

**Biomechanical analysis of foot contact in junior
sprinters**

ELMIE HUGO

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Study Leader: Dr F.F. Coetzee

Co-Study leader: Dr. M.C. Opperman

DECLARATION

I, Elmie Hugo, hereby declare that the work on which this dissertation is based is my original work (except where acknowledgements indicate otherwise) and that neither the whole work, nor any part of it, has been, is being, or is to be submitted for another degree at this or any other university.

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Abstract

The purpose of this study was to determine the effects of different foot types (normal, flat and high arch) with regards to speed, roll-over and impact forces, thus attempting to indicate if a specific foot type is dominant amongst sprinters. The different foot types of ten junior sprint athletes and ten non-sprinters were determined by walking over a pressure platform (RSscan International's Footscan® 7.x plate system). The effects of foot roll-over and peak pressures during sprinting were determined for left and right feet respectively. The subjects ran barefoot at their top speed (sprinted) over 20 meters, crossing a pressure platform (RSscan International's Footscan® 7.x plate system) comprising the last two meters of the 20 meter distance. The initial contact, final contact, time to peak pressure and the duration of contact of the different sub-areas of the foot were measured. The results of the sprinters' trials were averaged and compared to the non-sprinters' averaged trials by performing a statistical T-test. The control group (non-sprinters) dominantly has a high arch foot type for both feet. In the sprinter group, the different foot types are all represented almost equally with regards to right feet, whereas the left feet are dominantly normal type, followed by high arch and then flat foot types. There was a significant difference ($p < 0.05$) during the Foot flat phase (FFP) between the sprinter group (mean left: 4.04ms, mean right: 4.34ms) and control group (mean left: 26.40ms, mean right: 24.46ms), left: $p=0.007$; right: $p=0.022$. This indicates that the FFP time is significantly faster for the sprinter group than for the control group. The control group spent a higher percentage of time on the rear foot than the sprinters did (left: $p=0.0057$, right: $p=0.0268$). The control group's peak plantar pressures were predominantly on the sub-areas of the heel (mean:HL=Left: 327.69, right: 351.44; mean HM= Left: 434.08, right: 423.19) and M1, M2, M3, whereas the sprinters' peak plantar pressures are predominantly on the sub-areas of the M1, M2, M3, mid-foot and T1, meaning that sprinters predominantly have peak pressures on forefoot contact whereas the non-sprinters predominantly have peak pressures on heel contact. The results of this study therefore indicate that in general, sprinters dominantly have a

normal foot type whereas the non-sprinters have a high arch foot type, and sprinters predominantly have peak pressures on forefoot contact whereas the non-sprinters predominantly have peak pressures on heel contact during sprints.

Keywords: Foot types; Foot roll-over; Peak pressures; Barefoot sprinting; Sprinters; Non-sprinters; RSscan International

Uittreksel

Die doel van die studie was om die effek van verskillende voetsoorte (normaal, plat of hoë voetbrug) ten opsigte van spoed, voet bewegingspatroon en piekdrukking te bepaal, ten einde te poog om vas te stel of daar 'n spesifieke voetsoort is wat dominant is onder naellopers. Die voetsoort van tien junior naellopers en tien nie-naellopers (kontrole groep) is bepaal deur oor 'n drukplaat (RSscan International's Footscan® 7.x plaat-sisteem) te stap. Die effek van die bewegingspatroon en piekdrukking van die voet gedurende naellope is vir die linker- en regtervoet afsonderlik bepaal. Die toetsgroep het kaalvoet teen hul maksimale spoed oor 'n afstand van 20 meter gehardloop waarvan die laaste 2 meter die RSscan International's Footscan® 7.x plaat-sisteem ingesluit het. Die aanvanklike kontak, finale kontak, tydsduur tot piekdrukking en die tydsduur van kontak van die verskillende subareas van die voet is gemeet. Die naellopers se gemiddelde proeflopie is deur 'n statistiese T-toets vergelyk met dié van die nie-naellopers. Die kontrolegroep het 'n dominante hoë linker- en regtervoetbrug. Die naellopers se regtervoetsoort is eweredig versprei tussen die verskillende tipes voetsoorte terwyl die linkervoete dominant normaal is, gevolg deur hoë- en laebrug voetsoorte. Daar was 'n noemenswaardige verskil ($p < 0.05$) tussen die naellopers (gemiddeld links: 4.04ms, gemiddeld regs: 4.34ms) en die kontrolegroep (gemiddeld links: 26.40ms, gemiddeld regs: 24.46ms), links: $p=0.007$; regs: $p=0.022$, gedurende die Voet plat fase (VPF). Dit dui dus aan dat die naellopers se VPF tyd aansienlik vinniger as die kontrolegroep se tyd is. Die kontrolegroep het 'n hoër persentasie tyd op die agtervoet spandeer in vergelyking met die naellopers (links: $p=0.0057$, regs: $p=0.0268$). Die kontrolegroep se piek plantardrukking was hoofsaaklik op die subareas van die hak (gemiddeld:HL=links: 327.69, regs: 351.44; gemiddeld HM= links: 434.08, regs: 423.19) en M1, M2, M3. Daarteenoor was die naellopers se piek plantardrukking hoofsaaklik op die subareas van die M1, M2, M3, midvoet, en T1 uitgeoefen. Dit toon aan dat naellopers hoofsaaklik voorvoet piekdrukking tydens kontak uitoefen terwyl die kontrolegroep hoofsaaklik hak piekdrukking uitoefen. Die resultate van hierdie studie dui

gevolglik aan dat naellopers oor die algemeen meestal 'n normale voetsoort het, terwyl die voete van die nie-naellopers deur 'n hoë voetbrug gekenmerk word. Die naellopers handhaaf ook oorwegend voorvoetkontak en – piekdrukking, in teenstelling met die kontrolegroep wat oorwegend hak piekdrukking handhaaf gedurende naellope.

Sleutelwoorde: Voetsoorte; Voet bewegingspatroon; Piekdrukking; Kaalvoet naelloop; Naellopers; Nie-naellopers; RSscan International

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CHAPTER 1

RESEARCH DESIGN

1.1 INTRODUCTION

The following information pertains to the problem statement, rationale, purpose and necessity of the research project and describes the focus and hypothesis of the study.

1.2 PROBLEM STATEMENT

Limited research on the biomechanical analysis of foot contact in sprinters exists. There are always the questions of what makes a sprinter a sprinter and people want guidelines to identify characteristics associated with sprinters and potential sprinters. There is ample information available in the literature on aspects such as running techniques, aspects of foot function, indicating how muscles, bones, tendons and ligaments interact with weight bearing ground contact, as well as on different foot types that exist. This research study will investigate the effects of different foot types, with regards to speed, roll-over and impact forces, thus attempting to indicate if a specific foot type is dominant amongst sprinters.

1.3 RATIONALE OF THE RESEARCH PROJECT

A summary of the rationale for the research project, as such, and the rationale for the research design, provides substantiation for the significance and the validity of the study.

1.4 PURPOSE

- To determine the ground contact time of the different foot types.
- To investigate the effects of roll-over action of the foot during ground contact time.
- To measure under foot peak pressures to determine if there are differences with regard to different foot types, with a possible specific foot type being dominant amongst sprinters.

1.5 NECESSITY OF THE RESEARCH PROJECT

Not only will the results of this study provide constructive information to athletes and coaches who would like to improve their performance, but it will also provide information for the establishment of a protocol for the identification of sprinters at an early age.

1.6 FOCUS AND HYPOTHESIS

1.6.1 Focus

The primary focus of this study is to provide relative information to sprinters and coaches regarding the best possible foot type for sprinting efficiency.

The secondary focus is to establish a protocol for the identification of sprinters at an early age.

1.6.2 Hypothesis

The RSscan will be able to provide information to sprinters and coaches regarding the best possible foot type for sprinting efficiency, the roll-over pattern of the foot while sprinting and differences in under foot peak pressures, and this information will provide constructive information for the establishment of a protocol for the identification of sprinters at an early age.

1.7 POSTULATES

Sprinters have access to immense information regarding running techniques and biomechanics, but with sound adjustments to the athlete's foot placement, ground reaction time and forces and the most efficient foot roll-over, performance may be enhanced.

CHAPTER 2

LITERATURE SURVEY

2.1 INTRODUCTION

This chapter will discuss the anatomy of the lower leg and how all these different parts (bones, joints, ligaments, muscles and tendons) function to create movement during walking and running. The different foot arches, foot types and foot movements will also be made clear. The analysis of running, regarding stride length, stride frequency, vertical and horizontal components, the differences between running and walking, ground force contact and foot strike contact according to centre of mass will give a good understanding of how human beings moves from one place to another while walking and running. The different phase of sprinting will help understand how a sprinter moves during running. Lastly, previous research done with the RSscan will present a good background on what other researchers have found with different studies made in running and walking.

2.1.1 Anatomy of the lower leg

2.1.1.1 *Bones*

Bones can be regarded as the building blocks of the human body. All additional structures that are involved in the mechanics of locomotion are associated with bones (Hagman, 2005:4). The skeletal structure of the foot starts at the ankle joint, where the foot is combined with the leg (Hamilton & Luttgens, 1997:219). Passive structures, such as ligaments and soft tissue, together with muscles of the foot and lower leg, are responsible for the maintenance and control of the foot shape and foot movement during functional motion (Abboud, 2002:173; De Cock, 2006:3). The foot has two functions which are of significant importance, namely that of support and propulsion (Hamilton, Weimar & Luttgens, 2008:190).

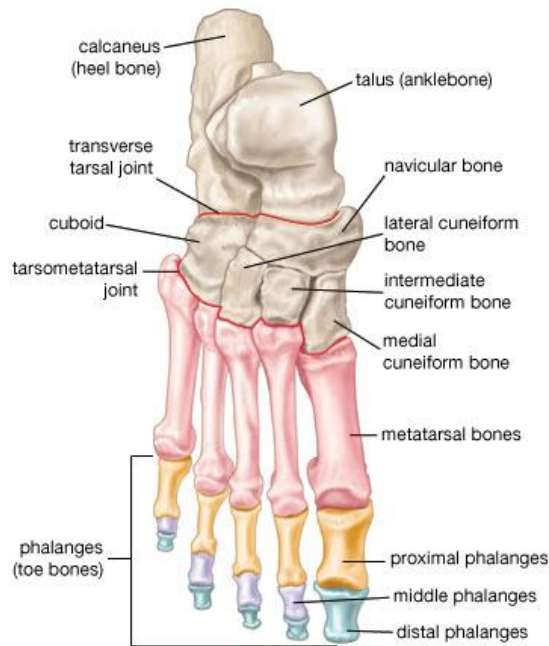


Figure 2.1 Bones of the foot (from <http://www.lighterliving.com/pilates/article>)

The foot consists of 26 bones, as indicated in Figure 2.1, made up of seven tarsal bones (Hamilton *et al.*, 2008:190) at the proximal part of the foot and five metatarsals and phalanges at the distal end of the foot. The forefoot consists of five metatarsal bones, and fourteen phalanges. The first metatarsal bone provides attachment for several tendons, bears the most weight, and plays the most important role in propulsion (Quinn, 2006:1). The Hallux has 2 phalanges and when looking closer, it can be seen that the foot has five digits and that the great toe (Hallux) has digits containing two bones, while all other digits have three bones (Hagman, 2005:4). The five metatarsals are firmly attached to the proximal row of tarsals. The main function of the metatarsal bones is to resist compressional loads. The second, third and fourth metatarsal bones are the most stable of the metatarsals, as they have minor tendon attachments which make them well protected. The mentioned metatarsals are, therefore, not subjected to strong pulling forces (Quinn, 2006:1).

The mid-foot includes five of the seven tarsal bones, the navicular, cuboid, and three cuneiforms (lateral, medial, and intermediate). The mid-foot is the

portion of the foot that is designed to absorb the shock created by human movement. The mid-foot meets the forefoot at the five tarso-metatarsal (TMT) joints, as indicated in Figure 2.1 (Quinn, 2006:1).

The foot is primarily supported at three points while standing and these parts are the calcaneus and the distal base of the first and fifth metatarsals. Bones in the foot which are involved with walking and running are the talus and calcaneus, and these two bones also make up the hind-foot (Pribut, 2005:1). The calcaneus is the largest tarsal bone, as well as the strongest bone in the foot and is located inferior to the talus and supports the talus bone forming the heel (Seeley, Stephens & Tate, 2006:241). The talus rests on top of the calcaneus and forms the pivot of the ankle (Quinn, 2006:1). The talus and calcaneus bones absorb the impact forces during the initial ground contact of the heel strike when a subject is running. The impact forces are then transmitted to the upper parts of the lower extremities. When the foot is twisted in one way (pronation or supination) by muscles from the foot and leg, these bones lock firmly in place. However, when turned in the opposite direction (pronation or supination), the bones unlock and they can flop around to be conventional to whatever surface the foot is contacting. One type of motion associated with the tarsal bones is pronation (Quinn, 2006:2).

2.1.1.2 Joints

The joints between the distal metatarsals and proximal phalanges form the ball of the foot. Thus, the ball of the foot is the connection between the metatarsals and phalanges (Seeley *et al.*, 2006:242). There exists little motion between the phalanges and the hallux. The foot and its 26 bones have many articulations (Hagman, 2005:4).

According to Hamilton *et al.* (2008:190), the ankle (talocrural) joint is a hinge joint while the joint formed by the talus and the calcaneus bones is called the subtalar joint (Pribut, 2005:1). The subtalar joint (talocalcaneal) is distal to the ankle joint, where the talus rests on and articulates with the calcaneus. The subtalar joint is a synovial joint between the inferior surface of the body of the

talus and the superior surface of the calcaneus. It is toughened by four small talocalcaneal ligaments (Hamilton *et al.*, 2008:194)

A fifth ligament, the plantar calcaneonavicular, is possibly the most important of all. It is a broad, thick ligament that connects the sustentaculum tali projection of the calcaneus with the inferior side of the navicular bone. It passes under the talus and aids in supporting it. It is actually part of the subtalar joint, because it contains a fibrocartilaginous facet that is lined with synovial membrane. The plantar calcaneonavicular ligament is also known as the spring ligament because of the yellow elastic fibres that give it its elasticity. The importance of this ligament can be readily understood when one remembers that the talus sustains the weight of the entire body. The shock absorbing function of this elastic support is understandable. Extreme prolonged pressure on this ligament through inappropriate use of the feet will cause it to stretch permanently, resulting in a lowered arch (Hamilton *et al.*, 2008:194). The movement that occurs in the subtalar joint is mainly eversion and inversion of the foot. Inversion of the heel and eversion when the calcaneus tilts into valgus, resulting in pronation of the foot. The rest of the foot is carried with the heel as it tilts (the foot is directly connected to the calcaneus through the calcaneocuboid joint), which results in supination, whereas valgus tilting of the heel (eversion) results in pronation of the foot (McRae, 2004:272). The main joint in the hind-foot, the subtalar joint allows pronation (together with dorsiflexion, abduction and eversion) and supination (together with plantar flexion, adduction and inversion) of the foot (McRae, 2004:273).

The mid-tarsal joint (Transverse Tarsal; Chopart's joint) is formed by the head of the talus and navicular on the medial side, and the calcaneus and cuboid on the lateral side (McRae, 2004:273; Pribut, 2005:1). The mid-tarsal joint consists of two articulations, the lateral being the calcaneocuboid joint, and the medial being the talonavicular. The talonavicular joint is a modified ball-and-socket joint and permits rather restricted movements concerning three axes. The calcaneocuboid joint is non-axial and permits only slight gliding motions. These appear additional or secondary to the freer motions of the

talonavicular joint. Several ligaments strengthen these joints, but the ones that give the most support are the long and short plantar (calcaneocuboid) ligaments. These are both wide, thick ligaments of great strength (Hamilton *et al.*, 2008:194-195).

The mid-tarsal joint links the hind-foot with the mid-foot. This joint has in effect two axes of movement; it acts as a hinge allowing slight dorsiflexion and plantar -flexion. Movement is coordinated with subtalar movement (McRae, 2004:273).

Plantar tarsometatarsal joints are non-axial, with the possible exception of the hallux joint, which looks slightly like a saddle joint. The movements are of a gliding nature, which bears a resemblance to a restricted form of flexion, extension, abduction and adduction (Hamilton *et al.*, 2008:195).

Inter-metatarsal joints include two sets of equal articulations, those between the bases and those between the heads of the metatarsal bones. They are all non-axial joints. The articulations among the heads of the metatarsal bones are a significant part of the metatarsal arch. The total result of the movements taking place there, is a spreading or flattening of the arch when the weight is on it and a return to its plantar concavity when the weight is taken off it. (Hamilton *et al.*, 2008:195).

Metatarsophalangeal joints may best be described as a modified form of condyloid joint. The joint of the hallux differs from the others, in that it is larger and has two sesamoid bones beneath it (Hamilton *et al.*, 2008:195).

2.1.1.3 Ligaments

Ligaments are the fibrous, slightly elastic connective tissues that connect bone with bone. Ligaments control the range of motion of a joint, and serve as static stabilizers of a joint so that the bones move in the proper alignment. Ligaments are composed of strands of collagen fibers intertwined with elastic fibers (Hagman, 2005:3).

