the vertical axis of the trunk with the midfoot at contact with the supporting surface caused a reduction in knee and an increase in ankle eccentric work compared with heel-toe and midfoot running styles. Heel-toe running was associated with the greatest magnitudes and loading rates of the vertical impact force. A flexed knee and neutral ankle distinguished the novel running style from the dorsiflexed and plantarflexed ankles in heel-toe and midfoot running, respectively in terminal swing.

### **8. Relationship between running style and injuries**

Anterior Knee Pain Syndrome was associated with greater negative knee mechanical joint work (also known as eccentric joint work) and lower working rates of the vertical impact forces in the support phase of stance. The movement pattern of the lower limb was similar between injured and injury-free runners.

### **Practical application of gait analysis to running injuries**

A proposal of how running style evaluation with clinical gait analysis may be practically integrated with the holistic and multidisciplinary management of the injured runner is presented in the final section of this chapter.

### **Limitations of the series of studies**

In order to interpret the findings of this series of studies objectively and arrive at informed opinions, it is prudent to review the limitations of the studies undertaken in this thesis. The limitations are presented in two categories: those that are general in nature and may be applied to all the studies in this thesis; and those that have specific reference to individual studies.

#### **1.1. General limitations relevant to all studies of this work**

The general limitations of all the studies may be attributed either to the collection of the unprocessed gait analysis data or the manner in which the data is processed. The runners were analysed in a laboratory setting under strongly controlled conditions that may not necessarily have allowed the runners to achieve a running style fully representative of that achieved during regular running activity. The length of the runway used to collect the data is perhaps the most significant limitation in this regard. The runway was eleven metres in length with the force platform mounted approximately midway. The run-up to the force platform requires that the runner accelerate to the desired self-selected running speed and achieve a natural running style. It is likely that this may not have been entirely achieved by all the runners recruited for the studies. The difference between the runners in being able to achieve a natural running style at the self-selected speed desired within the short run-up to the force platform, may be a confounding factor in interpretation of the data. All runners were however given ample opportunity to become familiar with the test procedure and practise the initiation and acceleration of the run to the self-selected running speed prior to collection of the data. These precautions may have limited the significance of the short runway as being a confounding factor in analysis of running style. All gait analysis data were collected with a conventional motion analysis system which required that visual information provided by retroreflective markers attached to the runner be recorded. The markers used were light-weight reflective spheres attached directly or by wands to the skin. The point of attachment represents predefined skeletal structures that are used to estimate the anatomical joint centres and movement of the anatomical segments about these. Excessive skin movement and excessive vibrations from markers mounted on wands are known to cause errors in the estimation of the movement of the anatomical segments (Stacoff et al., 1992). This may be exacerbated by the running activity in which more skin movement over the underlying skeleton occurs. Consequently the very nature of the data collection process may contribute to errors in the data analysis. The mathematical models used to estimate the position of the joint centres are complex and a detailed discussion is beyond the scope of this thesis. Suffice to say that the hip joint centre is determined from the position of the retroreflective markers on the pelvis. Based on the position of the hip joint centre, the knee and ankle joint centres are determined. Excessive pelvic subcutaneous adipose tissue may displace the retroreflective markers from the desired position and thereby lead to errors in the estimation of the hip joint centre and subsequently that of the knee and ankle. With this concern acknowledged, specific attention was devoted to the accuracy of positioning of the retroreflective markers. The amount of subcutaneous adipose tissue was not controlled and is acknowledged as a limitation. The significant repeatability values for all kinetic and kinematic variables studied are testament to the efforts taken to ensure accuracy of marker placement. The negative mechanical joint work estimated in stance is the amount of work the structures crossing the concerned joint would have to perform to prevent the limb from folding into a completely flexed position. To assist with clinical interpretation, this mechanical value is termed eccentric work. The eccentric joint work estimated is the nett work at the concerned joint and by the use of the term "nett" implies that other work activity in the structures

## Discussion and conclusion

crossing the joint occurs. This work may be concentric, isometric and eccentric. There is currently no known way to distinguish between eccentric, concentric or “isometric” activity of muscle, tendon and ligament structures at the concerned joint. However, it is assumed that the nett eccentric joint work reflects the work activity within the main supporting structures at the concerned joint. The value of eccentric joint work determined by this method of gait analysis warrants further study especially in regard its value to the aetiology of, and treatment and prevention of running injuries.