The ligaments in the foot are the first anatomical structure that restricts the amount of movement in the foot and provide stability (Hagman, 2005:4). This ligamentous tissue cannot be actively used for movement production, since it does not have the contractile essentials found in muscles, hence, the function of stability (Hagman, 2005:4). Fifty-seven joints are responsible for the flexibility of the foot in the adaptation to uneven surfaces (Abboud, 2002:168; De Cock, 2006:3). When the foot is plantar-flexed, some rotation, abduction and adduction of the ankle joint are possible (Moore & Dalley, 1999:635).

2.1.1.4 Muscles and Tendons

The muscles of the foot are active connections between the foot bones; so-called intrinsic foot muscles, or between a bone in the foot and a bone in the upper or lower leg; called eccentric foot muscles (Moore & Dalley, 1999:646, Hagman, 2005:4). The muscles, together with bone geometry and ligaments, describe the range of motion of two adjacent bones with respect to one another (Hagman, 2005:4). The human foot guarantees a stable support for the body, attenuates potentially harmful impact shocks and provides sensory information about the contact with the ground (Hagman, 2005:4).

Eleven of the twenty-two muscles of the ankle and foot are intrinsic small muscles or muscle groups that are located entirely within the foot (Hamilton *et al.*, 2008:197,203). All but one, the extensor digitorum brevis, are on the plantar surface and are usually expressed as being arranged in four layers (Hamilton *et al.*, 2008:203). The dorsal interossei muscle, although included in the deepest layer, is situated between the metatarsal bones rather than on either surface. The extensor digitorum brevis, which includes the hallucis, which is sometimes described as a separate muscle, is located on the dorsal surface of the foot. With the exception of the lumbricales and quadratus plantae, which help flex the lesser toes, the names of these muscles indicate their functions. These intrinsic muscles are much more highly developed in primitive people than in people usually wearing shoes (Hamilton *et al.*, 2008:203).

Intrinsic muscles act as a functional unit having a significant role in stabilization of the foot during propulsion and tend to show more activity in feet that are usually pronated. Activity cannot be seen during relaxed standing in either normal or pronated feet and are not active in the normal static support of the longitudinal arches. They do, on the other hand, show specific activity in voluntary attempts to raise the height of the arches. They are also definitely active in the movement of rising on the toes (Hamilton *et al.*, 2008:203-204).

The intrinsic muscles are located within the foot and cause movement of the phalanges. These muscles are flexors, extensors, abductors, and adductors of the phalanges. Several intrinsic muscles also help support the arches of the foot (Quinn, 2006:2). The adductor muscles of the foot are normally stronger than the abductor muscles. The intrinsic muscles also help support the arches of the foot during the stance phase (Moore & Dalley, 1999:646; Hagman, 2005:4).

The other eleven of the twenty-two muscles of the ankle and foot are extrinsic; they have distal tendon attachments on the foot, but are otherwise located outside of it. A twelfth extrinsic muscle, the plantaris, has been omitted because it is a trace often absent in human beings. When present it assists the ankle extensor muscles (Hamilton *et al.*, 2009:197).

The extrinsic muscles are divided into three groups which include: the anterior compartment, posterior compartment and lateral compartment groups, which are named according to the location of the separate compartments of the leg. The anterior leg muscles are involved in dorsiflexion and eversion or inversion of the foot and extension of the phalanges, which makes them extensor muscles (Seeley *et al.*, 2006:363). The lateral muscles are primarily everters of the foot however they also aid plantar flexion (Seeley *et al.*, 2006:367). The posterior compartment is made up of the tibialis posterior and the long toe flexors and is responsible for inversion of the foot and ankle in an open kinetic chain. These muscles help control pronation at the subtalar joint and internal rotation of the lower leg. Along with the soleus, the tibialis posterior will help

decelerate the forward momentum of the tibia during mid-stance phase of gait (Prentice, 1999:491).

Extrinsic muscles allow a person to point the foot and stand on tip-toe. The peroneal muscles are on the lateral side of the legs and they provide stability and allow eversion. These extrinsic muscles have long tendons that cross the ankle to attach on the bones of the foot and assist in movement, whereas the talus has no tendon attachments (Quinn, 2006:2). The extrinsic muscles are the superficial muscles of the lower leg; which the gastrocnemius muscle form part of (Quinn, 2006:2).

The tibialis anterior muscle lies along the full length of the anterior surface of the tibia from the lateral tibial condyle down to the medial aspect of the tarsometatarsal area. In the region of one and a half to two-thirds of the way down the leg, the tibialis anterior becomes tendinous. The tendon passes anterior to the medial malleolus on its way to the medial cuneiform. The muscle dorsiflexes the ankle and foot and supinates (inverts and adducts) the tarsal joints when the foot is dorsiflexed. The muscle is also active during the initial contact phase of walking, allowing the foot to be lowered to the ground in a controlled manner (Alcamo, 2003:92; Hamilton *et al.*, 2008:197).

The extensor digitorum longus muscle expands to the four lesser toes. It furthermore dorsiflexes both the ankle and the tarsal joints and helps eversion and abduct the ankle and tarsal joint. It is a structured muscle, situated lateral to the tibialis anterior muscle in the upper part of the leg and lateral to the extensor hallucis longus in the inferior part. Just anterior of the ankle joint, the tendon separates into four tendons, one for each of the lesser toes (Hamilton *et al.*, 2008:198).

The extensor hallucis longus muscle extends and hyper-extends the hallux. The ankle and the tarsal joints are also dorsiflexed by the extensor hallucis longus. This muscle is also penniform in structure. Its upper portion lies beneath the tibialis anterior and extensor digitorum longus, but about halfway down the leg the tendon emerges between these two muscles, thus becoming

superficial. After it reaches the ankle, the tendon slopes medially across the dorsal surface of the foot to the top of the hallux (Alcamo, 2003:92-94; Hamilton *et al.*, 2008:198).

The peroneus tertius muscle dorsiflexes and pronates (everts and abducts) the tarsal joints, and also dorsiflexes the ankle. It is a small muscle that lies laterally to the extensor digitorum longus, occasionally expressed as the fifth tendon of the latter muscle (Hamilton *et al.*, 2008:199).

The peroneus longus muscle plantar flexes, everts and abducts the tarsal joints, and plantar flexes the ankle. It is mainly active during the propulsive phase of walking. It is situated on the surface on the lateral aspect of the leg with its distal tendon passing behind the lateral malleolus and proceeding forward and downward to the edge of the foot, where it surpasses behind the tuberosity of the fifth metatarsal. At this point it turns under the foot, passes through the peroneal groove of the cuboid, and slopes forward across the plantar surface of the foot to its attachment at the bottom of the medial metatarsal and medial cuneiform, not far from the attachment of the tibialis anterior (Palastanga, Field, Soames, 1989:419-420; Hamilton *et al.*, 2008:199)

The peroneus brevis muscle plantar flexes, everts and abducts the tarsal joints and assists with plantar flexion of the ankle. It is also a penniform structured muscle, lying beneath the peroneus longus on the inferior half of the lateral aspect of the leg. Its tendon passes posterior to the lateral malleolus directly anterior to the tendon of longus and continues forward just above the longus tendon to its attachment on the tuberosity of the lateral metatarsal, below the attachment of the peroneus tertius (Hamilton *et al.*, 2008:200).

The gastrocnemius and soleus of the superficial muscles of the posterior compartment are involved in plantar flexion of the foot and inversion (Alcamo, 2003:92; Seeley *et al.*, 2006:367). The gastrocnemius is a powerful fast-twitch fibre muscle for plantar flexing the foot at the ankle joint. It is the most

superficial muscle on the posterior side of the leg and can be seen as two humps in the upper part of the calf when it is well developed. Its two heads, together with the soleus, make up the triceps surae. The lateral and medial portions of the muscle remain separate from each other as far down as the middle of the posterior side of the leg. They then combine to form the broad tendon of Achilles. The most familiar function of the gastrocnemius muscle is to enable plantar flexion. It is also active in most individuals during normal relaxed standing. The muscle has a great angle of pull, approximately 90 degrees, when the foot is in its original position. Its internal structure and its leverage combine to make it an exceedingly powerful muscle. The gastrocnemius is more active with the knee extended, than with a flexed knee (Clover, 2010:172-173, Hamilton *et al.*, 2008:200-201).

Like the gastrocnemius, the soleus muscle plantar flexes the foot at the ankle joint. It lies below the gastrocnemius, apart from along the lateral aspect of the inferior half of the calf where a portion of it lies laterally to the superior part of the Achilles tendon. Its fibres are inserted into the Achilles tendon in a bipenniform way. It is mostly comprised of slow-twitch fibers (Hamilton *et al.*, 2008:201)

The tibialis posterior muscle plantar flexes the tarsal joints and assists with plantar flexion of the ankle. It contributes in supination (inversion and adduction) when the foot is plantar flexed. It is the deepest muscle on the posterior side of the leg. The core part of the muscle covers the inter-muscular septum between the tibia and the fibula. In the lower anterior portion of the leg its tendon leans across the medial side of the ankle, passes behind the medial malleolus and above the sustentaculum tali and then turns inferior of the foot around the medial margin of the navicular bone to insert into its inferior aspect. The muscle is penniform in structure. Because of its direction of pull and its many attachments on the plantar surface of the tarsal bones, an important function of this muscle appears to be maintenance of the longitudinal arch in a reserve capacity such as is needed in a foot which is not as stable as it should be (Hamilton *et al.*, 2008:201-202).

The flexor digitorum longus muscle flexes the four lesser toes, plantar flexes and helps invert and adduct the tarsal joints and helps plantar flex the ankle. It is located on the medial side of the posterior side of the leg behind the tibia. Penniform in structure, its distal tendon passes behind the medial malleolus between the tendons of the tibialis posterior and flexor hallucis longus. Beneath the tarsal bones it separates into four tendons that go to the distal phalanx of each of the four lesser toes (Strauch, Vasconez, Hall-Findlay, Lee, 2009: 1500; Hamilton *et al.*, 2008:202).

The flexor hallucis longus muscle flexes the hallux, plantar flexes and helps invert and adduct the tarsal joints and helps plantar flex the ankle. It is located on the lateral side of the back of the leg, behind the fibula and the lateral portion of the tibia. The fibers connect with the distal tendon in a penniform manner. The tendon crosses posterior of the ankle to the medial side, passes posterior and inferior the sustentaculum tali and runs forward under the medial edge of the foot to the distal phalanx of the hallux. It is the most posterior of the three tendons that pass posterior of the medial malleolus. One of its important functions is to provide the push-off in walking, running, and jumping. It may be palpated on the medial border of the calcaneal tendon close to the calcaneus (Hamilton *et al.*, 2008:202-203).

Muscles have tendons which connect them to bones. The bones in a person's skeleton allow one to walk, run, jump, etc. Without the ability of tendons to connect the muscles to bones, that are responsible for controlling these actions, it would be impossible for the body to move in the way it does. The composition of tendons is much like gelatin, but harder and not as elastic. They are made of special cells called tenocytes, water and fibrous collagen proteins. Millions of these collagen proteins wave together to form the strong strand of flexible tissue called a tendon. Tendons attach to bone via the periosteum and form a strong mineralized connection (Hagman, 2005:4). The fat pads (which are also tendons) on the plantar side of the foot are located between the skin and the foot bones and play a vital role in the function of the foot. The fat pads help in dissipating impact energy over the plantar side of

the foot. Thus, they have been confirmed to be effective in damping the impact force during early heel-ground contact (Hagman, 2005:4).

On the plantar surface of the foot the muscles are covered by fascia (Plantar fascia), divided into medial, central and lateral portions. The middle part, known as the plantar aponeurosis, is particularly strong and fibrous. It extends under the whole length of the foot, connecting the tuberosity of the calcaneus with the bases of the proximal phalanges of the five toes. This is an extremely strong band that serves as an effective binding rod for the longitudinal arch. (Hamilton *et al.*, 2008:204)

Muscles and tendons help in supporting the arches (Abboud, 2002:176). The structural elements of the foot arches, which are necessary for support, balance and propulsion, include the 26 bones of the foot together with ligaments and lower leg muscles (Abboud, 2002:176; De Cock, 2006:3). The posterior tibial tendon, which supports the arch, attaches one of the smaller muscles of the calf to the plantar side of the foot. The anterior tibial tendon allows the foot to be dorsiflexed (De Cock, 2006:3).

2.1.1.5 Foot arches

The arches of the foot are maintained by a combination for bony structure, aponeuroses, ligaments and tendons. The irregular tarsal bones fit together to form the basic structure of the longitudinal arch. The plantar fascia and the tendons of the deep plantar flexors act as a cable holding the arch shape. The calcaneonavicular/spring ligament, the deltoid ligament and the interosseus ligaments provide stability within the tarsal region and between the tarsal bones and the talus (Hamilton *et al.*, 2008:205). In a strong foot, muscle activity is involved for balance, adjusting the foot when encountering uneven surfaces, during locomotion and when bringing upon you other stresses such as with plantar flexion. Muscles play a greater role in a weak foot, such as with flat feet. However, it has been demonstrated consistently that bones and ligaments are the primary structure for maintaining the arches (Hamilton *et al.*, 2008:205).

The foot has the important function of weight bearing and propulsion and therefore, requires a high degree of stability. The multiple bones form an arch to support any weight for the flexible foot (Quinn, 2006:2). The foot contains different arches, of which the medial longitudinal arch is the most important (McRae, 2004:274) and extends from the heel to the heads of the five metatarsals (Hamilton *et al.*, 2008:193). The medial longitudinal arch is primarily affected in pes planus and pes cavus. The medial longitudinal arch is formed by the calcaneus, talus, navicular, three cuneiforms and medial three metatarsals (McRae, 2004:274; Hamilton *et al.*, 2008:193). The medial arch is supported by the calcaneonavicular/spring ligament which shoulders the head of the talus and plantar fascia, which acts as a tie and which lifts the centre of the arch and helps support the head of the talus (McRae, 2004:274). The medial longitudinal arch with its greater flexibility and its curving arch is adapted to the function of shock absorption, which is important in all forms of locomotion (Hamilton *et al.*, 2008:193).

The lateral longitudinal arch is formed by the calcaneus, cuboid and fourth and fifth metatarsals. This arch is very shallow and generally flattens out during weight bearing (McRae, 2004:272). The lateral longitudinal arch is much flatter than the medial part of the arch and rests on the ground during standing (Moore & Dalley, 1999:640). The lateral component lacks mobility because it has a nearly flat shape; hence it is better adapted to the function of support (Hamilton *et al.*, 2008:193).

The transverse arch is formed by the basis of all five metatarsals and cuboid. The transverse arch stretches across the sole in the coronal plane (from side to side). The whole arch is comprised out of both feet, meaning that one foot is in fact only a half arch. The shape of the cuneiforms helps maintain the arch. The anterior arch lies in the coronal plane and its bony components comprise the metatarsal heads. The metatarsal heads flatten out under load which is not a characteristic of the weight bearing foot (Moore & Dalley, 1999 635; McRae, 2004:274).

The sole of the foot is divided into sub-areas with the help of the RSscan, identified on the plantar surface of important anatomical structures of the foot. This enables the analysis of the local interaction of the ground reaction force with the plantar surface of the foot (De Cock, 2006:4).

2.1.1.6 Foot types

Runners have different types of feet, such as high arch, normal or flat feet (which are determined by the height of the arch). There are also different types of foot strikes during ground contact; for example, a heel striker, a forefoot striker or a mid-foot striker. Another factor to be considered is if the athlete pronates or supinates when running (<http://www.nwhealth.edu>).

2.1.1.6.1 Patterns of foot strike

A heel strike pattern is suited for long-distance running because the heel pad has a better ability to absorb high impact force. Some athletes have a mid-foot strike pattern or whole-foot strike patterns. The forefoot strike pattern is seen mostly in athletes competing in sprinting events. The most important event during foot strike is to absorb the initial impact on the foot, striking the ground through rapid extension of the hip, flexion of the knee, internal rotation of the tibia, pronation of the subtalar joint, shoes and/or orthoses (Moore & Dalley, 1999:641).

2.1.1.6.2 Flat feet / pes planus or fallen arches

Pes planus is a term used when the foot arch collapses (fallen arches), usually the medial parts of the longitudinal arches and where the entire sole (the medial border) of the foot come into contact or near-complete contact with the ground. In some individuals (Moore & Dalley, 1999:642; Solomon, Warwick & Naygam, 2005:243) the foot arch simply never develops in one foot or both. It is also noted that being flatfooted does not decrease foot speed meaning that flat feet does not affect one's response to the plantar reflex test. Training of the feet, especially by foot gymnastics and going barefoot on changeable terrain, can facilitate the formation of arches during childhood, with a developed arch occurring for most by the age of four to six years (Solomon *et al.*, 2005:243).

Flat feet can also develop in adults as a result of injuries, illness, unusual or prolonged stress to the foot (standing for prolonged periods of time), faulty biomechanics, or as part of normal aging process. A flexible foot is when an adult appears flatfooted but an arch can be seen when the person dorsiflexes while standing (Solomon *et al.*, 2005:244).

Flat footedness is caused by excess pronation. This overload pronation causes the foot's arch to collapse and elongate, giving the appearance of a flat foot. Flat footed athletes over-pronate and the foot and ankle fail to stabilize the body, which decrease the ability to absorb shock properly. Runners with low arches tend to over-pronate (<http://www.nwhealth.edu>).

2.1.1.6.3 Normal (medium) arch

This is where the foot has a normal pronation and the foot can support the body weight without a problem (<http://www.nwhealth.edu>).

2.1.1.6.4 High arch feet / Pes cavus

In Pes cavus the arch is higher than normal and it often accompanies clawing of the toes. There are lateral variation and rotation of the hallux, together with hypertrophy of the medial part of metatarsal head and an overlying bursa which together form a prominent bunion on the medial side. Lateral variation of the hallux may lead to overcrowding and occasionally overriding of the lateral toes (Solomon *et al.*, 2005:245).

This athlete usually under-pronates which means the force of impact is not evenly distributed resulting in too much shock traveling up the legs (<http://www.nwhealth.edu>).

2.1.1.7 Foot movements

2.1.1.7.1 Pronation

Pronation is a motion that occurs when a person runs or walks; this is when landing on the lateral edge of the foot and when the foot rolls medially. Some people over-pronate or under-pronate (<http://www.nwhealth.edu>). Pronation

involves eversion, abduction and dorsiflexion of the calcaneus (Pribut, 2005:4).

When the athlete's foot is abducted (everted or pointing outward), greater pronation is observed. Such increased pronation increases the side to side movement of the runner's centre of mass, which means that the runner's centre of mass will be moved from side to side and not forward down the track. The velocity and magnitude of pronation will be greater with more abduction (Pribut, 2005:4).

2.1.1.7.2 Normal pronation

The foot makes initial contact with the ground on the lateral section of the heel/calcaneus, the foot rolls about five percent inwards and comes in complete contact with the ground, allowing the athlete to support their body weight. This medial rolling of the foot helps to distribute the force of impact evenly, which is critical for proper shock absorption. The athlete pushes off evenly from the distal part of the foot at the end of the cycle. Foot-strike is neutral, meaning the foot rolls somewhat inward then slightly outward again during the time it is in contact with the ground, keeping the body properly aligned. Pronation allows the feet to adapt to a surface sloping at right-angles to the direction of travel and the major part of this movement involves the subtalar joint (McRae, 2004:272).

2.1.1.7.3 Over pronation

Initial contact is on the lateral section of the heel and the foot rolls medially/inward, more than the ideal five percent. The foot and ankle is unable to properly stabilize the body and the shock is not absorbed competently. The hallux and the second toe/phalange have to do all the work at the end of the cycle because the foot pushes off unevenly. Over pronation is related with overly flexible arches and muscle strength imbalances. Some athletes' feet may have a normal arch when standing or walking, but then over pronate when the forces of running are encountered (<http://www.nwhealth.edu>).

2.1.1.7.4 Under pronation (supination)

Supination is when the soles of the feet are medially rotated to face one another (McRae, 2004:272). The lateral part of the heel makes contact with the ground and the foot rolls medially/inward less than four percent. Forces of impact focus on the smaller portion of the foot and are unevenly distributed. Now the smaller phalanges are doing the most of the work at the end of the cycle. There is a lack of in-roll of the foot (supination) resulting in an outward movement of the foot and the impact is not absorbed well. The foot rolls laterally when the athlete runs and such runners usually have rigid feet that do not absorb shock very well. Supination regarding the subtalar joint axis involves the calcaneus adducting, inverting and plantar flexing (Pribut, 2005:4).

2.1.1.8 Foot motion in running

The motion of the foot during running is a complex motion along all axes.

- The foot is supinated and generally strikes the ground at the lateral heel to mid-foot with heel strike supination (<http://www.teamoregon.com>).
- Shock is absorbed by the inward rotation (pronation) of the lower leg when there is weighted pronation. Pronation unlocks the joints of the mid-foot allowing them to cushion the shock (<http://www.teamoregon.com>).
- To properly re-lock the bones of the foot for a rigid toe-off, and to allow external rotation of the leg, the ankle must rotate recover outwardly or be supinated to a neutral position as the weight is transferred further forward to the ball of the foot when weight is neutral (<http://www.teamoregon.com>).
- At toe-off the foot is slightly supinated and provides a rigid lever with supination at toe-off (<http://www.teamoregon.com>).
- During the recovery phase, the foot and leg are accelerated forward and then backwards again to match the speed of the runner before the next heel strike (<http://www.teamoregon.com>).

2.2 RUNNING ANALYSIS

Reaction force of the earth on athletes: Locomotion is the act of moving from place to place by means of one's own mechanisms or power. Locomotion in human beings is the result of the action of the body levers propelling the body. In all locomotion there must be a resistance against which the body part can push to generate a reaction force if motion is to occur. All forms of locomotion performed on the ground make up the category of motor skills of moving one's body on the ground or on other resistant surfaces (walking, running, jumping, skipping, hopping, bicycling, skating, skiing, ice skating, walking on hands, crutch walking, cartwheels), (Hamilton *et al.*, 2008:467).

The earth reacts to the athlete's weight by pushing upward against the athlete with an equal and opposite force based on Newton's third law of action and reaction. The earth pushes upwards and forward with the same amount of force that the athlete's weight is pushing downwards and backwards. The force pushing up against the athlete is called a ground reaction force (every action has an equal and opposite reaction based on Newton's third law of motion) (Carr, 1997:20). The magnitude of the earth's reaction force pushing against the athlete depends on how much the athlete pushes against the ground. The reaction force of the earth not only depends on the weight of the athlete but also on the types of movements the athlete makes (Carr, 1997:21).

The acceleration of any sprinter's body mass is proportional to how much force the athlete applies at the time frame during which this force is applied. When sprinters have the same mass and apply force for the same amount of time, the athlete who applies more force will accelerate more (Carr, 1997:31).

2.2.1 Stride length, stride frequency and running

Sprinting is a series of ballistic strides in which the body is repeatedly launched forward as a projectile (Thomas & Roger, 2000:474). The speed of running is overseen by the length of the stride and the frequency of the stride (Hamilton *et al.*, 2008:480,481). Speed is the product of stride length (distance hips travel in a stride; ground contact of leg to the ground contact of the same leg) and stride frequency (number of steps given in a particular time

period), (Carr, 1997:162; Thomas & Roger, 2000:474). There must be an optimal balance between stride frequency and stride length (<http://www.HPCsport.com>). Variation in either stride frequency or stride length will change the velocity of the run. Keep in mind the restraining, or braking force, when it might seem that simply increasing stride length would be an effective way to increase running speed. As stride length is increasing forward, the restraining force will increase an ineffective trade-off. Maintaining running efficiency is critical when modifying running speed (Hamilton *et al.*, 2008:480).

Stride frequency is the time required to complete a stride and is limited by the length of the stride. Stride frequency tends to vary among individuals and is usually believed to be more trainable (Dintiman, Ward & Tellez, 1998:172).

The stride rate of the run is affected by the speed of muscle contraction and the skill of the performer (Hamilton *et al.*, 2008:482). Cadence can be improved by maximizing the effort in removing the support foot from the ground. This maximized use of gravity should pull the runner forward. Stride frequency is the direct result of the athlete performing the sprint cycle correctly. When the athlete can achieve this, the ground reaction time (this is the largest contributor to stride frequency) should become faster. It is known that almost all athletes spend approximately the same amount of time in the air during the sprint stride, so the big difference comes in the amount of time spent on the ground. Sprinters should try to spend as little time on the ground as possible (<http://www.gillathletics.com>). Greater force application also benefits increased stride frequency (ground contact time and flight time). Studies have shown that elite sprinters spend less time on the ground and this is because they produce greater forces. As a result, despite not moving their limbs significantly faster through the air, better sprinters tend to have greater stride frequency because they reduce the amount of time they spend on the ground. This is, on the other hand, a challenge to an athlete striving to move at even greater speeds meaning they must produce greater forces over increasingly shorter periods of time (<http://www.HPCsport.com>).

Better runners have a greater stride length per given pace than poorer runners. The length of the stride is determined by the length of the leg, the range of motion in the hip and the power of the leg extensors, which drive the entire body forward. Like any projectile, the distance the body will move once it is driven into the air depends on the angle of take-off (distance that centre of gravity is ahead of take-off foot), the speed of the body's projection and the height of the centre of gravity at take-off and landing (Hamilton *et al.*, 2008:481).

Stride length is the distance one leg travel from take-off (toe-off) to touchdown (heel strike) (<http://www.gillathletics.com>) and this is dependent on leg length, angle of hip rising and strength of the leg extensors. (<http://www.pt.ntu.edu>). The distance of the stride length can be affected when the foot is placed too far in front of the centre of mass (COM) and this will lead to a braking action in each stride (<http://www.gillathletics.com>) When the ground contact is too far in front of the body, also known as over-stride, this will cause a braking effect, resulting in a loss of speed (Dintiman & Ward, 2003:232). The benefit of greater force application will increase stride length and, if all else is equal, a greater force application to the ground will cause a greater displacement of the athlete's body (greater distances will be covered with each stride) (<http://www.HPCsport.com>).

2.2.2 Vertical and horizontal component

In accordance with Newton's Law of Reaction, every action has an equal and opposite reaction. The force for the run is provided through the upward and forward ground reaction force in response to the downward, backward drive of the foot. The smaller the vertical component of this force, the greater the horizontal or driving component. In the most efficient run, vertical movements of the centre of gravity are reduced to a minimum. There should be no bounce in running (Hamilton *et al.*, 2008:483).

In an efficient run, the foot should strike the ground as close as possible to the line of gravity. If the foot should strike ahead of the line of gravity, the reaction

force to this forward and downward thrust will be a backward and upward force, acting to delay forward motion (Hamilton *et al.*,2008:483).

The more completely the horizontal force is directed straight backward, the greater its contribution to the forward motion of the body. Lateral motions are inefficient and detract from forward propulsion (Hamilton *et al.*, 2008:483).

The knees should be lifted directly upward and forward, with the motion of the entire lower extremity occurring within the sagittal plane. The arm swing should exactly counter-balance the twist of the pelvis and should not cause additional lateral motion (Hamilton *et al.*, 2008:483).

Since running is a linear motion of the entire body, the horizontal component of the momentum is much more important than the vertical component (<http://www.pt.ntu.edu>). After preparing for ground contact, the emphasis is moved to a vertical pushing motion for maximal velocity sprinting. Although sprinting is a combination of pushing and pulling, the emphasis on vertical pushes will ensure that the athlete actively accelerates the thigh down towards the ground during the flight phase and will increase leg stiffness once ground contact time is made. This in turn will reduce ground contact time, recovery mechanics and increase stride frequency and length (<http://www.HPCsport.com>). Greater horizontal velocity at touchdown also translates from shortened distances from the centre of mass. This means that the athlete is traveling faster as the body passes over the touchdown foot. Elite sprinters are capable of achieving top speeds up to 12 m/second by executing approximately five strides per second; the duration of the support phase ranges from 0.08 to 0.10 seconds, and the flight phase ranges from 0.12 to 0.14 seconds (Thomas & Roger, 2000:475). Given the same ground reaction force, a smaller vertical component of the leg drive will precede a greater horizontal component of running velocity (<http://www.pt.ntu.edu>).

The application of force is important and another factor which is equally important, is the direction of that force application. Athletes should minimize horizontal braking forces and maximize vertical propulsive forces. Once

momentum has been maximally developed during the acceleration period, the body will tend to keep moving forward at the same speed as long as the internal and external forces acting on the body are balanced, which is why propulsive forces are important. When sufficient vertical forces are generated, momentum and velocity are more easily maintained. Having the correct technique will help the athlete handle the forces better (<http://www.pt.ntu.edu.>).

Foot landing distance is the horizontal displacement of the foot relative to the centre of gravity. A sprinter should minimize this distance, as large landing distances tend to increase the braking forces (forces decelerating the runner's forward velocity) that occur at foot strike. Over striding causes a significant deceleration in running velocity at foot strike. Deceleration can be minimized if the foot is moved slightly backward prior to foot strike. The main cause of excessive braking forces is making ground contact too far in front of the athlete's centre of mass (Novacheck, 1998:77).

2.2.3 Differences between running and walking

The most prominent factors differentiating the run from the walk are the period of double support, characteristic of the walk, but not present in the run, and the period of no support, characteristic of the run, but not present in the walk (Hamilton *et al.*, 2008:479).

The differentiation between walking and running occurs when periods of double support during the stance phase of the gait cycle (both feet are simultaneously in contact with the ground). In reality there is a double support base with both feet in contact with the ground. Normally speed increases further and initial contact changes from being on the hind-foot to the forefoot. This typically marks the distinction between running and sprinting. Running is performed over longer distances and approximately 80% of these runners are mostly rear-foot strikers (Novacheck, 1998:78). Most of the remainder are characterized as mid-foot strikers. Sprinting is done over shorter distances at faster speeds. Sprinters run with a forefoot initial contact and rarely get heel

contact. When the one foot comes in contact with the ground and ends with contact of the same foot, it is called the gait cycle (Novacheck, 1998:78).

2.2.4 Ground force contact

According to <http://albaspectrum.com>, the performance of a sprinter is based on the philosophy of how efficiently the athlete can transfer ground forces through the kinetic chain (foot – ground force generation – toe – ankle – lower leg – knee – thigh – hip – trunk – shoulders – arms). Forward motion depends a great deal on the foot that has to *push-off* powerfully from the ground. As the athlete accelerates to maximum stride, ground contact time decreases and impulse production becomes increasingly dependent on the ability to generate explosive ground reaction forces (Thomas & Roger, 2000:475). Top speeds are created by applying 'optimal' force to the ground, which means that ground contact time is an important factor to consider with running speed (<http://www.albaspectrum.com>). Previous research indicates that force applied at ground contact is the most important determinant of running speed (<http://www.HPCsport.com>). The ground contact period in maximal velocity sprinting is so short (~0.1s) that it is not possible for an athlete to sufficiently produce the required forces during the stance phase without preparing the support leg prior to ground contact (<http://www.albaspectrum.com>).

2.2.5 Foot strike contact according to Centre of mass

When running the foot hits the ground in front of the body's centre of gravity, but not as far in front of the body as when walking. When running at a faster speed, the distance at which the foot hits the ground in front of the body decreases until the foot contact is almost directly under the body's centre of gravity. This position reduces the restraining part of the support phase and gives greater emphasis to the propulsive part (Hamilton *et al.*, 2008:479). At maximum speed, the restraining part disappears entirely, the use of the term 'driving phase' for the support phase in running indicates its propulsive nature (Hamilton *et al.*, 2008:480).

Stride length is best improved by increasing force against the ground. The resulting reaction drives the body's centre of mass farther forward,

lengthening the stride naturally. When the foot makes contact with the ground, it must be directly under the body's center of gravity. (Dintiman & Ward, 2003:232).

When running speed increases, the duration of the contact period decreases and the swing phase increases. As the foot strikes on the ground, the foot is in front of the centre of mass (COM) of the body, but the distance from foot contact to the COM is shorter in running as compared to walking. This distance becomes shorter with the increase of speed (<http://www.pt.ntu.edu>). Foot strike close to the centre of gravity (COG) plays an important role in running, especially with sprinting. In order to have the line of gravity passing through the ankle joint, it is better to have a mid-foot or forefoot strike. If the foot strikes ahead of the center of gravity, the ground reaction force creates an upward and backward moment that will slow down forward motion. Therefore, as the running speed increases, the distance between the contact point of foot strike and the centre of gravity decreases in order to reduce the stance and facilitate propulsion. The body will fall forward when the foot strikes behind the center of gravity and the ground reaction force will create an upward and forward momentum. (<http://www.pt.ntu.edu>).

When the foot is placed too far in front of the centre of mass, this may allow more force to the ground, but it will take more time to move the body past the foot and then get off the ground. Good elite sprinters (9.8 - 10.0 seconds) make contact with the ground at an average distance of about 17 centimeter in front of the COM. Athletes in the 10.3 - 10.5 seconds (poor elite) range on average land about 28 centimeter from the COM (<http://www.gillathletics.com>). The extension of the lower leg is another preparation to touchdown. The upper leg should be near 90 degrees in relation to the track as the takeoff leg moves forward to a position in front of the COM. The lower leg will begin to unfold / extend when the upper leg begins to move in a downward back motion. When the athlete forces this action, over-extension will occur, causing the foot to be placed further in front of the COM than what is desired. By allowing the lower leg to unfold / extend as the upper leg is being pulled back into the track, a better angle will be

achieved at touchdown allowing the foot to be placed closer to the COM (<http://www.gillathletics.com>).

The foot recovery height is fast in sprinting. To sprint faster, you need to have a quicker leg recovery technique to get the foot to the ground as soon as possible where it can be driven into the ground again. The most efficient method of returning the leg from the hip extended toe-off position to the pre-foot strike position is to flex the leg deeply at the knee prior to hip flexion (Thomas & Roger, 2000:475). Optimal recovery mechanics are another important determinant of sprinting speed and efficiency because the leg must be properly positioned for ground contact as it swings forward. By deeply flexing the knee joint, the length of the lever is effectively shortened, resulting in a more efficient and potentially faster leg recovery (Thomas & Roger, 2000:477).

Regardless of speed, alternate periods of acceleration and deceleration occur during running referred to as absorption and generation. During the period of absorption, the body's centre of mass falls from its peak height during double float. This period is divided by initial contact into swing phase absorption and stance phase absorption. The velocity of the centre of gravity decelerates horizontally during this period as well. After stance phase reversal, the centre of mass is propelled upward and forward during stance phase generation and kinetic and potential energy increase. The limb is then propelled into swing phase after toe-off. The next period of absorption begins at swing phase reversal (Novacheck, 1998:79).