### 1.2. Limitations relevant to specific studies of this work

The order of the limitations of the methods recognised to have reference to individual studies are random with no importance implied by the order. The absence of a fatigue component in the comparison of two or more runner populations requires comment. These comments may be relevant to both the gender and injury association studies. However, they are discussed specifically with regard the association between running style and injury. The eccentric joint work and impact forces were different between injured and injury-free runners. Fatigue is associated with a change in running style, specifically shortening of the stride and step length, and an increase in cadence. The suggestion that fatigue may have a role in the aetiology of injury is acknowledged. A relevant fatigue component in the running style-injury association study may have contributed to more profound differences in the measured gait analysis variables between the injured and injury-free groups. A fatigue component was not introduced in this specific study as difficulty was experienced in pilot work with inducing a fatigue component in the runners and then preparing the runners for data collection. The delay caused by the preparation of the runners for running style analysis allowed the runners to recover from the fatigued condition. The potential for greater information to be gained from the introduction of a relevant fatigue component in two or more runner populations is acknowledged and future work in this area is recommended. Similarly the effect of omission of hip, trunk and centre of mass data from the analysis is relevant to the interpretation of all the studies undertaken in this thesis. The absence of this data has specific reference to the injured: injury-free, barefoot-shod and heel-toe, midfoot and Pose method running style comparisons. The gait analysis data included in these studies did not include hip joint kinetics and kinematics. The exclusion of hip gait analysis data was necessitated by time constraints imposed by the lengthy manual process of calculating the knee and ankle gait analysis data. It is likely that the hip gait analysis data may be significant with regard understanding the presented knee and ankle data particularly in these three studies. Anterior Knee Pain Syndrome is described to be associated with high knee eccentric work (Chapter Six). In contrast, Ilio-Tibial Band Friction Syndrome is not. The attachment of the Ilio-Tibial Band proximal to the hip makes a study of hip dynamics in this regard appear relevant. The hip gait analysis is anticipated to be presented in a separate work. Data related to the trunk kinematics and the dynamics of the centre of mass, may be important in the interpretation of the knee and ankle data and understanding the association of knee and ankle eccentric work to injury, the use of running shoes and Pose method running style. With regards injury, the eccentric work was higher despite similar lower limb kinematics. This observation infers that a change in the moment arm at the knee may have lead to the greater eccentric work estimated. The trunk position or the whole body centre of mass determine the direction of the ground reaction force and may thereby have a role in the change of the moment arm. Similarly the association of knee and ankle eccentric work with running shoes and adoption of a novel running style may be related to a change in trunk and whole body centre of mass position. This is suggested in view of the similarity of lower limb geometry between the test conditions in these two studies. Unfortunately the modified Helen-Hayes marker set selected to collect running style gait analysis data did not extend above the

pelvic brim. Consequently, trunk kinematics and whole body dynamics required for estimation of centre of mass positioning is not available for analysis. Trunk and centre of mass data should be included in future analysis of running style.

### Working hypothesis

Running injuries occur when stress accumulates within susceptible musculoskeletal structures of the lower limb to exceed a critical threshold (Figure 1.1). Training errors such as running “too far, too quickly, too soon” accelerate the accumulation of stress to exceed the critical threshold for injury (Messier et al., 1991). Personal characteristics of the runner and the environmental conditions in which the running activity is conducted, may determine the threshold that requires stress accumulation to breach for injury to occur (Messier et al., 1991). Severe personal characteristics or environmental conditions are associated with a lower threshold for injury. In addition to the factors traditionally associated with injury, the results of this series of studies suggest that running style may be an associated factor and a working hypothesis based on a synthesis of the main findings of the series of studies in this work is described below and referred to in the accompanying diagram (Figure 11.1). The results of the series of studies in this thesis suggest that (A) running style is one of many factors that are associated with running injuries. The other factors associated with running injuries may be grouped as (B) training errors, (C) personal characteristics of the runner and (D) factors in the running environment. All associated factors should be evaluated and addressed in the management of the injured runner. Running style is associated with injury by virtue of the report that injured runners have a greater knee eccentric work than injury-free runners (a). The similarity of lower limb geometry of the injured and injury-free runners, lead to the suggestion that the greater knee eccentric work in injured runners, may be due to the posture of the trunk, head and upper limbs (Study Eight). The total body posture determines the position of the whole body centre of mass (Lake, 2000) and the centre of mass may therefore determine the path of the ground reaction force past the lower limb joint centres (Figure 2.3.6). The distance between the ground reaction force and the joint centres is termed the force lever arm and is an important variable in the estimation of the joint work (Vaughan, 1996). The eccentric joint work of the runner in the shod state (with running shoes) may be altered by at least three mechanisms described in this work. The three mechanisms may be divided into two groups: (1) modification of the interaction of the runner with the supporting surface and (2) modification of the running style. The interaction of the shod runner with the supporting surface may be modified with the use of semi-rigid orthoses (1.1). Semi-rigid orthoses place the ankle into a plantarflexed position within the running shoe (McCulloch et al., 1993) and may therefore change the position of the ankle joint centre with regard to the path of the ground reaction force. The change in the ankle joint centre position may lead to a change in the magnitude of the concerned lever arm and hence the eccentric work estimated (Study Six). Semi-rigid orthoses do not have an effect on the knee eccentric load, where an association between eccentric load and injury is reported. Running style modification may be beneficial in this regard. The running style of the runner may be modified by the introduction of the (2.1) barefoot state or by learning the (2.2) Pose method of running. Runners are reported to alter their running style in response to the barefoot condition (de Wit et al., 2000) in what appears to be an “instinctive” Central Nervous System mediated response to the runners’ perception of the “impact hardness” of the running condition (Milani et al., 1997).

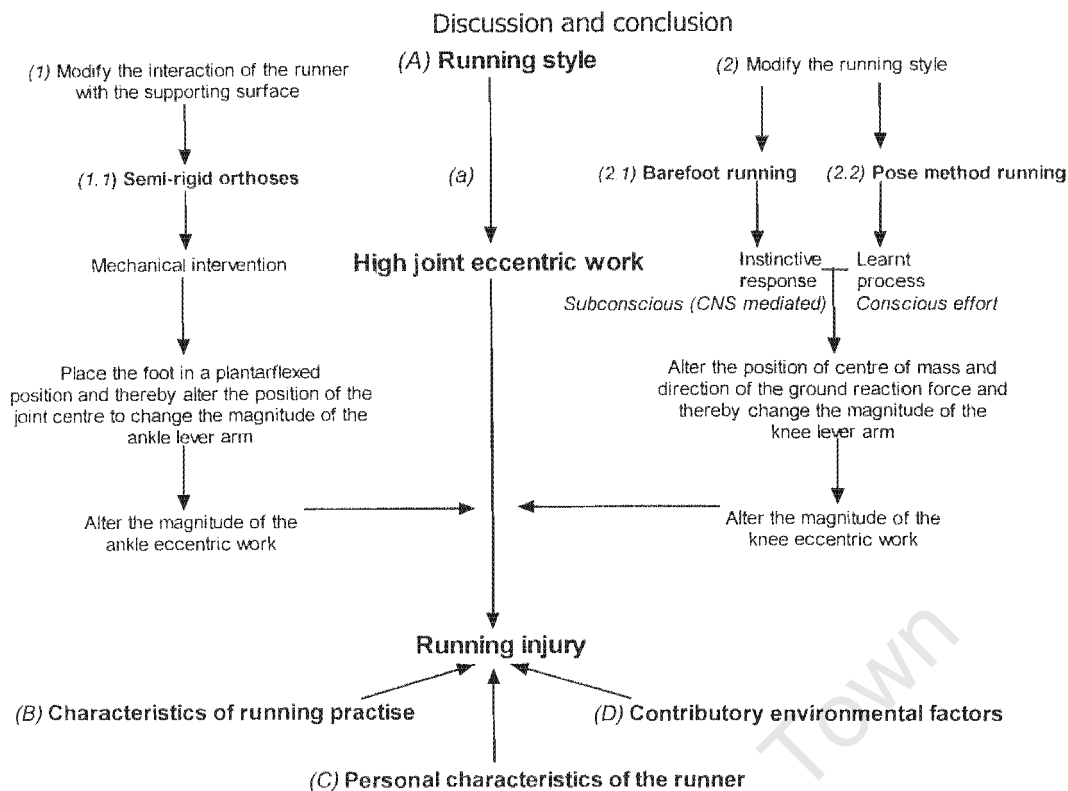


Figure 11.1. Working hypothesis of the relationship between running style and injuries (refer to text for detailed explanation)

Barefoot running in this work is associated with a lower knee eccentric work and the reduction is proposed to be due to a change in the total body posture with a reduction of the lever arm at the knee (Study Four). Barefoot running is therefore a potential intervention method for the management of running injuries. Pose method running involves active learning of a specific posture of the whole body while running (2.2). A conscious effort appears necessary to maintain the running style and therefore differs from the running style changes that occur with barefoot running. One of the consequences of maintaining the unique posture of Pose method running is that the knee eccentric work is reduced (Study Seven). A similar rationale that includes a change in the whole body centre of mass position and the path of the ground reaction force past the lower limb joint appears relevant to the lower knee eccentric load estimated. In summary, in addition to the characteristics of the running practice, personal characteristics of the runner and relevant environmental concerns, the running style is important in the evaluation of the injured runner. The variables that associate running style with injury may be addressed by modifying the interaction of the runner with the supporting surface or modifying the running style. Semi-rigid orthoses may reduce the eccentric load at the ankle by repositioning the ankle within the shoe. Barefoot running may reduce the knee eccentric load by an “instinctive” centrally mediated response while Pose method running requires the conscious application of a “learned” method of running to achieve the same.

## Conclusion

Management of the injured runner demands identification and correction of the multiple factors commonly associated with injury. Management of running injuries requires that all implicated factors be identified and corrected. Clinical gait analysis in this work was applied to the evaluation of the gait analysis variables descriptive of running style with regard injury, and traditional and novel clinical interventions. The test-retest repeatability of the running style gait analysis variables selected was comparable with the literature. Age, gender and self-selected running speed were important in the comparison of two or more groups of runners. Injured runners had greater knee eccentric works than injury-free matched controls. Running shoe use compared with barefoot running was associated with an increase in knee eccentric work. Semi-rigid orthoses reduced the eccentric work at the ankle but not the knee. Modification of running style from heel-toe to midfoot, and repositioning the trunk over the supporting foot was associated with reductions in impact force and eccentric work at the knee. Clinical gait analysis may be used in the dynamic evaluation of the injured runner, and to determine the effects of selected clinical intervention methods that include shoe and semi-rigid orthoses prescription, and running style modification. A working model of the association between the gait analysis variables descriptive of running style and injury is proposed. A multidisciplinary team management plan with the aid of clinical gait analysis is described.

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### Clinical application of gait analysis to running injuries

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## APPENDIX ONE

### Comparison of the gait analysis variables of a heterogeneous group of injured runners with injury-free runners

#### A.1.1. Purpose

The aims of this study are to compare the running style gait analysis variables of a heterogeneous group of runners with various common running injuries with that of injury-free runners, to determine if there is an effect on the running style gait analysis variables common to the various injuries.