2.3 DIFFERENT PHASES IN RUNNING

During the drive phase, the power of the athlete comes from a pushing action off the ball of the foot. Stride length and sprinting speed is as a result of a pushing action. There should be maximal push-off from the ground during the drive phase and the runner should push-off from the ball of the foot. The athlete will be slower when pushing off through the toes (Dintiman & Ward, 2003:232) due to a loss of force production.

2.3.1 Acceleration

In accordance with the Law of Acceleration (acceleration in the run is directly proportional to the force production), the greater the power of the leg drive, the greater the acceleration of the runner (Hamilton *et al.*,2008:483). The period of acceleration is characterized by a gradual decrease in the inclination of the trunk, a lengthening of the stride (made possible by raising the center of gravity as the trunk becomes more erect) and a decrease of the knee thrust, resulting from the gradual straightening of the knee at the moment of foot contact with the ground (Hamilton *et al.*,2008:483).

The drive phase is emphasized during the start and acceleration (Thomas & Roger, 2000:478). A sprinter should always have an erect body position when sprinting, except during the acceleration phase. During sprinting, the lead foot will (normally) land under the centre of mass of the body. When accelerating, the athlete will be leaning forward and the centre of mass will not be directly above the hips and the lead foot will land in front of the hips, causing a braking action every time that the foot makes ground contact. During the acceleration phase of the race, the trunk is more erect so that the length of the stride increase is dependent on the angle that the hip joint raises (<http://www.pt.ntu.edu>).

2.3.2 Stance Phase

2.3.2.1 Ground contact - Heel contact

The support phase begins with the contact of the foot and ends at toe-off when the body is driven into the air for the float phase (no support). During this time the knee and ankle 'give' in flexion and then extend as the body passes over the foot and is driven into the air. As the speed of the run increases, the support time decreases (Hamilton *et al.*, 2008:481).

During the support phase, the foot makes initial contact with the ground on the outside edge of the ball of the foot. The faster the speed, the higher the contact point on the ball of the foot. When striking the ground first with this part of the foot will maximize speed, however this will take great energy. When the speed is slower the contact point moves toward the rear of the foot

between the arch and heel. The heel makes brief, but definite contact with the ground when sprinting (Dintiman & Ward, 2003:233).

The first segment of the stance phase is ground contact and this phase begins with the contact of the heel to the ground until the remainder of the foot touches the ground (<http://www.HPCsport.com>). The first motion in rotation begins at the calcaneo-astragaloid joint and is continued by the astragalo-scaphoid and other small joints in this region. The force application of the contraction of the foot and leg muscles is not the same for as when there is no weight and when the weight of the body is on the foot. With weight bearing the foot cannot move, thus the force is not applied at the insertion of the muscles, but by their tendons and those points where motion is most easily possible. Inversion and eversion of the tibia and fibula is possible with weight bearing and, therefore, the astragalus corrects or increases pronation. In weak and relaxed feet, pronation may be most easily and usefully corrected by preventing its occurrence at the calcaneo-astragaloid joint and at the beginning of weight bearing. The leg is internally rotating and the foot is absorbing shock and functioning as a mobile adaptor to the ground surface (Pribut, 2005:2).

As the athlete enters the mid-stance phase, they must absorb the impact forces generated during ground contact. When an athlete's hips drop or postural deviations occur during the early moments of the mid-stance phase, it is often as a result of the athlete's failure to prepare for ground contact during the flight phase. When the athlete is over and in front of the support foot, the athlete is no longer absorbing the forces of the ground contact and has started to apply vertical and horizontal propulsive forces to the ground (<http://www.HPCsport.com>). During ground support, the role of the plantar flexors is indicated by the high moment at the ankle joint. Elastic strain energy is stored and recovered via the stretch shortening cycle in the gastrocnemius and soleus muscles. Eccentric knee extensor activity also allows elastic energy to be stored and recovered in the quadriceps muscle group, again helping to transfer power to the leg (Thomas & Roger, 2000:475).

Ground contact should be made as close as possible to the bottom dead - centre position of the foot (almost like a cyclist's foot in the pedal) (Thomas & Roger, 2000:480). When there is an overemphasis on kicking the gluteal muscles (lifting the heel too much to the gluteal muscles), there will be early grounding of the swing leg which is referred to as too much positive foot speed and it is potentially disruptive to efficient sprinting because it can increase braking forces at ground contact. The foot should move backward with respect to the body when touchdown occurs. This is also referred to as negative foot speed at ground contact (<http://www.HPCsport.com>).

As the recovery leg swings forward, eccentric knee flexor activity controls its forward momentum and helps prepare for efficient touchdown. Consequently, maximum muscle lengths and extremely high stretching rates are achieved in the hamstring group. This muscle group's activity then switches from eccentric to concentric actions and continues briefly into the support phase, facilitating power transfer to the leg (Thomas & Roger, 2000:475). The foot of the swing leg should step over the support knee and the heel should remain tucked to the buttocks when posture is correct. As the thigh of the swing leg moves in front of the body, the lower leg should begin to 'unfold' and extend at the knee. Excessive backside running mechanics is almost always the cause of 'unfolding' the lower leg prior to this point (<http://www.HPCsport.com>).

The stance phase is only 22% of the running action (<http://www.pt.ntu.edu>). Faster runners and elite sprinters spend much less time than 22% in the stance phase (Novacheck, 1998:78). While running, 40% of the time is spent in the stance phase to complete the gait cycle and 60% with walking. There is also a big difference in the time period during which force is applied (Pribut, 2005:1).

2.3.2.2 Stance phase - Mid-stance sub phase

This phase begins when the whole foot has made ground contact. The other foot is off the ground, which means that the foot in contact with the ground is bearing all the body weight. The leg is externally rotating and the foot is supinating at the subtalar joint (Pribut, 2005:2,3). At the take-off, the foot has

to act as a rigid lever to propel the body forward and there will be supination of the subtalar joint, locking of the mid-tarsal joint and dorsiflexion (extension) of the metatarsophalangeal joint (MP joint) of the hallux (<http://www.pt.ntu.edu.>).

A tight Achilles tendon or gastroc-soleus is classified as equinus. If this exists, it can be defined as when the foot cannot dorsiflex more than 10 degrees. For normal gait to occur, there should at least be 10 degrees dorsiflexion. The mid-stance phase will be early when there is an equinus heel-off. This might be one of the reasons why sprinters have tight calves and restricted dorsiflexion, because they do not allow their heels to drop once they are sprinting (Pribut, 2005:5).

2.3.2.3 Stance phase - Propulsion

Because a long lever develops greater speed at the distal end than a short lever, the length of the leg in the driving phase should be as great as possible when speed is a consideration. Leg drive should be maximized as early as possible in the stance phase (Hamilton *et al.*,2008:483).

The subtalar joint becomes a rigid lever in order to propel the body forward during the final portion of the stance phase, known as propulsion (Pribut, 2005:2,3). Propulsion begins after heel-off and ends with toe-off. The body is propelled forward as weight is shifted to the opposite foot as it makes contact with the ground (Pribut, 2005:3). The stance phase ends when the foot is no longer in contact with the ground, while toe-off marks the beginning of the swing phase (Novacheck, 1998:78).

2.3.2.4 Toe-off

The athlete's posture should remain upright. The hip of the swing leg should be projected forward slightly and the knee should be high and in front of the body. The hamstring and gluteal muscles are on stretch with the 'high knee' position which boosts their capacity for speed and force development when they accelerate the thigh down toward the ground for the following ground

contact. Better sprinters tend to toe-off closer to bottom dead centre than the less efficient sprinter (<http://www.HPCsport.com>).

Before 50% of the gait cycle is completed, toe-off occurs in running. Both feet are in the air twice during the gait cycle, once at the beginning and once at the end of swing, also referred to as double float. Toe-off occurs at 39% and 36% of the gait cycle for running and sprinting respectively. Elite sprinters toe-off as early as at 22% of the gait cycle (Novacheck, 1998:78).

2.3.2.5 The swing phase

The swing phase begins with toe-off and ends with the foot landing. The swing phase is longer than the support phase. In fast running, the initial foot contact may be on the ball of the foot, whereas in slow running the heel or the entire foot might make contact with the ground. The flexed leg in the swing phase brings the mass of the leg close to the hip, reducing the moment of inertia and increasing the angular velocity of the forward-swinging thigh, which in turn drives the centre of gravity of the body forward (Hamilton *et al.*, 2008:481).

The swing phase begins immediately after toe-off (Pribut, 2005:3) when the athlete breaks contact with the ground (<http://www.HPCsport.com>). The first portion of the swing phase is the forward swing which occurs as the foot is being carried forward (Pribut, 2005:3).

Lifting technique is normally reached at the point of maximum speed; when coordination balances precariously on the brink of risk. The foot contact is at its briefest. As momentum catapults the body past each contact, that contact must contribute to the momentum. To keep contact for even a millisecond too long in trying to express strength will result in speed loss (Pribut, 2005:3).

Resistance forces that are due to the moment of inertia of the free leg during the swing phase can be minimized. By flexing the free leg at the knee and carrying the heel high up under the hip, the leg is moved more rapidly as well

as more economically. This high knee lift increases as speed increases (Hamilton *et al.*, 2008:483).

The heel should be recovered up toward the buttocks directly following toe-off. The knee flexion observed following toe-off is largely a result of the aggressive hip flexion that occurs once the athlete has left the ground and not due to the active contraction of the hamstrings. The opposite leg should have moved to a position entirely in front of the body normally referred to as a 'high knee' position. At the end of this forward movement the leg should forcefully accelerate down and back towards the ground, then the knee naturally extends and the lower leg 'opens up'. The athlete should now prepare for the stance phase while still in flight (<http://www.HPCsport.com>). The hip flexion in sprinting continues until the recovery thigh is approximately parallel with the ground. This high knee lift enables the foot to be accelerated rapidly down and back prior to ground contact and as a result potentially increases the impact (propulsive) forces at foot strike (Morag & Cavanagh, 1999:365).

The foot recovery height is fast in sprinting. To sprint faster, you need to have a quicker leg recovery technique to get the foot to the ground as soon as possible, where it can be driven into the ground again. The most efficient method of returning the leg from the hip extended toe-off position to the pre-foot strike position, is to flex the leg deeply at the knee prior to hip flexion. By deeply flexing the knee joint, the length of the lever is effectively shortened, resulting in a more efficient and potentially faster leg recovery (Morag & Cavanagh, 1999:365).

The knee is flexed and the foot is dorsiflexed during this phase, then the foot descends as the foot is being positioned in preparation for weight bearing and the muscles are stabilizing the body to absorb the shock during heel contact (Pribut, 2005:3). The ankle should be stabilized appropriately prior to ground contact because this joint may be the weakest link in the leg spring system. The ankle should be dorsiflexed because, compared to a plantar-flexed ankle joint, ground contact will be delayed by a fraction of a second, which means that the soon-to-be supported leg foot has a few moments longer to move

closer to bottom dead centre and this reduction could be as great as 2 – 3 cm, which is enough to drastically reduce braking forces. A dorsiflexed foot places an increased stretch on the fascial linkages of the posterior anatomy and should theoretically produce a faster downward acceleration of the thigh and lower leg. This greater acceleration should create better negative foot speed and help to reduce braking forces at ground contact. The gastroc-soleus muscle complex is also on stretch, which increases its capacity for elastic force production upon ground contact. All of these points mentioned ensure that the weakest link of the leg is in the best position possible to resist the effect of gravity at ground contact (<http://www.HPCsport.com>).

Sprinters need to drive off the ground with a complete extension of the take-off leg and this produces extra force against the ground, but delays the athlete getting to the next stride. Top sprinters' feet are leaving the ground before the take-off leg reaches full extension, where the slower sprinters' feet are coming off the ground closer to full extension, but even they are not reaching full extension. By getting off the ground more rapidly, the sprinter is able to implement a more efficient recovery in preparation for touchdown of the next stride. The longer the foot stays on the ground at take-off, the longer it takes to reach full extension before it must be brought through to prepare for touchdown. The ankle crosses the opposite knee at a 34° angle for a good elite sprinter, whereas the angle is 46° for a poor elite sprinter. Thus a good sprinter is in a better position to prepare for touchdown. By crossing over the opposite knee at a tighter angle, the foot can be pulled through to a better position on the foot side to allow the sprinter to keep their touchdown distance closer to the COM (<http://www.gillathletics.com>).

When the heel contacts the ground a new gait cycle begins. In normal walking, the foot firstly contacts at the heel. When the speed is increased there might be no initial heel contact. An individual may contact at the mid-foot and then rock backwards onto the heel or not touch the heel down at all (Brukner & Khan, 1993:51; Pribut, 2005:3).

There are shoes for sprinters, middle distance and distance runners incorporating sharp spikes or like traction devices under the toe section and raised cushion cleats under the heel portion for keeping the heel in an elevated position for a good running posture and to supply cushioning as well as traction during heel contact (Pribut, 2005:6).

2.4 CURRENT RESEARCH IN THIS MILLIEU

2.4.1 Previous studies

According to Hagman (2005:4), in previous years, scientists based their conclusions regarding the impact energy dissipation role of the fat pads on the plantar side of the foot purely on anatomy and a sharp mind. Many of those conclusions have since been proven valid by experimental research. Nevertheless, a number of observations about foot structures and function were, on the other hand, disproved (Hagman, 2005:4). Early methods of load distribution under the human foot during various activities were also estimated by plantar forces from foot impressions in plaster-of-paris and clay and later on cinematographic recordings were used (Hennig & Rosenbaum, 1999:310). In 1934, Elftman was the first to use instantaneous pressure distributions. He increased the contact area of the pyramids with a glass plate and when stepping on a rubber mat whilst filming the illuminated glass plate, he was able to record instantaneous foot pressures. Some studies determine foot functions from static measurements like X-ray radiTherographs and anthropometric measurements (De Cock, 2006:4; Morag & Cavanagh, 1999:366; Novacheck, 1998:83).

Aristotle said 'Further, the forces of that which causes movement and of that which remains still must be made equal. Just as the pusher pushes, so the pusher is pushed'. In 1836, the Weber brothers, Wilhelm and Eduard, who listed 150 hypotheses including that the limb can act as a pendulum, set the outline for future research with the most detailed paper on walking and running gait to date. According to Novacheck (1998:77) the French scientist Etienne Jules Marey (1830-1904), was among the first to employ photography and use it as a true photogrammetric tool and he also designed and built the first force platform. The pendulum model for gait devised by the Weber

brothers, together with the chronography of Professor Marey, formed the basis for a detailed description of locomotion, while the chambered shoes of Marey and his associates were the first 'pressure devices' used in the analysis of human locomotion and were the first step in the quantification of gait (Cappozzo & Paul, 1997:17; Cavanagh, 1990:23; De Cock, 2006:5).

The introduction of pressure plate systems and force plate systems were helpful in studying the interaction between the foot (with or without shoe) and ground. Both devices were introduced in the last century and they arose at the same time as the use of photogrammetry to study motion. However, the restricted capabilities of the electronics used at that time did not allow for detailed studies of the movement of the foot and its segments (Hagman, 2005:8).

In the last decennia, motion analysis systems based on video methods have progressively improved. Motion analysis was two-dimensional and focused on whole-body movements in the early periods (Hagman, 2005:8). There is a dynamic process with changes in direction and magnitude of the ground reaction force acting on the foot-ankle complex thus resulting in changes in foot biomechanics during foot-ground interaction in locomotion (Abboud, 2002:169; De Cock, 2006:3). With two dimensional (2D) and three dimensional (3D) motion analysis systems, opportunities are provided to describe and study the kinematical characteristics of locomotion. Borghese, Bianchi and Lacquaniti (1996:371) and Zatsiorky, Werner and Kaimin (1994:115) did walking studies while Areblad, Nigg, Ekstrand, Olsson and Ekstrom (1990:938), McClay and Manal (1999:1633), Novacheck (1998:80) and Williams (2000:178,179) did studies on running (De Cock, 2006:4).

2.4.2 Capabilities of recent measuring devices

Recent measuring devices provide a homogenous sensor grid, applied in a plate as well as in in-sole systems and these innovative sensor technologies and high frequency digital sampling techniques allow accurate plantar pressure measurements at sampling rates of 500Hz or more and with high spatial resolution (>2sensors per cm²) in large surface pressure plates

(0.5m²). Present-day innovative techniques and devices such as in-shoe pressure transducers, load cells, force plates, floor-mounted transducers matrices and glass plates using critical light reflection techniques, provide a detailed registration and analysis of foot-to-ground interaction, even during running, as a detailed pressure image of the entire foot sole can be obtained (De Cock, 2006:5; Orlin & McPoil, 2000:404). In pressure plate devices, the pressure distribution underneath the whole sole of the foot is reflected (De Cock, 2006:6).