#### A.1.2. Methods

##### A.1.2.1. Subjects

Twenty-six (26) recreational runners diagnosed with common running injuries that include Anterior Knee Pain Syndrome (AKPS), Ilio-Tibial Band Friction Syndrome (ITB), Medial Tibial Stress Syndrome (MTSS) and Achilles' Tendinopathy (AT) at the right lower limb were recruited from the sports medicine and physiotherapy practices at the Sports Science Institute of South Africa (SSISA), Cape Town, South Africa. The injured runners (I) were compared with forty-three (43) injury-free runners (IF) matched for age, gender and self-selected running speed (Table A.1.1). The injury-free runners were recruited from a well-runner sports-shoe clinic at the SSISA, which they voluntarily attended for the prescription of running shoes.

Table A.1.1. Comparison of the demographic variables between injured and injury-free runners.

	Injured (n=26)	Uninjured (n=43)
Age (years)	32.2± 7.1	33.4± 11.8
Height (m)	1.76± 0.08	1.73± 0.09
Mass (kg)	74.6± 13.7	71.4± 13.2
Speed (m/s)	2.84± 0.27	2.96± 0.40

The I runners were asymptomatic at the time of the assessment and both I and IF runners met the relevant inclusion and exclusion criteria for the study (Table 6.2; Chapter Six).

##### A.1.2.2. Informed consent

Informed consent was sought from the runners prior to their participation in the study. Ethical approval for the study was obtained from the Research Ethics Committee of the University of Cape Town.

##### A.1.2.3. Clinical assessment

Of the twenty-six (26) I runners, seventeen (17) were referred with a diagnosis of AKPS, four (4) with ITB, three (3) with MTSS and two (2) with AT. None of the I runners was referred with a

diagnosis of Plantar Fascial Injury. As the runners were asymptomatic at the time of assessment, the appropriate clinical records were reviewed to ensure that the diagnostic criteria were fulfilled.

The diagnostic criteria for the specific injuries were as follows:

#### Ilio-Tibial Band Friction Syndrome

- Pain is localised to the lateral aspect of the knee and may radiate to the superior portion of the tibia (James and Jones, 1990).
- The onset of lateral knee pain is not related to an acute traumatic episode (James and Jones, 1990).
- The knee pain is associated with onset at a specific distance of running, is worse with continued running after the pain commences, aggravated by downhill running and relieved by walking (Krivickas, 1997).
- The pain is present at 30° of knee flexion after the knee is extended from 90° of flexion while pressure is applied over the lateral femoral epicondyle (Noble, 1979).

#### Medial Tibial Stress Syndrome

- Clinical evidence of injury to the fascial origin of the soleus muscle or periosteum beneath the origin of the tibialis posterior muscle, which is worse on running and relieved by rest (Touliopoulos and Hershman, 1999).
- The injury is not associated with an acute traumatic episode (Gillespie and Grant, 2000).
- The clinical and special investigations exclude the diagnoses of stress fractures of the tibia and chronic exertional compartment syndrome (Kiuru et al., 2003).

#### Achilles' Tendinosis

- Pain in the Achilles' is gradual and progressive in onset and associated with running activity (Maffulli et al., 2003).
- The Achilles' pain is not associated with an acute traumatic episode (Smart et al., 1980).
- Clinical and special investigations successfully exclude other differential diagnosis (Paavola et al., 2002).

### A.1.2.4. Test procedure

All runners followed the standard testing procedure described in Chapter Six.

### A.1.3. Statistical analysis

Statistical tests were undertaken of the gait analysis variables using a commercial statistical program (StatSoft, Inc. (2000). STATISTICA for Windows [Computer program manual] Tulsa, OK, USA). Due to the small subject numbers in the ITB, MTSS and AT groups, a heterogeneous group of I runners was created with the AKPS runners and the running speed, ground reaction forces, and knee and ankle joint angles and, work and power of the I group were compared with the IF runners with an independent t-test. A statistical significance level of  $p < 0.05$  was set.

## A.1.4. Results

### A.1.4.1. Running speed

The running speeds were similar between I ( $2.87 \pm 0.27$  m/s) and IF ( $2.96 \pm 0.40$  m/s [ $p = 0.176$ ]).

### A.1.4.2. Ground reaction forces

The horizontal propulsive force was greater in IF ( $0.18 \pm 0.04$  BW) than I ( $0.16 \pm 0.03$  BW [ $p = 0.030$ ]) (Table A.1.2). The loading rate of the vertical impact force at the peak magnitude (VLR) was greater in IF (VLR:  $44.46 \pm 9.51$  BW/s) than I (VLR:  $39.80 \pm 8.59$  BW/s [ $p = 0.030$ ]). There were no differences in the other ground reaction force variables between the IF and I.

Table A.1.2. Comparison of the ground reaction forces between injury-free and injured runners.

	Injured runners (n= 26)	Injury-free runners (n=43)	p-values
HBF	0.23±0.05	0.22±0.05	p= 0.484
HPF	0.16±0.03	0.18±0.04	p= 0.030*
VIF25	1.16±0.27	1.17±0.21	p= 0.814
VLR25	40.6±10.1	44.8±9.2	p= 0.069
VIF	1.25±0.17	1.24±0.22	p= 0.799
VLR	39.8±8.6	44.5±9.5	p= 0.030*
VPF	2.25±0.24	2.25±0.21	p= 0.521

\* significant differences between the injured and injury-free groups HBF: Horizontal braking force [BW], HPF: Horizontal propulsive force [BW], VIF25: Vertical impact force at 25ms [BW], VLR25: Vertical impact forces at 25ms loading rate [BW/s], VIF: Vertical impact force peak [BW], VLR: Vertical impact force loading rate [BW/s], VPF: Vertical propulsive force peak [BW]

### A.1.4.3. Joint angles

There were no differences in the knee and ankle joint angle variables between the I and IF runners (Table A.1.3).

Table A.1.3. Comparison of joint angles between injured and injury-free runners

	Injured runners (n= 26)	Injury-free runners (n=43)	p-values
KswF	84.3±3.8	85.3±2.6	p= 0.192
KswE	19.9±6.4	20.5±6.7	p= 0.623
Kic	24.7±6.4	25.3±5.5	p= 0.603
Kst	46.1±5.4	46.2±5.5	p= 0.692
Asw	12.6±4.5	12.9±13.6	p= 0.641
Aic	11.6±4.1	10.1±4.5	p= 0.428
Ast	25.6±2.9	24.4±3.1	p= 0.798

Knee swing phase peak flexion angle ( $^{\circ}$ ) [KswF], Knee angle in terminal swing phase ( $^{\circ}$ ) [KswE], Knee angle at initial supporting surface contact ( $^{\circ}$ ) [Kic], Knee angle in midstance ( $^{\circ}$ ) [Kst], Ankle angle in terminal swing phase ( $^{\circ}$ ) [Asw], Ankle angle at initial supporting surface contact ( $^{\circ}$ ) [Aic], Ankle angle in midstance ( $^{\circ}$ ) [Ast]  
No difference between injured and injury-free knee joint angles.

### A.1.4.4. Joint power and work

The eccentric knee work was greater in I (EKW:  $0.47 \pm 0.13$  J/kg) than IF (EKW:  $0.40 \pm 0.16$  J/kg [ $p = 0.023$ ]) (Table A.1.4). The knee power absorption was greater in I (KPA:  $7.64 \pm 1.84$  Watts/kg)

than IF (KPA: 6.61-2.07 Watts/kg [ $p= 0.011$ ]). There were no other differences in the knee and ankle dynamic variables between I and IF runners.

Table A.1.4. Comparison of joint power and work between injured ( $n= 26$ ) and injury-free ( $n= 43$ ) runners.

	Injured runners ( $n= 26$ )	Injury-free runners ( $n=43$ )	p-values
KPA	7.64±1.84	6.61±2.07	$p= 0.011^*$
KPG	5.84±1.43	5.87±1.77	$p= 0.962$
APA	6.42±2.12	6.46±1.87	$p= 0.620$
APG	7.80±2.15	7.64±1.65	$p= 0.373$
EKW	0.47±0.13	0.40±0.16	$p= 0.023^*$
CKW	0.38±0.10	0.38±0.13	$p= 0.925$
EAW	0.50±0.17	0.50±0.13	$p= 0.741$
CAW	0.51±0.14	0.49±0.10	$p= 0.250$

\*: Significant differences between the injured and injury-free groups Knee power absorption (Watt/kg) [KPA], Knee power generation (Watt/kg) [KPG], Ankle power absorption (Watt/kg) [APA], Ankle power generation (Watt/kg) [APG], Eccentric knee work (J/kg) [EKW] Concentric knee work (J/kg) [CKW], Eccentric ankle work (J/kg) [EAW], Concentric ankle work (J/kg) [CAW]

### A.1.5. Discussion and conclusion

As discussed in Chapter Six, the design of the present study does not allow a cause-effect relationship between injury and the changes in the gait analysis variables descriptive of running style to be concluded. However, the associations between injury and the changes in the concerned variables should be explored in future studies to determine the exact nature of the relationship.

Although a relationship between AKPS and a high eccentric knee work is intuitive (Chapter Six), it is difficult to extend the rationale for an association between high knee eccentric work and ITB, MTSS and AT, for this heterogeneous group of injuries. The small numbers of subjects in these specific injury groups may one reason for the difficulty in rationalizing relationships between eccentric joint work and the various injuries. Elaboration of the current study with the recruitment of greater numbers of runners with the relevant running injuries is encouraged and is currently being undertaken at the University of Cape Town's, Sport Science Institute of South Africa-based, Gait analysis research unit. The results of the individual injuries will be presented in future work.