Matrix measurements of plantar pressures often used larger sub-areas or masks, either manually or automatically defined, to analyse local pressure distribution. A manual detection of sub-areas is dependent on the accuracy of the operator and may influence the repeatability of the measurements. Plantar surface areas of interest are divided in most cases by automated or semi-automated techniques. The automatic selection of foot sub-areas is mostly based on the geometric characteristics of the footprint (Giacomozzi, Macellari, Laerdini & Bendetti, 2000:158; De Cock, 2006:6). A general mask is then scaled to the specific dimensions of an individual foot print. To reflect the automated making, in semi-automated devices, the researcher is able to adjust the area selection manually either based on a qualitative interpretation of the foot pressure print or on the peak pressures of the footprint. The most common sub-areas to analyze pressure distributions underneath the sole of the foot are the rear-foot, mid-foot and forefoot. The rear-foot (heel) area is subdivided into two sub-areas (Hennig & Rosenbaum, 1991:307; Hennig, Staats & Rosenbaum, 1994:39; De Cock, 2006:7) to differentiate between lateral and medial heel loading during gait. The forefoot area is divided into sub-areas covering one or more of the metatarsal heads, the hallux or the lesser toes (Hennig & Rosenbaum, 1991:308; Hughes, Clark, Linge & Kienerman, 1993:515; Hennig *et al.*, 1994:39; Rosenbaum, Hautmann, Gold & Claes, 1994:195; Kernozek & LaMott, 1995:143; Walker & Fan, 1998:380; McPoil, Cornwall, Dupuis & Cornwall, 1999:500; Bryant, Tinley & Singer, 1999:118; Bryant, Tinley & Singer, 2000:297; VanZant, Mcpoil & Cornwall, 2001:339; De Cock, 2006:7).

2.4.3 Foot contact sites

According to Hagman (2005:8), anatomy books often state that the foot basically makes contact with the ground through three bony contact sites: the calcaneus, the head of the first metatarsal and the head of the fifth metatarsal. The latter two were supposed to form the medial-lateral foot arch. It might be that the observation of a medial-lateral arch was made while the feet were non weight-bearing (Hagman, 2005:8). With the introduction of plantar pressure measurement systems, it was possible to monitor this observation (Hennig & Rosenbaum, 1991:307; Hallemans, D'Aout, De Clercq & Aerts, 2003:17). De Cock, De Clercq, Willems and Witvrouw (2005:434) indicated that during walking and running there was no such thing as a medial-lateral foot arch because of significant high pressures underneath the central forefoot and that in most individuals the second and third metatarsal head supports the larger amount of pressure and not the first and fifth metatarsal head (Hagman, 2005:8).

2.4.4 Foot motion

The motion of the foot that could be described in the whole-body motion was the dorsal/plantar flexion of the foot around the ankle joint. The foot was assumed to be one rigid body defined by a line through the length axis of the foot. The attention was then shifted away from the whole body to the lower leg by some authors (Hagman, 2005:8). Pronation/supination and calcaneal inversion/eversion motions were quantified during two-dimensional studies (Nigg, Cole & Nachbauer, 1993:909) where the focus was on the so-called rear-foot motion, which is the motion of the rear part of the foot (calcaneus and talus) and the lower leg (tibia and fibula) in the frontal plane. This motion was experimentally examined in a variety of conditions, for example barefoot, shod, over ground, on a treadmill and during different velocities. From epidemiology studies (McClay, 2000:142), this motion pattern could be related to certain sustained injuries (Hagman, 2005:8).

Pressure distribution measurement techniques are useful in analyzing the mechanical behavior of the human foot during static and dynamic loading situations in people (Hennig & Rosenbaum, 1991:308).

2.4.5 Plantar pressure devices and ground interaction

There are many complexities which one is not aware of when walking or running. The ground reaction force acts on the foot, which is the only interface between the human body and the ground during walking and running (Abboud, 2002:171; De Cock, 2006:3). Apart from the key role of the foot in the body's forward progression and the maintenance of stability during locomotion, the foot also performs other major biomechanical functions during the stance phase (Abboud, 2002:166,172; De Cock, 2006:4).

Multi-segmented foot models provide insights in the interaction of the rear-foot, mid-foot and forefoot during gait (Leardini, Benedetti, Catani, Simoncini & Giannini, 1999:529; Carson, Harrington, Thompson, O'Connor & Theologis, 2001:1302; Hunt, Smith, Torode, Keenan, 2001:597; Arampatzis, Bruggeman & Morey Klapsing, 2002:130; MacWilliams, Cowley, Nicholson, 2003:220). Motion track systems and force plate systems are usually combined in gait analysis to quantify the interaction of the ground reaction force on the locomotor system. Information is gathered about the action of the vertical and shear component of the ground reaction force during the stance phase. Force plate measurements provide little information about the forces that are created between the human body and the ground because these forces are distributed over various supporting structures of the foot (Hennig & Lafortune, 1997:120; Orlin & McPoil, 2000:406 De Cock, 2006:4).

In a multi-segmented foot model, the force interaction underneath those sub-areas of the plantar surface could provide insights into the dynamic and functional behavior of the supporting foot structures during the stance phase. Plantar pressure devices are used to quantify the local loads underneath the sub-areas. Direct and objective information on how various foot structures interact with the ground and an opportunity to characterize functional aspects of the ankle-foot complex during the foot-floor or foot-shoe interaction during gait can be gathered from plantar pressure measurements (Alexander, Chao & Johnson, 1990:163; Bennett & Duplock, 1993:674; Harrison & Folland, 1997:52; Orlin & McPoil, 2000:400; De Cock, 2006:4).

Studies performed by Stacoff, Kalin and Segesser (1989:384, 1991:489) were probably the first to introduce a multi-segment foot model. His model consisted of a rear-foot (calcaneus) and a forefoot (head of metatarsal one and five) (Hagman, 2005:8). He studied the torsion between the two segments in the frontal plane. One is able to extract torsion curves that have a sharp increase at the end of the stance phase when one looks at the findings of Stacoff *et al.* (1989:385, 1991:489). This is perhaps not real torsion motion. One of the tribulations with two-dimensional motion analysis is the parallax errors. The plane of the camera should be parallel to the plane of motion that one wants to study when only one camera is being used. This is not feasible in the case of foot motion since a foot-unroll is not constrained to one camera plane. The frontal plane of the foot experiences a motion of about 90° with respect to the transverse ground plane. This problem is inherent to the two-dimensional approach, which was the standard at that time. It became possible to measure motion in its true three-dimensional nature with the additional development of motion analysis systems (Hagman, 2005:9).

Of the first to describe rear-foot motion in three dimensions were Soutas-Little, Beavis, Verstraete and Markus (1987:289) using an Euler or Cardan representation of motion. They compared the supination/pronation or inversion/eversion motion of the foot with respect to the two-dimensional approach. New research appeared exploring foot motion in different conditions such as barefoot, shod, standing, walking, running, but also on methodology of measurements such as the relationship between the measurements of external kinematics to the motion of the underlying bone (Areblad *et al.*, 1990:934; Nigg *et al.*, 1993:911; Reinschmidt & Nigg, 1995:412; Eng & Winter, 1995:753; Benedetti, Catani, Leardini, Pignotti & Giannini, 1998:209; McClay & Manal, 1999:1632;). Better resolution and higher measurement frequencies were attained with relatively less expensive systems because of the performance of motion analysis systems that kept improving. These performance enhancements led to the introduction of multiple-segment foot models being measured three dimensionally (Carson *et al.*, 2001:1304; Hunt *et al.*, 2001:597; Arampatzis *et al.*, 2002:134; Hunt & Smith, 2004:396; Hagman, 2005:10).

2.4.6 The centre of pressure (COP) and pressure time curves

Nowadays, technologically advanced measuring devices with their high recording speed and high spatial resolution provide a considerable volume of data. The graphical representation of the measurement is a first step in the interpretation of plantar pressure distribution (De Cock, 2006:8).

There are different colors for different types of pressure under the foot. The centre of pressure (COP) is the instantaneous point of application of the ground reaction force and its location changes during the stance phase (Miller, 1990:209,210; De Cock, 2006:8). The location of the COP is mostly defined with respect to the foot y-axis, drawn from mid-heel to mid-forefoot and the x-axis perpendicular to the foot axis. Displacements in medial-lateral and anterior- posterior directions, together with the maximal distances and the range of displacement, are the most common variables used in the analysis of the COP. The velocity of the COP reflects the dynamics of the foot when making contact with the ground and may be a better indicator of foot function than displacement (De Cock, 2006:9).

Pressure-time curves underneath sub-areas reflect the pressure distribution over time during the stance phase. From these time-curves, instant of first contact, instant of last contact, instant of peak pressure and contact duration for a specific area are derived. Based on the timing variables, an image of the foot roll-over can be reconstructed which helps with the interpretation (Blanc, Blamer, Landis & Vingerhoets, 1999:102; De Cock, 2006:9).

During running, most athletes first hit the ground with the lateral border of the shoe – some with the rear lateral part of the shoe (rear-foot strikers) and most others with the middle lateral region of the shoe (mid-foot strikers) (<http://www.pponline.co.uk>). Long distance runners are mostly rear-foot ('heel') strikers and faster runners (sprinters) are mid-foot strikers. Keep in mind that sometimes even forefoot strikers usually let the heel hit the ground at some point during the foot strike. Forefoot strikers have slightly shorter ground-contact times than rear-foot strikers - an effect which can improve stride rate. Force-plate studies discovered that the maximal vertical ground

reaction force during running is typically about three times the body weight for both rear-foot and mid-foot strikers; in other words, hitting the ground with the mid-foot does not reduce or cushion this impact force (<http://www.pponline.co.uk>).

There are, however, some subtle differences in the centre of pressure (COP), the geometric centre of the distribution of force applied by the foot to the ground. A rear-foot striker moves their COP from the rear lateral border of the foot to the midline within about 15 milliseconds of initial contact and then continues along the midline to the centre of the forefoot, where it remains for most of the stance phase of gait. Mid-foot strikers have an initial COP at about 50% of shoe length, which then moves backwards until the rear part of the shoe makes contact with the ground. After moving to the back of the foot, the COP then moves forward to the middle of the forefoot (to approximately the same place as for rear-foot running) and stays there until toe-off (<http://www.pponline.co.uk>).

Due to the complexity of the foot segment it is difficult to analyze the foot-to-ground contact during the stance phase in locomotion. Recent studies used multi-segmented foot models to provide information about kinematics and kinetics of the rear-foot, mid-foot and forefoot and how they interact during gait (Leardini *et al.*, 1999:530; MacWilliams, Cowley & Nicholson, 2003:217). Pressure measurements provide direct information on how the various foot structures and the ground interact (Alexander *et al.*, 1990:156; Titianova *et al.*, 2004:278). Different sub-areas of the sole of the foot have been proposed for plantar pressure measurements (Bryant *et al.*, 2000:299; MacWilliams *et al.*, 2003:218; McPoil *et al.*, 1999:498; Titianova *et al.*, 2004:278). For example, the sole of the foot has been considered as one area to interpret subtalar motion through plantar pressure measurements. Some studies reported the use of sensors placed on the sole by palpation of the anatomical structures (Alexander *et al.*, 1990:158; Giacomozzi *et al.*, 2000:159). Limitations of this technique are the relatively small size of sensors and an altered foot-to-floor contact due to the sensors under the foot (Giacomozzi *et al.*, 2000:159).

More recent measuring devices applied as a plate or as insole system, create a pressure image of the entire sole. On the pressure images, masks or sub-areas can be found which are based on the anatomical structures of the foot and can be resultant of radiographic data (Cavanagh, Rodgers & Liboshi, 1987:265; Hastings, Commean, Smith & Pilgram, 2003:878).

The most common sub-areas to analyze pressure distributions are the rear-foot (often divided into medial, central and lateral heel areas), mid-foot and forefoot (metatarsal heads, hallux and lesser toes), (Rosenbaum *et al.*, 1994:194; Hennig *et al.*, 1994:35; Walker & Fan, 1998:380; McPoil *et al.*, 1999:498; Bryant *et al.*, 2000:297). The data collected from these sub-areas provide peak and mean pressure values and pressure-time integrals (Hennig *et al.*, 1994:36; Walker & Fan, 1998:380; Bryant *et al.*, 2000:297). Timings of plantar pressure data also describe foot dynamics in stance (Blanc *et al.*, 1999:102; Titianova *et al.*, 2004:277) and could explain the etiology of overuse injuries in running, as the mechanism of unrolling the foot during stance in running seems to be important (Hintermann & Nigg, 1998:175; McClay, 2000:145). Current technologies allow accurate plantar pressure measurements at sampling rates of 400 Hz or more and with high spatial resolution (>1 sensor per cm²) in large surface pressure plates (>0.5m²), which permits analysis of foot-to-ground interaction during running.

2.4.7 Running differs from walking

Running differs from walking by having larger impact and push-off forces (Keller, Weisberger, Ray, Hasan, Shiavi & Spengler, 1996:253) and a shorter stance phase (Blanc *et al.*, 1999:101). De Cock *et al.* (2005:433) did a study to establish a reference dataset for temporal parameters describing the succession contact times of important anatomical plantar pressure sub-areas in the foot roll-over during barefoot jogging. They also studied conflicting views about gender differences, analysis of asymmetry and intra-individual variability. They used data from literature regarding foot roll-over in walking to compare it with foot roll-over characteristics in running.

The study was done on a population of 220 healthy young adults without foot pathologies and they provided a 'stable' running pattern at sub-maximal jogging speed on an indoor runway. Good (93% > 0.75) and very good (18% > 0.90) Intra Class Correlations (ICCs) between trials were found in almost all temporal characteristics of the foot roll-over except for the heel sub-areas (Wearing, Urry, Smeathers & Battistutta, 1999:260). During initial contact phase, the initial impact force peak occurs, which is a reflection of the fast deceleration of the distal segments of the support leg along with the slower deceleration of the head, arms and trunk (Bobbert *et al.*, 1992:228). A minor change in timing of the acceleration of one of the segments during initial contact can change the timing of total impact force peak ($t_i = 14 \pm 5$ ms), (De Wit, De Clercq & Aerts, 2000:274) occurring during initial contact phase. This could cause a greater intra-subject variability of time to peak pressure underneath the heel. An additional possible explanation for this increased variability is based on the location and magnitude of the heel areas.

Gait is commonly assumed to be symmetrical (Goble, Marino & Potvin, 2003:279), and in previous studies symmetry has been found for stride, swing and stance durations during gait at a self-selected speed (Keller *et al.*, 1996:255; Titianova *et al.*, 2004:278). Some differences were found between the left and right feet for temporal aspects in foot unroll during the studies done by De Cock (2006:30).

Partial squared eta values revealed that only a very low percentage of the variance could be explained by asymmetry analysis of the foot roll-over of the large population but, for the individual, the analysis should always include the left and right foot separately (Cavanagh & Lafortune, 1980:397). Previous research (Blanc *et al.*, 1999:101; Wearing *et al.*, 2001:658) described foot roll-over patterns based on the on- and off-switching of four sub-areas underneath the foot (heel, M₅, M₁, hallux). The most common pattern that was found in both studies was heel-M₅-M₁-hallux, both for initial contacts and final contacts. De Cock (2006:30) used more sub-areas of the sole of the foot and some of the areas could be grouped together, as there was no discrimination in timing between initial or final contact during foot roll-over. Initial contact patterns

were the heel lateral and heel medial and also metatarsal five and metatarsal four grouped. No differences were found in timing between metatarsal three and metatarsal one when push-off occurred and the forefoot areas reached the end of contact with the ground. A common roll-over pattern for final contacts of the sub-areas, heel lateral, heel medial, metatarsal five, metatarsal four, metatarsal three and one, metatarsal two and toe one was found for almost 81% of the entire population while 8.5% revealed a more central final push-off over M_2 in their roll-over pattern.

Initial contact phase starts with first foot contact and ends at FMC (first metatarsal contact). During initial contact phase, the peak pressure underneath the two heel areas occurs at approximately 4% of total foot contact (TFC), reflecting the impact. This impact peak timing concurs with timing of the first force peak in the vertical ground reaction force in barefoot running. Previous studies showed that the foot contact in walking and running starts with a more lateral loading of the heel, followed by medial loading (Alexander *et al.*, 1990:156; Novacheck, 1998:79). The study of De Cock (2006:31) revealed that heel lateral and heel medial could be considered as one single area making contact with the ground. No differences were found between the two heel areas with regard to time to peak pressure.

2.4.8 Leg stiffness and high arched runners

Leg stiffness is one of the mechanical parameters that may be related to arch structures. Stiffness may be an important factor during running as it represents the ability of the entire lower extremity to attenuate the excessive forces generated during the stance phase (Dorsey *et al.*, 2003:1).

Leg stiffness has recently been found to differ in individuals with different dynamic foot orientations during running. With a high-arched individual an increased height of the medial longitudinal arch is often linked with a more supinated position of the foot which is why the foot may show decreased pronation throughout the stance phase (Dorsey *et al.*, 2003:1).

2.4.9 Barefoot versus shod running

De Wit *et al.* (2000:269) did a study on nine trained male long distance runners to provide a comprehensive description of barefoot running using a statistical representative data set (Kistler force plate, Ariel Performance Analysis System Inc, infrared photocells) to compare barefoot with shod running. Spatio-temporal variables, ground reaction forces and sagittal and frontal plane kinematics of barefoot and shod running at three different velocities were analyzed and compared (De Wit *et al.*, 2000:269).

Regarding the sagittal plane kinematics, a more extended body position and a smaller touchdown velocity of the foot were found during barefoot running. De Wit *et al.* (2000:270) found that for all the tested velocities, runners take considerably smaller steps at a higher frequency for the barefoot condition and a shorter contact time. Barefoot running had a larger landing rate than shod running and more than one impact peak was found. The maximal local pressure underneath the heel was for the barefoot condition. Eversion at impact was considerably smaller with barefoot running. They also found that the placement of the foot is a lot more horizontal in barefoot running than in the shod condition. This is caused by a larger plantar flexion of the ankle and a significantly more vertical position of the shank in the barefoot condition. This can be caused by the larger knee flexion because there is no difference in thigh orientation at touchdown between barefoot and shod running (De Wit *et al.*, 2000:273). This more horizontal foot placement is prepared well before touchdown.

The horizontal component of the touchdown velocity is significantly smaller in barefoot running. As awareness of mechanical inputs and pain is well established in the foot sole, it is assumed that runners take on a flatter foot position in barefoot running in an effort to limit the local pressure below the heel (De Wit *et al.*, 2000:273,275). This assumption agrees with the findings of Hennig & Lafortune (1997:112), who measured a considerable decrease in heel loading, with a shift towards more weight bearing in the forefoot, when running with shoes with harder soles (De Wit *et al.*, 2000:275).

The vertical deceleration distance of the ankle is significantly reduced in barefoot running when concerning the initial ground contact phase. This can be attributed to the absence of a deformable shoe sole and to a smaller movement range for plantar flexion through the flatter foot placement in barefoot running. Frontal plane kinematics showed initial eversion between contact and the occurrence of the impact peak is also considerably smaller for barefoot than for shod running. The biomechanical model of Stacoff *et al.* (1989:383,384) supposed that a larger initial eversion offers an additional deceleration mechanism during initial foot contact (De Wit *et al.*, 2000:275). As a consequence, the momentum of the support leg will be less adequately decelerated in barefoot running (Bobbert, Yeadon & Nigg, 1992:228; De Wit *et al.*, 2000:274).

The support leg changes from a more extended to a more flexed configuration in shod running compared to barefoot running during the initial ground contact phase. Impact peak occurs significantly later for shod running. The more flexed knee position in shod running continues throughout mid-stance resulting in a larger maximal knee flexion in the shod condition. Kinematic differences between both conditions disappear towards the end of the stance phase at push-off. External forces are non-different during mid-stance. This implies the overall stiffness of the support leg to be higher during barefoot running. The ratio of the maximal vertical ground reaction force can be taken as a measure for overall leg stiffness during stance phase in locomotion and indeed displays significantly higher values for the barefoot condition. Runners adjust their leg stiffness to accommodate for rather large changes in surface stiffness.

Ground contact time and stride frequency remain the same on different surfaces. The foot-ground interface is less compliant in the barefoot running condition, but the overall leg stiffness during stance phase is higher compared to shod running. This presumes that there is no equivalent compensation towards a constant vertical stiffness, which can be indirect from the significantly smaller foot contact time in barefoot running and relating from this is the higher step frequency. The horizontal distance traveled through the

stance phase is smaller in barefoot running and explains to a large extent the reduction in step length. The flight phase, on the other hand, remains unaffected with the distance and duration of the airborne phase being the same for both conditions (De Wit *et al.*, 2000:276).

Adaptations in stride kinematics to barefoot running are primarily due to changes in touchdown geometry and the following joint movements during initial ground contact. The most well-known difference between both conditions is the much flatter foot placement at touchdown, realized by a larger plantar flexion and by more knee flexion. This causes the heel to be placed closer to the vertical projection of the hip and explains to a great amount the reduction in the horizontal distance traveled during the stance phase. A high consistency between the runners in sagittal plane kinematics cannot be found for the foot and ankle movements in the frontal plane. The lack of consistency in this regard could not be explained by the results of De Wit *et al.* (2000:276).

2.4.10 Rear-foot versus forefoot strikers

De Wit *et al.* (2000:276) investigated ground reaction force parameters with respect to adaptations to speed and mode of progression and to type of foot-strike. Six subjects were classified as rear-foot strikers and six as forefoot strikers. Increased speed was accompanied by shorter force periods and larger peak forces. According to De Wit *et al.* (2000:276) the changeover from walking to running resulted in a shorter support phase duration and a change in the shape of the vertical reaction force curve.

The vertical force and peak impact showed at the touch-down among the rear-foot strikers during running but normally not among forefoot strikers. The first mediolateral force peak was laterally directed for the rear-foot strikers but medially for the forefoot strikers. There is a change with speed in the complex interaction between vertical and horizontal forces needed for propulsion and equilibrium during human locomotion.

CHAPTER 3

MATERIALS AND METHODS

3.1 INTRODUCTION

The following information pertains to the materials and methods of this study. It includes the study site, study design, study population, exercise mode and apparatus as well as measurement techniques.

3.2 STUDY SITE

All tests for the study were conducted at the Free State Sport Science Institute (FSSSI) situated in Bloemfontein in the Free State Province. The FSSSI provide sport science services to Free State provincial athletes and therefore, the FSSSI was the ideal institution to approach for assistance with the research project. The materials used for the research are also located at this facility. It is a laboratory environment, which is preferred for research studies.

3.3 STUDY DESIGN

This study was presented to the Ethics Committee of the University of the Free State prior to commencement.

3.4 STUDY POPULATION

The following points will discuss the selection criteria for the study population.

3.4.1 Number of subjects

Ten male Free State provincial sprint athletes between the ages of 16 and 18 years were chosen for the study. All were actively training with the same coach at the time the tests were conducted and were in their pre-season cycle of the macro-cycle of their periodization. Thus, the athletic skills training session was handled by the coach according to the pre-season cycle.

Ten male subjects between the ages of 16 and 18 years were chosen to participate as the control group for the study. The control group consisted of

non-sprinters, who had a general training frequency history of training sessions one to three times per week for the purpose of basic physical conditioning. The subjects in the control group do not compete in sport events, but train only for recreational purposes.

3.4.2 Inclusion criteria

Participants considered for inclusion in the study had to comply with the following criteria:

- Must be a current Free State provincial sprinter
- Male between the ages of 16 and 18 years

3.4.3 Exclusion criteria

A participant was excluded if he:

- Refused to participate
- Is currently injured
- Just finished rehabilitation related to an injury
- Is not healthy and currently on medication

3.4.4 Justification for the inclusion and exclusion criteria

- The participants had to give consent before they could be enrolled in this study.
- Each participant signed an Informed Consent form.

3.4.5 Subject identification

Individuals were randomly selected by means of the inclusion of any of the first ten participants responding to the invitation to participate in one of the two specified groups (sprinters and control group) in the study.

3.4.6 Withdrawal

Participants could withdraw from the project at any stage, without any consequences and would be replaced with suitable candidates. All of the participants of the research study, sprinters and non-sprinters, completed the study. There were no withdrawals in this study.

3.4.7 Financial implications for the participants

The FSSSI availed the facilities, materials and apparatus at no cost to the researcher and the participants. A request from the FSSSI was made towards the researcher to avail the study thesis results for possible implementation at the FSSSI.

3.5 EXERCISE MODE AND APPARATUS

3.5.1 Apparatus

The RSscan International's Footscan® 7.x plate system was used to conduct the tests in conjunction with the Brower Timing system. The RSscan was used to measure foot ground contact, foot roll-over and foot pressure forces. The Brower Timing system was used to capture sprinting time over 10 meter and 20 meter distances.

3.5.2 Protocol

The research started with five walking trials on the RSscan. Both feet had to have gone through their walking cycles on the RSscan plate for the recording to be valid. Where foot placements were cut off at the different end ranges of the RSscan plate, the trial was discarded and had to be repeated by the participant.

The participants in both the sprinter and control group conducted their own personal warm up routines. They had to warm up properly in order for them to run at maximal sprinting speed and to avoid any injuries. All of the participants had to be barefoot while doing the test. The participants started the 20 meter sprint on their own time, as soon as the researcher was ready to take the measurements. With every trial, the participants had to sprint past the last timing gate (Brower Timing system) before slowing down, in order for the researcher to have a valid 20 meter speed time. The participants had ample resting time between trials, as they could only do their next trial once fully rested. All of the subjects had to run eight 20 meter trials. The eight trials consisted of four trials of a left foot strike on the RSscan plate and four trials of a right foot strike on the RSscan plate. All valid trials (where the foot made proper contact with the RSscan) were saved as recordings and all invalid

trials (where foot placements were cut off at the different end ranges of the RSscan plate or if there were more than four readings on the same foot) were discarded.

3.6 MEASUREMENT TECHNIQUES

The following paragraphs will describe the measurement techniques used in this study.

3.6.1 Procedures

- Before the practical trials commenced, all the apparatus were placed in their determined positions.
- The RSscan system (computer, 2m plate, cables, 3D box), as well as the Brower Timing system was placed in position on the tartan track. The RSscan plate was placed on the 18 – 20 meter mark.
- The sprinting trials were performed on an under-roof tartan track.
- Three two-meter long PVA mats (1cm thick), were placed in front of the RSscan plate and one two-meter long PVA mat, after the RSscan plate. Thus, of the 20 meter distance, the last two meters was run on the RSscan plate. Due to the fact that the RSscan is 1cm in height, PVA mats which are 1cm thick were used to ensure that there was no difference in height when the participants made foot contact with the RSscan plate. A difference in height would have changed the biomechanics and therefore, the readings would have been invalid if the PVA mats were not used.
- The Brower timing gates were aligned on the following measurement indicators: 0 meters, 10 and 20 meters.
- A calibration test was completed to ensure that all the equipment was calibrated before the testing commenced. The researcher captured the data as each participant did their various trials.

3.6.2 Quality control

Quality control of the apparatus is performed on a daily basis, according to the manufacturer's specifications. This is to verify that the RSscan system is performing correctly and also to ensure accuracy and reliability.

3.6.3 Statistical analysis

Data was captured electronically by the researcher on Microsoft Excel (Microsoft Office 2007). The RSscan software was used for further analysis of the data and descriptive statistics, standard deviations, minimum and maximum values, were calculated. The calculated values are presented in the various tables and figures in chapter four.

The mean values of the sprinter group were compared to the control group. The student t-test was used to test for significant differences between the groups. A p-value of ≤ 0.05 was accepted as statistical significant throughout the study.

CHAPTER 4

RESULTS OF THE RESEARCH

4.1 INTRODUCTION

Ten sprinters (the test group) and ten non-sprinters (the control group) participated in this research study. The research was mainly focused on: a) the classification of the three different foot types, b) the determination of the foot roll-over during sprinting and; c) the peak pressures of the different sub-areas of the foot during sprinting.

The sprinting speed and ground contact times were also used to support the areas of main focus, as described above. All of the participants were tested barefoot. Data collected from the test results was statistically analyzed to show the classification of sprinters and non-sprinters with regards to the three different foot types, the foot roll-over and the peak pressures of the different sub-areas of the foot of all the participants. The test result analyses are subsequently discussed.

4.2 RESULTS

4.2.1 Classification of the different foot types (barefoot walking results)

Measurements were derived from the barefoot walking results to classify the foot types (flat, normal, high arch foot) of all participants. Results furthermore show the differences between the classification of foot types of sprinters vs. control group (**Table 4.1** and **Figure 4.1**).

As illustrated in **Table 4.1**, there were no significant differences ($p < 0.05$) between the left foot type (classification) for sprinters versus the left foot type of the control group ($p=0.3317$). However, the right foot type (classification) showed a significant difference ($p=0.0198$) between sprinters versus the control group.

Table 4.1: Results for the classification of different foot types for sprinters and the control group.

LEFT SIDE			RIGHT SIDE		
Foot type	Group		Foot type	Group	
	Sprinters	Control		Sprinters	Control
Flat	2	0	Flat	4	0
High	3	6	High	3	9
Normal	5	4	Normal	3	1
Total	N=10	N=10	Total	N=10	N=10
<i>p = 0.3317</i>			<i>p = 0.0198</i>		

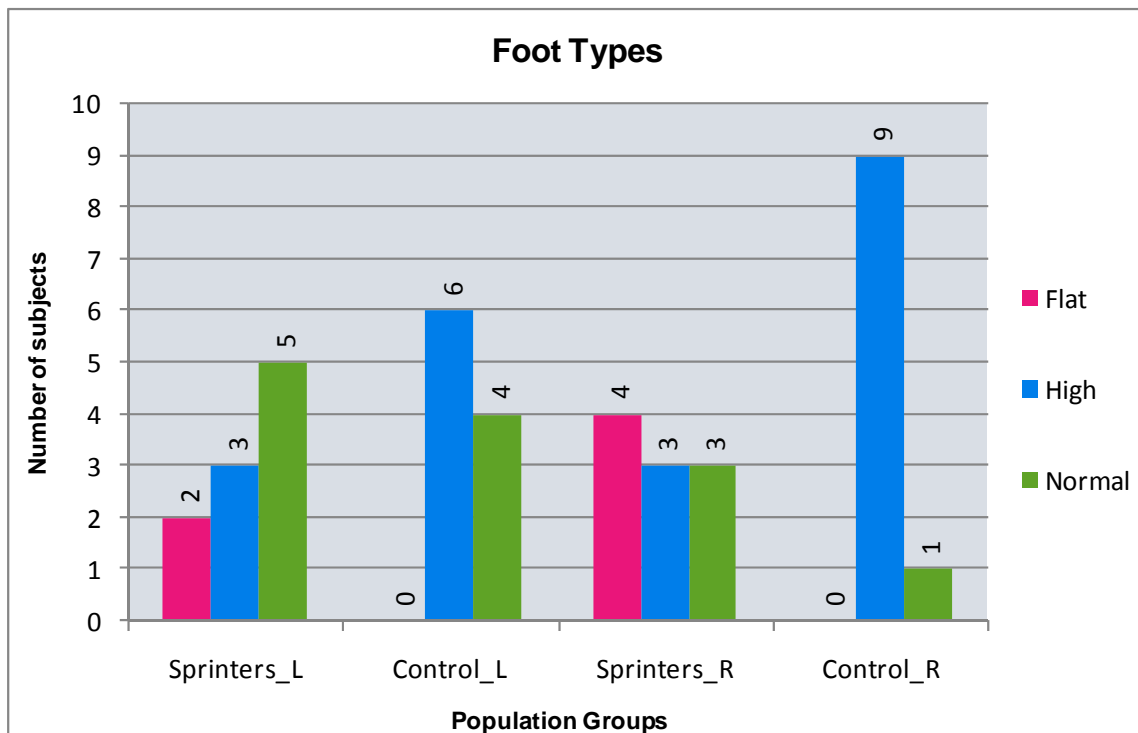


Figure 4.1: Indication of foot type classification according to results.

Table 4.2 and **Figure 4.2** which were derived from **Table 4.1**, indicate the combined results of the left foot and right foot of the sprinters vs. the control group, from the barefoot walking results of the RSscan measurements.

Table 4.2: Barefoot walking: foot types for sprinters left foot and right foot combined versus control group left and right foot combined

Foot type	Group		Total	Foot type	Group		Total
	Sprinters L	Sprinters R			Control L	Control R	
Flat	2	4	6	Flat	0	0	0
High	3	3	6	High	6	9	15
Normal	5	3	8	Normal	4	1	5
Total	N=10	N=10	N=20	Total	N=10	N=10	N=20

Figure 4.2 indicates that the control group dominantly have a high foot type and the sprinters dominantly have a normal foot type. There are no significant ($p < 0.05$) differences between the classification for high, normal and flat foot types for the measurements derived from the sprinters' results.

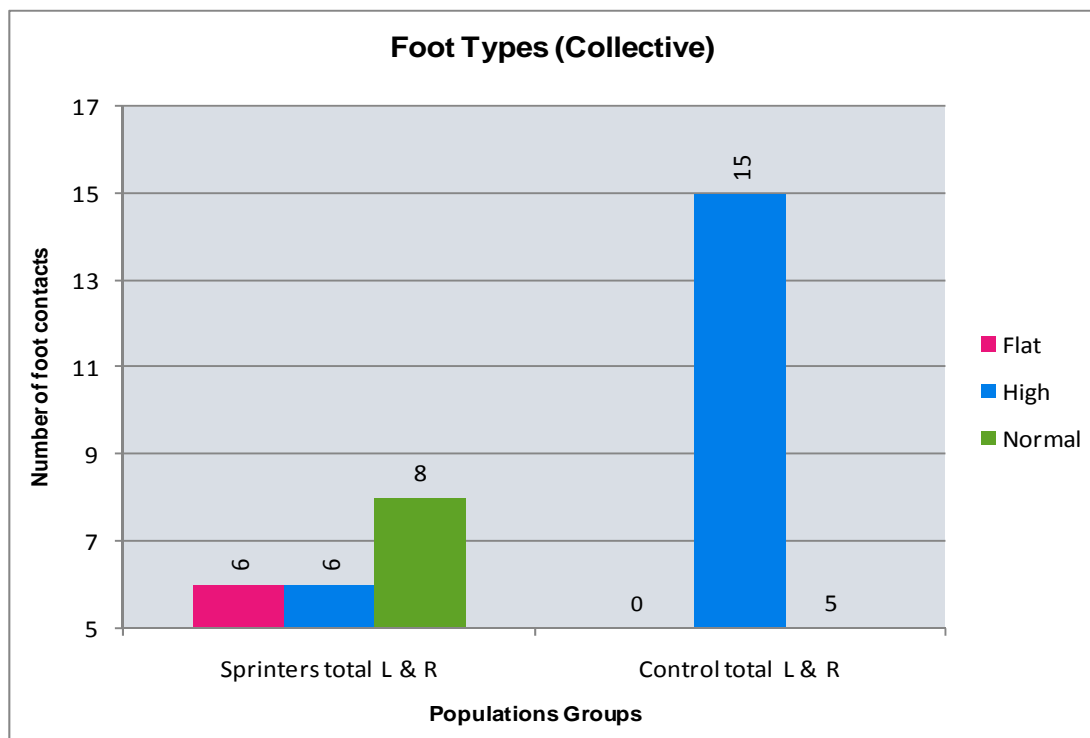


Figure 4.2: Foot type classification for sprinters vs. control group

4.2.2 Foot roll-over (barefoot sprinting results)

All research participants sprinted barefoot to determine the barefoot foot roll-over during sprinting. The barefoot sprinting results were used to analyse the difference between the foot roll-over of sprinters vs. control group. The RSscan classifies foot-roll-over in different foot contact phases during sprinting.