## APPENDIX TWO

### UNIVERSITY OF CAPE TOWN



**FACULTY OF HEALTH SCIENCES  
Marilyn de Vries**

Barnard Fuller Building, Anzio Road, Observatory 7925  
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22 August, 2001

**Dr R Arendse  
P O Box 44229  
CLAREMONT  
7735**

Dear Mr Arendse

**PhD Proposal**

**Candidate:** Arendse, R (ARNREG004) MBChB (Natal) 1992  
**Degree:** PhD in Exercise Science  
**Department:** Human Biology  
**Title:** A biomechanical analysis of overuse musculoskeletal running injuries  
**Supervisor:** Prof M Schwellnus, Dr A St Clair Gibson, Prof C Vaughan

I am happy to advise that the Chairman of the Dissertations Committee has recommended approval of your candidature for the above degree on behalf of the Faculty of Health Sciences. This recommendation will then be sent to the Doctoral Degrees Board for further consideration, and you will hear from Ms Veda Naidoo of the DDB in due course.

With best wishes.

Sincerely

**MARILYN DE VRIES  
POSTGRADUATE OFFICER**

## APPENDIX THREE

UNIVERSITY OF CAPE TOWN

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Research Ethics Committee  
Faculty of Health Sciences  
Anzio Road, Observatory, 7925  
Queries : Xolile Fula  
Tel : (021) 406-6492 Fax: 406-6390  
E-mail : Xfula@curie.uct.ac.za

04 July 2001

**REC REF: 177/2001**

Dr RE Arendse  
Human Biology

Dear Dr. Arendse

**A BIOMECHANICAL ANALYSIS OF OVERUSE MUSCULOSKELETAL  
RUNNING INJURIES**

Thank you very much for submitting your study to the Research Ethics Committee for review.

*It is a pleasure to inform you that the Committee has formally **approved your study on the 29 June 2001.***

**Please quote the Reference number in all correspondence.**

Attached is a list of members who attended the meeting

Yours sincerely



**PROF. CR SWANÉPOEL**  
**CHAIRPERSON**

# APPENDIX FOUR

## Abbreviated *Curriculum Vitae* of Dr Regan Arendse (2005)

### Academic History

1987-1992	MBChB (University of Natal)
1998-1999	MSc Sports Medicine with distinction (University of Pretoria)
2000-2005	PhD Sports Medicine (University of Cape Town)
2002-2003	Research student in the Department of Engineering Science, Nuffield Orthopaedic Centre, Gait Laboratory (University of Oxford)

### Clinical Medicine Experience

1993-1994	Medical Internship at Grey's-Northdale Hospital Complex, South Africa
1994-1999	General Medical Practitioner with an interest in Sports Medicine, SA
2000-2002	Sports Physician, Sports Science Institute of South Africa (SSISA)
2001-2002	Sports Biomechanics and Gait Analysis Laboratory Coordinator (SSISA)
2002-2003	Sports Physician, Nuffield Orthopaedic Centre Gait Lab, United Kingdom
2002-2003	Sports Physician, 144 Harley Street, London, UK
2004	Emergency Medicine Experience: BLS, ACLS, ATLS, South Africa
2004-2005	Sports Physician, Claremont Hospital, Cape Town, South Africa

### Sports Medicine Experience

1997	World Veteran Athletics Championships Team Physician (South Africa)
1998	South African National Cycling Team Physician (Tour of Morocco)
1999	7 <sup>th</sup> All Africa Games Team Physician (South Africa)
2000	Medical Screening Team for South African Olympic Squad (South Africa)
2001	2 <sup>nd</sup> Iron Man Africa Race Medical Services Coordinator (South Africa)
2002	Running Style Modification Study (University of Cape Town)
2003	Running Style Assessment Study (University of Oxford)
2005	Medical Screening Team for South African Cricket Team (South Africa)

### Publications

2001	Arendse et al., Does lower limb alignment determine the kinematic response to variations in boundary conditions? 5 <sup>th</sup> Symposium on Footwear Biomechanics, International Society of Biomechanics, Zurich, Switzerland.
2001	Arendse and Schweltnus. Biomechanical Analysis and Treatment of a Common Running Injury (Case Study). International Sports Medicine Journal, 2000.
2003	Arendse & Schweltnus. The biomechanics of common running injuries. Abstract American College of Sports Medicine Annual Meeting, San Francisco, USA.
2004	Arendse et al. Reduced eccentric loading of the knee with the Pose running method. Medicine and Science in Sports and Exercise, 2004.
2004	Arendse. A biomechanical basis for the prescription of orthoses in the treatment of common running injuries. Medical Hypothesis, 2004.

### Academic awards

2000	University of Pretoria: Academic Honorary Colours
2000	UCT Benfara Scholarship
2001	SA National Research Foundation Research Grant
2002	UCT Exercise Science and Sport Medicine Scholarship
2001-2003	UCT Sainsbury Scholarship

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# APPENDIX FIVE

## Working plan for a running injury clinic

The principles of this hypothesis are described below with regard the practical application of clinical gait analysis to the management of the injured runner.

### **Multidisciplinary team management of running injuries**

In view of the interpretations of the results of this series of studies, a multidisciplinary team management of the injured runner with the aid of gait analysis is proposed.

#### **1. Multidisciplinary team**

Running injuries are multifactorial in aetiology and as such should ideally be managed by a multidisciplinary team with a holistic approach. The multidisciplinary team should include among the possible concerned health professions: a clinician, a biokinetician/ physical therapist and a biomechanist (clinical gait analysis) (Figure 11.2). The coach of the runner should be involved in the management of the injured runner from the presentation of the injury to the discharge of the runner from the care of the multidisciplinary team. The coach would be able to provide continued care to the runner and be a confidential source of vital collateral information of all aspects of the runner's history.

##### The clinician

The clinician would be expected to present to the multidisciplinary team a detailed current and relevant past medical and surgical history; and the main findings of a general and injury-specific clinical examination. All special investigations required to confirm the clinical diagnosis would be presented by the clinician. An appropriate clinical management plan guided by the information of the team will be proposed by the clinician.

##### The biokinetician

A detailed training and racing history of the injured runner, with the identification of training errors would be presented by a biokinetician. A detailed running shoe and orthoses history and an assessment of the appropriateness of current and future running shoes to the runner's lower limb alignment would be presented. An evaluation of the runner's style during training and racing, in actual or simulated conditions would be recorded by the biokinetician using digital video technology.

##### The biomechanist/ clinical gait analyst

Laboratory based, objective gait analysis of the injured runner under controlled conditions would be conducted by the biomechanist. This would include the capture, processing and presentation of the data to the multidisciplinary team by the biomechanist. This data would be compared with gait analysis data captured after any management programme recommended by the team.

## APPENDIX FIVE

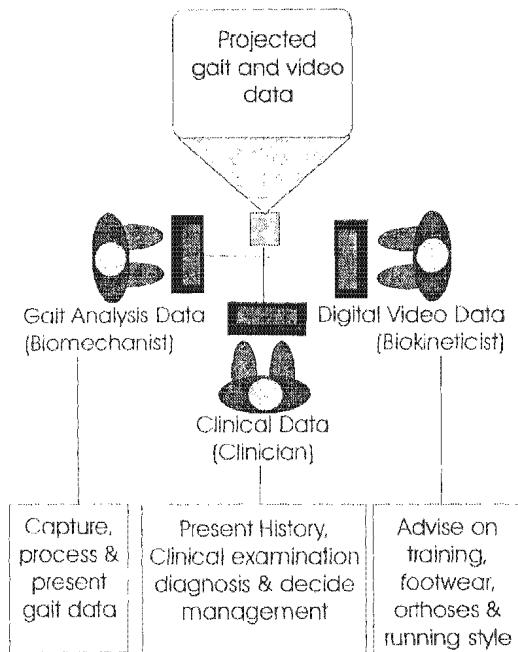


Figure 11.2. Multidisciplinary management team of the injured runner

### **Aim of the multidisciplinary team:**

The aim of the multidisciplinary team is to effectively treat runner with common injuries, reduce the risk of a recurrence of the injury or the occurrence of another running injury, while maintaining participation of the runner in training and racing activities.

### **Objectives of the multidisciplinary team:**

- Confirmation of the diagnosis of the running injury and exclusion of confounding diagnoses.
- Recognition of the multifactorial aetiology of the running injury and identification of specific factors that may have a role in the aetiology of the injury.
- Characterisation of the running style with subjective video analysis in training and racing conditions and objective laboratory based gait analysis and determination of whether the injured runner has a running style that would benefit from semi-rigid orthoses prescription or running style modification, through either barefoot or Pose method running.
- Monitor the outcome of treatment from acute medical management, correction of aetiological factors and running style modification where indicated.

# APPENDIX FIVE

## Management plan of the injured runner

The assessment of the injured runner should ideally be completed within a single visit to expedite treatment. However in practical terms it is likely to extend over five or more visits as is described in the multidisciplinary team management plan of the injured runner (Table 11.2).

### First visit

On the first visit, a definitive diagnosis of the running injury will be determined by the clinician. A detailed history of the presenting complaint and relevant past personal medical and surgical history will assist with establishing a diagnosis. This should be complemented by a general clinical examination to exclude the existence of co-existing chronic disease and the stigmata of multi-system disease that may initially present as a musculoskeletal injury (Plantar Fasciitis in patients with Ankylosing Spondylitis is an example). A detailed local examination of the injury should be conducted to confirm the diagnosis. If there is conflicting evidence in the history and clinical examination such as a history of trauma, night pain or systemic symptoms such as fever or morning joint stiffness, then special investigations to exclude other diagnosis (ESR and Full Blood Count) and confirm the local musculo-skeletal injury (X-ray, Ultrasound, Magnetic Resonance Images, Radio-Isope Bone scan and compartment pressure testing), where indicated should be undertaken. The clinician will discuss with the runner the merits of management by a multidisciplinary team and make the necessary introductions if agreed. In conjunction with a physical therapist or biokinetician, the acute management of the running injury should be undertaken with the aim of relieving acute inflammation and a return to pain-free running.