4.2.2.1 Contact phases

Table 4.3 and Figure 4.3 indicate the different foot contact phases of the control group and the sprinters respectively.

Table 4.3: Temporal characteristics of the foot roll-over during the different contact phases of barefoot sprinting

LEFT SIDE	N=10		compare mean values	N=10	
	SPRINTERS		p-value	CONTROL	
	Mean	Std Dev	Sprinters vs Control	Mean	Std Dev
ICP_Perc	1.02	6.44	0.5604	-0.40	3.94
FFCP_Perc	1.52	1.67	0.4035	2.40	2.81
FFP_Perc	4.04	13.82	0.007	26.40	18.66
FFPOP_Perc	89.47	15.38	0.1292	99.79	13.59

RIGHT SIDE	N=10		compare mean values	N=10	
	SPRINTERS		p-value	CONTROL	
	Mean	Std Dev	Sprinters vs Control	Mean	Std Dev
ICP_Perc	1.08	5.22	0.7783	0.47	4.40
FFCP_Perc	1.18	1.51	0.4654	0.73	1.17
FFP_Perc	4.34	13.65	0.022	24.46	21.39
FFPOP_Perc	91.87	13.58	0.0742	104.89	16.96

There was no significant difference ($p < 0.05$) in the contact time during the initial contact phase (ICP); the forefoot contact phase (FFCP) and the forefoot push-off phase (FFPOP) measurements. The amount of percentage contact spent on the ground for the left and right foot during these different contact phases were almost the same for the sprinters and the control group, however, the foot-flat phase (FFP) of the sprinters have a much lower contact percentage than the control group.

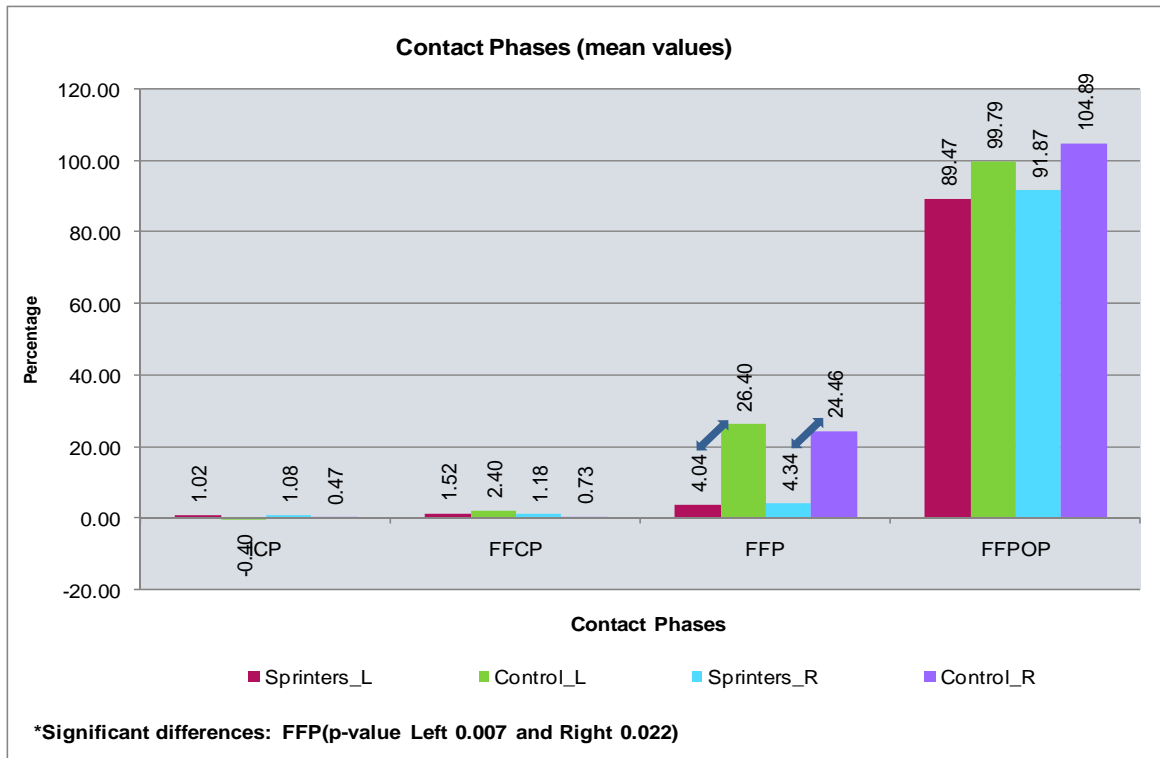


Figure 4.3: Temporal characteristics of the foot roll-over during different sprinting contact phases, indicated as percentages.

Three surface areas were classified in the results during the ground contact whilst sprinting. The three areas include the rear-foot, the mid-foot and the forefoot.

When differentiating between the different areas of the foot (**Table 4.4**), it is clear that the control group have a significantly ($p < 0.05$) higher percentage of time spent on the rear-foot than the sprinters (left: $p = 0.0057$, right: $p = 0.0268$).

As indicated in **Table 4.4**, the rear-foot contact time percentage of the control group (mean = left: 15.86, right: 13.81) is significantly higher ($p < 0.05$) than that of the sprinters (mean = left: 4.77, right: 4.65), with the calculated values being $p = 0.0057$ and $p = 0.0268$ for left and right respectively. As expected the sprinters have a forefoot strike while the control group has a more rear-foot (heel) strike.

Table 4.4: Foot contact surfaces during sprinting

LEFT SIDE	N=10		compare mean values	N=10	
	SPRINTERS		p-value	CONTROL	
	Mean	Std Dev	Sprinters vs Control	Mean	Std Dev
Rearfoot_Surf_Perc	4.77	6.74	0.0057	15.86	8.94
Midfoot_Surf_Perc	18.67	9.27	0.7993	17.75	6.30
Forefoot_Surf_Perc	76.57	14.16	0.0338	61.58	15.01

RIGHT SIDE	N=10		compare mean values	N=10	
	SPRINTERS		p-value	CONTROL	
	Mean	Std Dev	Sprinters vs Control	Mean	Std Dev
Rearfoot_Surf_Perc	4.65	6.33	0.0268	13.81	10.20
Midfoot_Surf_Perc	21.71	9.10	0.9777	21.82	8.51
Forefoot_Surf_Perc	73.91	14.32	0.1578	63.90	16.00

Figure 4.4 which was derived from **Table 4.4** shows significant differences ($p < 0.05$) in the rear-foot and forefoot surface percentage between the control group and the sprinters.

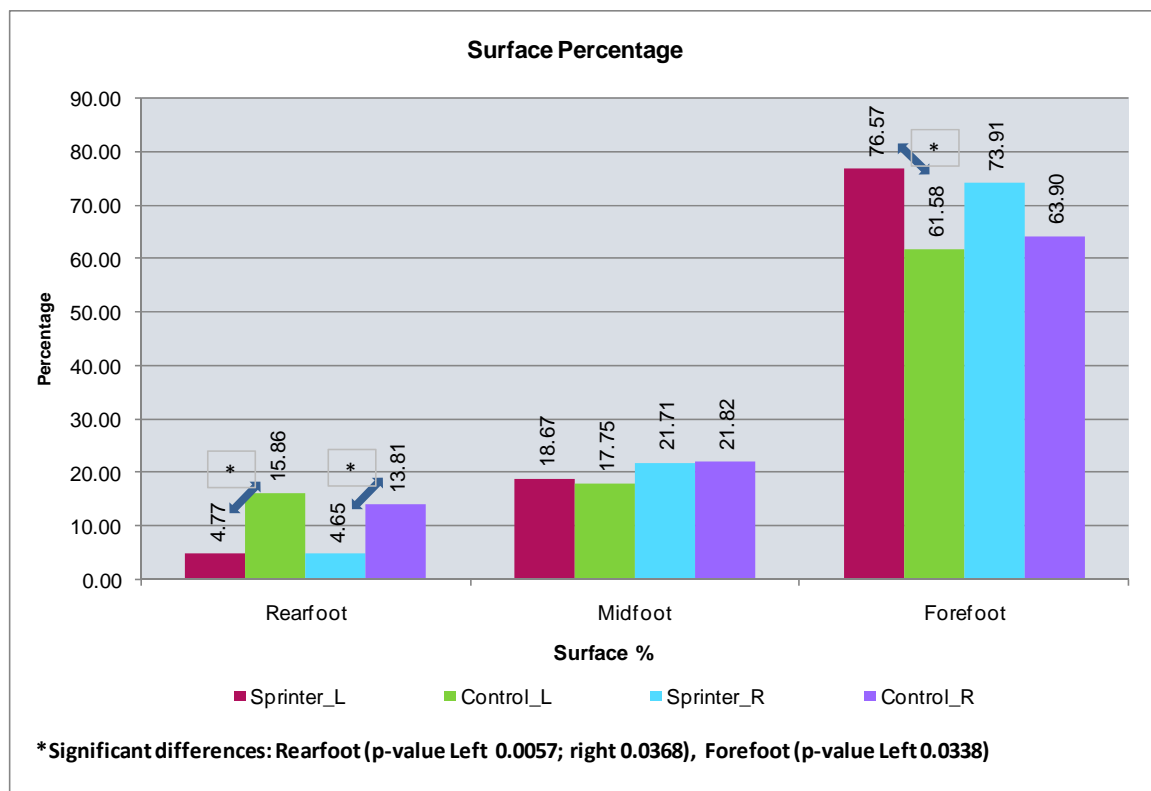


Figure 4.4: Foot contact surfaces during sprinting for sprinters versus control group for left and right foot respectively.

Table 4.5: Newton peak pressure ratings from highest to lowest: different sub-areas of sprinters and the control group left and right foot.

Weight 80kg		Weight 64kg	
Sub area	Control_L	Sub area	Sprinter_L
Meta 1	441.07	Midfoot	279.95
Heel medial	434.08	Meta 2	178.72
Meta 2	362.62	Toe 1	175.02
Heel Lateral	327.69	Meta 3	139.82
Meta 3	271.08	Meta 1	129.91
Toe 1	227.32	Meta 4	101.78
Meta 5	206.47	Meta 5	85.73
Meta 4	177.27	Toe 2-5	76.32
Midfoot	174.32	Heel medial	45.26
Toe 2-5	65.91	Heel Lateral	33.58

Weight 80kg		Weight 64kg	
Sub area	Control_R	Sub area	Sprinter_R
Meta 1	485.47	Midfoot	324.97
Heel medial	423.19	Meta 1	176.30
Meta 2	355.30	Toe 1	145.07
Heel Lateral	351.44	Meta 2	115.25
Toe 1	307.90	Meta 3	77.69
Midfoot	201.72	Toe 2-5	71.23
Meta 3	178.07	Meta 4	67.63
Meta 4	129.82	Meta 5	50.36
Meta 5	120.60	Heel medial	27.10
Toe 2-5	63.56	Heel Lateral	21.05

Table 4.5 demonstrates that the control group forces were not as high on the mid-foot compared to those of the sprinters. The forces were high in most of the foot sub-areas of the control group's feet, whereas the sprinters only had high forces in the forefoot sub-areas of the foot. The acceleration of any sprinter's body mass is proportional to how much force the athlete applies at the time frame during which this force is applied. When sprinters have the same mass and apply force for the same amount of time, the athlete who applies more force will accelerate more (Carr, 1997:31).

The magnitude of the earth's reaction force pushing against the athlete depends on how much the athlete pushes against the ground. The reaction force of the earth not only depends on the weight of the athlete, but also on the types of movements the athlete makes (Carr, 1997:21).

Force-plate studies discovered that the maximal vertical ground reaction force during running is typically about three times the body weight for both rear-foot and mid-foot strikers; in other words, hitting the ground with the mid-foot does not reduce or cushion this impact force. The ground reaction force acts on the foot, which is the only interface between the human body and the ground during walking and running (Abboud, 2002:171; De Cock, 2006:3). Faster runners and elite sprinters spend much less time than 22% in the stance phase (Novacheck, 1998:78). While running, 40% of the time is spent in the stance phase to complete the gait cycle and 60% with walking. There is also a big difference in the time period during which forces are applied (Pribut, 2005:1). The benefit of greater force application will increase stride length and, if all else is equal, a greater force application to the ground will cause a greater displacement of the athlete's body and greater distances will be covered with each stride (<http://www.HPCsport.com>).

4.2.2.2 Sprinting speed

Figure 4.5 shows that the 10 meter and 20 meter sprinting speed significantly differ ($p < 0.05$) between the sprinters and the control group. The sprinters' times over the 10 meter and 20 meter distances were, as expected, faster than that of the control group.

Table 4.6: Sprinting speeds over 10 meter and 20 meter, for sprinters versus control group.

LEFT SIDE	N=10		compare mean values	N=10	
	SPRINTERS		p-value	CONTROL	
	Mean	Std Dev	Sprinters vs Control	Mean	Std Dev
Weight	64.09	7.87	0.0086	80.19	15.38
10m	1.85	0.05	0.0007	2.09	0.16
20m	3.07	0.07	0.0012	3.50	0.29

RIGHT SIDE	N=10		compare mean values	N=10	
	SPRINTERS		p-value	CONTROL	
	Mean	Std Dev	Sprinters vs Control	Mean	Std Dev
Weight	64.09	7.87	0.0086	80.19	15.38
10m	1.91	0.05	0.0016	2.10	0.14
20m	3.13	0.06	0.0011	3.51	0.26

In the 20 meter sprint test, the sprinters' mean time left foot was 3.07 seconds, and the right foot 3.13 seconds, whereas the control group's mean left foot time was 3.50 seconds and the right foot, 3.51 seconds. When the left and right foot indicators of the sprinters and control group were compared, the following p-values were obtained: left: $p = 0.0012$ and right: $p = 0.0011$ and it can, thus, be concluded that the sprinting speed over 10 and 20 meter is significantly ($p < 0.05$) faster for the sprinters than that of the control group.

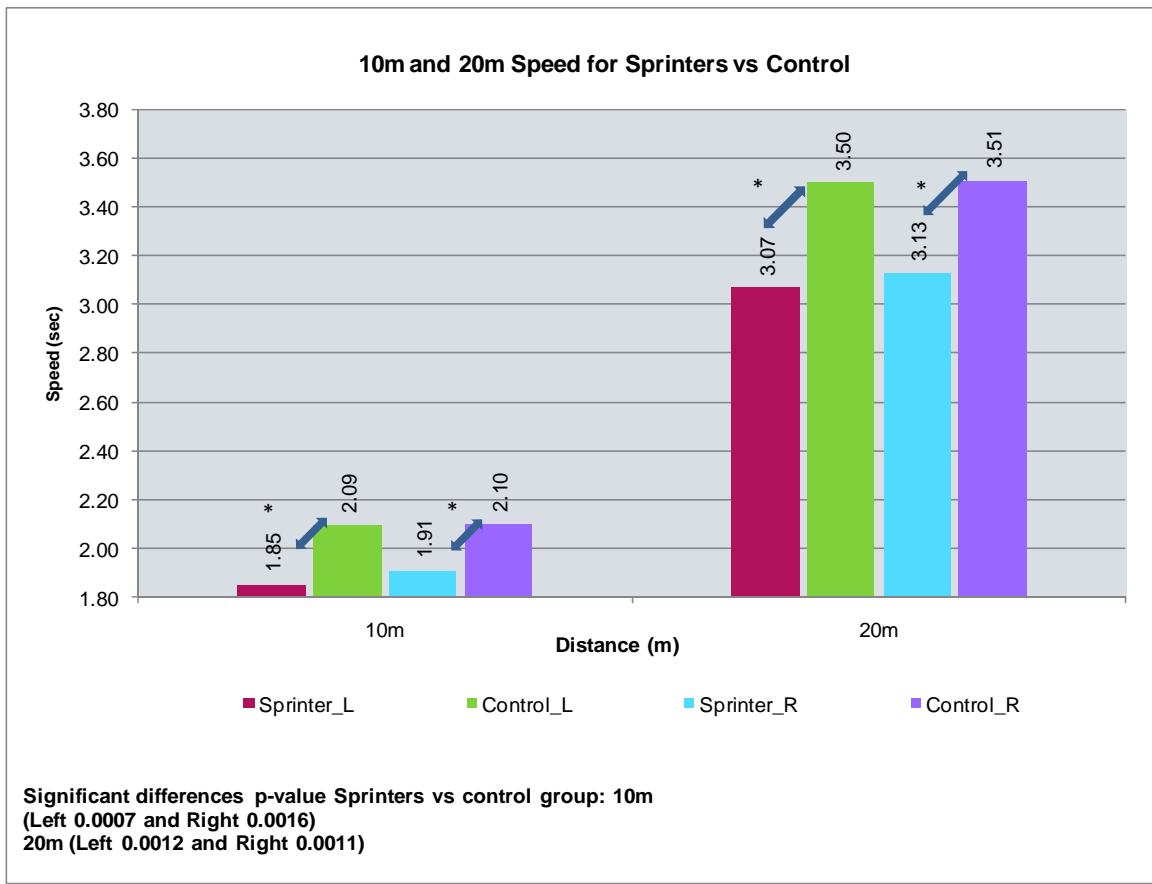


Figure 4.5: 10m and 20m sprinting speed for sprinters versus control group.