Table 11.2 Multidisciplinary team management plan

Clinician	Biokinetician	Biomechanist
<b>Initial visit</b>		
Establish diagnosis by means of history, physical examination and special investigations	Evaluate training programme and identify training errors	Orientation of runner to the gait analysis laboratory
Introduce the multidisciplinary management team	Document lower limb alignment and nature of the running shoes and orthoses	Nature of the data explained and the interpretation discussed
Initiate acute management		
<b>Second visit</b>		
Determine the initial response to treatment	Record the runners' style of running in the field in fatigued and non-fatigued state	Collect and process running data in gait laboratory
Fitness of the runner to participate in the dynamics testing determined		Format data for presentation
<b>Third visit</b>		
Invite runner and coach to multidisciplinary team meeting		
Presentation of the various components of the injured runners assessment and treatment		
Relationship between running style and injury determined		
Management decided with view to rehabilitate and reduce risk of recurrence of injury		
Need for running style modification programme discussed		

# APPENDIX FIVE

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## Fourth visit

Determine the response of the injury to the treatment

Trouble shoot problems encountered in the running style modification programme

Repeat gait analysis of running style for comparison

## Fifth visit

Second meeting of the multidisciplinary team to review the management of the injured runner  
Make recommendations to the runner and coach of further management  
Discharge if the response to treatment has been satisfactory

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The biokinetician will also consult the runner on the first or separately arranged visit to determine the current training work (particularly weekly running distance, intensity and 10km personal best time), goals of training (future race events) and expectation from the running activity (weight management or cardiovascular health pursuits). Specific attention will be devoted to the identification of sudden changes in training habits such as an increase in training volume, intensity or frequency. The lower limb alignment and flexibility will be documented with standard methods (Neely, 1998). The type of running shoes and orthoses (soft or semi-rigid) previously and recently used will be recorded. The recently used running shoes will be examined to identify wear features that make them unsuitable for continued use (Noakes2001). The biomechanist will introduce the injured runner to the gait analysis laboratory and familiarise him/ her with the test equipment (the length of the runway, motion analysis system, force platform and electromyographic equipment). The nature of the data (kinetic, kinematic and electromyography) that will be captured will be explained and the interpretation thereof discussed (movement patterns of the limbs; trunk, joint torques and work; and muscle electrical activity patterns).

## Second visit

At the second visit, the runner's injury should be reassessed by the clinician to determine the initial response to treatment and exclude co-existing pathology. The eligibility of the runner to participate in the dynamics testing should be determined by the clinician. The biokineticist will record the runners' style of running on a field in the non-fatigued state with a digital video camera. The data should be collected at 80% of the personal best 10km race pace and at standard running speeds of 3.5 and 4.5 m/s. The runner will then be encouraged to complete a training work sufficient to induce fatigue appropriate to the current level of running fitness. The runner's style will then be recorded again, this time in the fatigued state. All digital video recording should be made in both the frontal and coronal planes. The biomechanist will then evaluate the runner in the non-fatigued state in the gait analysis laboratory. All data as discussed in the first visit will be collected and processed by the biomechanist. The data will be collected at 80% of the personal best 10km race pace and at standard running speeds of 3.5 and 4.5 m/s. The processed data should then be formatted in a standard manner appropriate for interpretation by the multidisciplinary team.

## Third visit

The injured runner and coach will be invited to participate in the first multidisciplinary team meeting. At the meeting, the multidisciplinary team will present the various components of the injured runners assessment and treatment. The clinician will present the diagnosis, supported by the history, clinical examination and special investigations, and the response to initial treatment. The biokineticist will present the current running activity, training work and goals. The subject

## APPENDIX FIVE

analysis of the running style should be undertaken by the biokineticist. This should include the geometry of the trunk, pelvis, hip joints, knee joints, and ankle immediately prior to contact with the supporting surface, at initial contact, midstance and at terminal stance, in both frontal and coronal planes. The nature of the foot contact with the supporting surface (heel-toe, midfoot or forefoot only) should be determined. The objective running style analysis by means of interpretation of the gait analysis data will be presented by the biomechanist. This should include sagittal, coronal and transverse plane kinematics of the trunk, pelvis, hip joints, knee joints and ankle joints. The kinetics of the hip, knee and ankle, which include moments, mechanical power and work and Centre of Mass dynamics should be presented. The temporal distance parameters of stride length, frequency and duration should be presented. The muscle firing patterns of the rectus femoris, hamstrings, tibialis anterior and medial head of gastrocnemius should be presented. The multidisciplinary team will determine the contributions from training methods, intrinsic characteristics of the runner, the use of running shoes and orthoses, and the nature of the running style to the aetiology of the running injury. Based on this assessment, an appropriate management plan should be proposed for the future management of the runner to reduce the risk of recurrence of the injury and prevent the occurrence of another injury. The runner will be assessed for the suitability of entering a running style modification programme to aid in the management of the injury. The running style modification programme may be either barefoot or Pose method running. The runner should then be advised on appropriate further management including running style modification if indicated.

### **Fourth visit**

At a fourth visit, the runner should be assessed by the clinician to determine the response of the injury to the treatment offered. A general examination will be conducted to confirm the general well being of the runner and exclude any other injuries. The biokinetician will assess the response of the runner to the various interventions suggested and trouble shoot problems encountered in the running style modification programme. The progress of the runner in the preparation for the immediate and long term training and racing goals should be evaluated. The biomechanist will evaluate the runner to determine if there is an objective change in the running style, including which running style characteristics have been modified.

### **Fifth visit**

A second meeting of the multidisciplinary team will be convened to review the management of the injured runner and discuss the future management with the runner and coach. The injured runner may be discharged if the response to treatment has been satisfactory. The merit of the structure, purpose and effectiveness of the multidisciplinary team approach to the management of injured runners will be determined in future work.