During ground contact on the RSscan, the different sub-areas of the foot are classified, and with these sub-areas the foot roll-over patterns can be determined. **Table 4.6** provides information regarding the sub-area making the longest contact and the sub-area which was the fastest (shortest time) on the ground. The sub-areas had different contact times and were classified into Start time, End time, Total time and Peak time, indicating the amount of time spent in the different sub-areas of the foot.

Figure 4.6 illustrates the foot roll-over time during ground contact of the left foot and shows that there were significant differences ($p < 0.05$) on the sub-area of Metatarsal 1 between the sprinters and the control group during the End time and Peak time. The times of the other two timing zones were relatively similar for the sprinters and the control group.

4.2.2.3 Foot sub-areas relative to time

Significant differences ($p < 0.05$) were found in the left foot roll-over with regards to the End time ($p = 0.0361$) and Peak time ($p = 0.0234$), between the sprinters and the control group on the sub area, M1.

Significant differences ($p < 0.05$) were found between the Start time on the sub-areas of heel medial ($p = 0.0185$), heel lateral ($p = 0.0170$), Total time on the sub-areas of heel medial ($p = 0.0379$) and Peak time for sub-areas heel medial ($p = 0.0238$), heel lateral ($p = 0.0141$) and M1 ($p = 0.0024$) for the right foot, foot roll-over between the sprinters and control group on sub area, M1.

Data as derived from **Table 4.7** and **Table 4.8** shows that sprinters (left: $N = 5$ out of $N = 10$ subjects for HM and HL; right: $N = 4$ out of $N = 10$ subjects for HM and HL) have less medial and lateral heel contact, whereas more subjects in the control group (left: $N = 9$ out of $N = 10$ subjects for HM and HL; right: $N = 7$ out of $N = 10$ subjects for HM and HL) achieve heel contact. These results support the findings of Novacheck (1998:78) that sprinters rarely have heel contact during sprinting.

Figure 4.7 derived from **Table 4.8** shows the foot roll-over time during ground contact of the right foot had significant differences in the sub-area of Metatarsal 1 between the sprinters and the control group during the End time and Peak time. The results of the other two timing zones (Start time and Total time) were relatively similar for the sprinters and the control group.

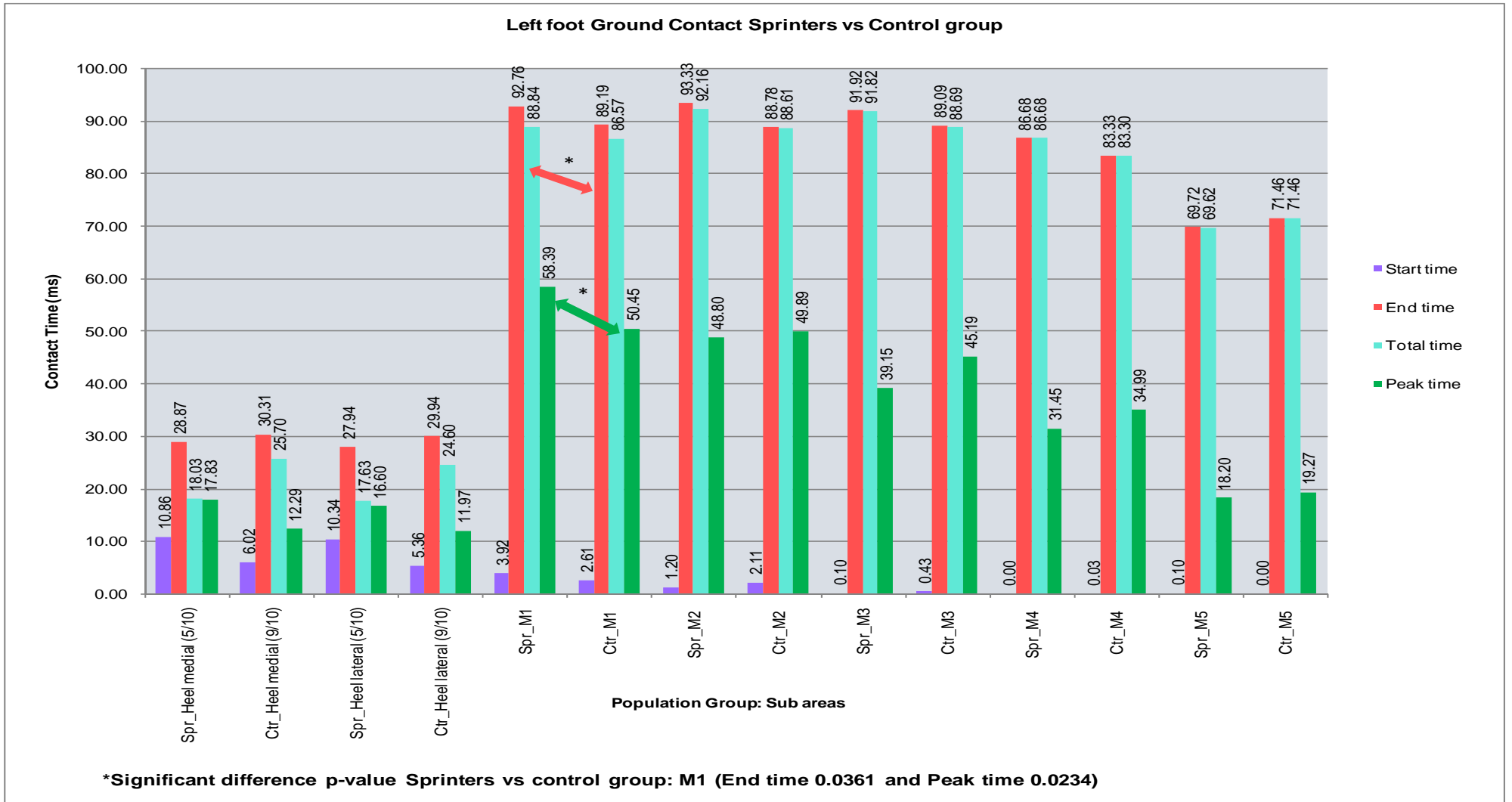


Figure 4.6: Foot roll-over for the left foot for different sub-areas in sprinting relative to Start time, End time, Total time and Peak time.

Table 4.7: Foot roll-over of the left foot for the different sub-areas of sprinting, relative to Start time, End time, Total time and Peak time.

					<i>compare mean values</i>						<i>compare mean values</i>						<i>compare mean values</i>					
LEFT SIDE		Start time		p-value			End time		p-value			Total time		p-value			Peak time		p-value			
N=		Mean	Std	<i>Sprinters vs Control</i>			Mean	Std	<i>Sprinters vs Control</i>			Mean	Std	<i>Sprinters vs Control</i>			Mean	Std	<i>Sprinters vs Control</i>			
Sprinters	Heel medial	5	10.86	7.74	0.2726			28.87	4.71	0.7493			18.03	4.35	0.1957			17.83	6.81	0.1898		
	Heel lateral	5	10.34	7.77	0.2595			27.94	6.08	0.7110			17.63	2.74	0.1099			16.60	7.07	0.3635		
	M1	10	3.92	3.44	0.3431			92.76	3.44	0.0361			88.84	5.24	0.3225			58.39	7.77	0.0234		
	M2	10	1.20	1.73	0.3344			93.33	2.51	0.1410			92.16	2.82	0.0642			48.80	4.09	0.6676		
	M3	10	0.10	0.21	0.1584			91.92	3.05	0.1424			91.82	3.15	0.1247			39.15	4.05	0.0965		
	M4	10	0.00	0.00	0.3434			86.68	3.63	0.1745			86.68	3.63	0.1707			31.45	4.68	0.4227		
	M5	10	0.10	0.32	0.3306			69.72	6.60	0.6220			69.62	6.50	0.6004			18.20	6.98	0.8463		
Control	Heel medial	9	6.02	7.45				30.31	9.07				25.70	11.90				12.29	7.30			
	Heel lateral	9	5.36	7.42				29.94	10.74				24.60	11.28				11.97	9.55			
	M1	10	2.61	2.53				89.19	3.62				86.57	4.72				50.45	6.49			
	M2	10	2.11	2.31				88.78	8.68				88.61	4.94				49.89	6.76			
	M3	10	0.43	0.66				89.09	4.99				88.69	5.28				45.19	9.77			
	M4	10	0.03	0.09				83.33	6.55				83.30	6.55				34.99	12.83			
	M5	10	0.00	0.00				71.46	8.79				71.46	8.79				19.27	15.63			

Table 4.8: Foot roll-over for the right foot, for different sub-areas in sprinting, relative to Start time, End time, Total time and Peak time.

		compare mean values			compare mean values			compare mean values			compare mean values			
RIGHT SIDE	N=	Start time		p-value	End time		p-value	Total time		p-value	Peak time		p-value	
		Mean	Std	Sprinters vs Control	Mean	Std	Sprinters vs Control	Mean	Std	Sprinters vs Control	Mean	Std	Sprinters vs Control	
Sprinters	Heel medial	4	10.42	4.67	0.0185	28.70	4.93	0.5885	18.29	0.58	0.0379	17.15	5.73	0.0238
	Heel lateral	4	9.59	3.76	0.0170	30.08	5.77	0.6012	17.51	2.33	0.1435	16.41	5.26	0.0141
	M1	0	3.09	3.26	0.2808	92.16	3.75	0.1115	89.06	2.76	0.5781	55.02	3.62	0.0024
	M2	10	0.81	1.23	0.8919	92.36	3.24	0.1216	91.54	3.25	0.0954	46.20	6.42	0.4564
	M3	10	0.00	0.00	0.3434	90.06	3.74	0.1975	95.07	16.92	0.1549	38.80	6.03	0.5270
	M4	10	0.00	0.00	0.3434	81.06	7.06	0.42045	81.06	7.06	0.3795	27.07	8.26	0.8750
	M5	10	0.29	0.66	0.9805	64.64	11.70	0.6388	64.35	12.04	0.7235	15.91	5.61	0.7085
Control	Heel medial	7	3.77	3.10		30.86	6.68		27.07	8.76		10.52	2.52	
	Heel lateral	7	3.56	3.03		28.04	6.15		24.47	8.33		9.01	2.97	
	M1	10	1.81	1.67		89.84	2.26		88.37	2.69		49.13	3.86	
	M2	10	0.90	1.51		90.05	3.10		89.16	2.78		48.65	7.89	
	M3	10	0.35	1.11		86.62	7.22		86.27	7.00		41.32	10.79	
	M4	10	0.26	0.83		77.73	10.79		77.46	10.46		27.96	15.59	
	M5	10	0.30	0.83		61.78	14.94		62.15	15.14		17.76	14.21	

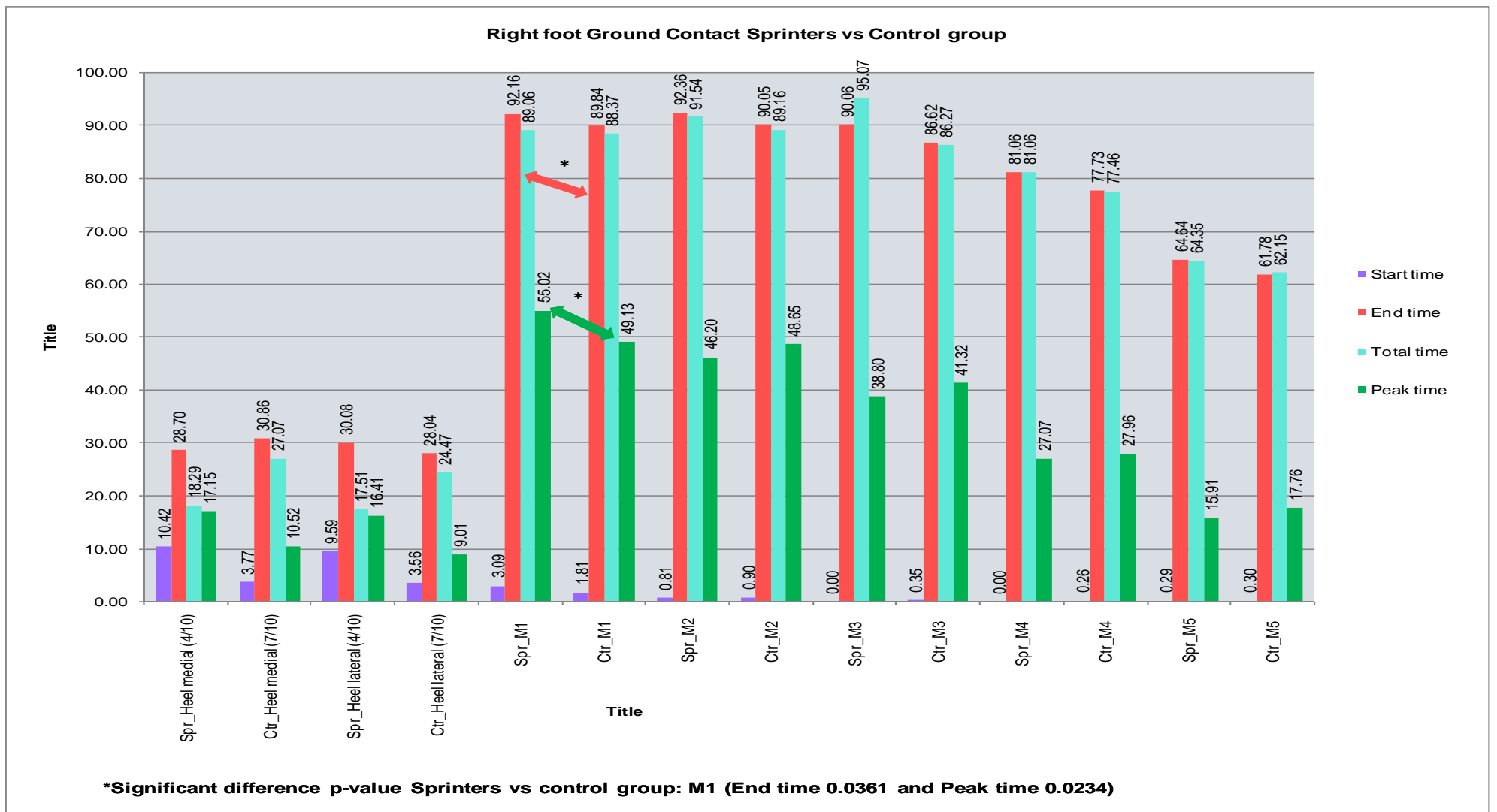


Figure 4.7: Roll-over for the right foot for different sub-areas in sprinting, relative to Start time, End time, Total time and Peak time.

Data derived from **Table 4.7** and **4.8** represents the sequentially order (**Table 4.9** and **4.10**) for the onset of the seven plantar pressure sub-areas (initial contact - start time, final contact - end time).

Table 4.9: Plantar pressure area patterns during barefoot sprinting.

Patterns for making Contact of plantar pressure areas during barefoot sprinting									
Sprinters and Control Group with left and right foot	N= (sub-area)	Plantar pressure sub-area							
Sprinters Left foot	10 (M1-5) 5 (HL, HM)	M4	M5,3	M2	M1	HL	HM		
Sprinters Right foot	10 (M1-5) 4 (HL, HM)	M3,4	M5	M2	M1	HL	HM		
Control group Left foot	10 (M1-5) 9 (HL, HM)	M5	M4	M3	M2	M1	HL	HM	
Control group Right foot	10 (M1-5) 7 (HL, HM)	M4	M5	M3	M1	M2	HL	HM	

Table 4.10: Plantar pressure area patterns for push-off during barefoot

Patterns for plantar pressure areas push off during barefoot sprinting									
Sprinters and Control Group with left and right foot	N= (sub-area)	Plantar pressure sub-area							
Sprinters Left foot	10 (M1-5) 5 (HL, HM)	HL	HM	M5	M4	M3	M1	M2	
Sprinters Right foot	10 (M1-5) 4 (HL, HM)	HM	HL	M5	M4	M3	M1	M2	
Control group Left foot	10 (M1-5) 9 (HL, HM)	HL	HM	M5	M4	M2	M3	M1	
Control group Right foot	10 (M1-5) 7 (HL, HM)	HL	HM	M5	M4	M3	M1	M2	

No significant differences ($p < 0.05$) were found in timing between the seven plantar pressure sub-areas during Start time (initial contact) and End time (final contact).

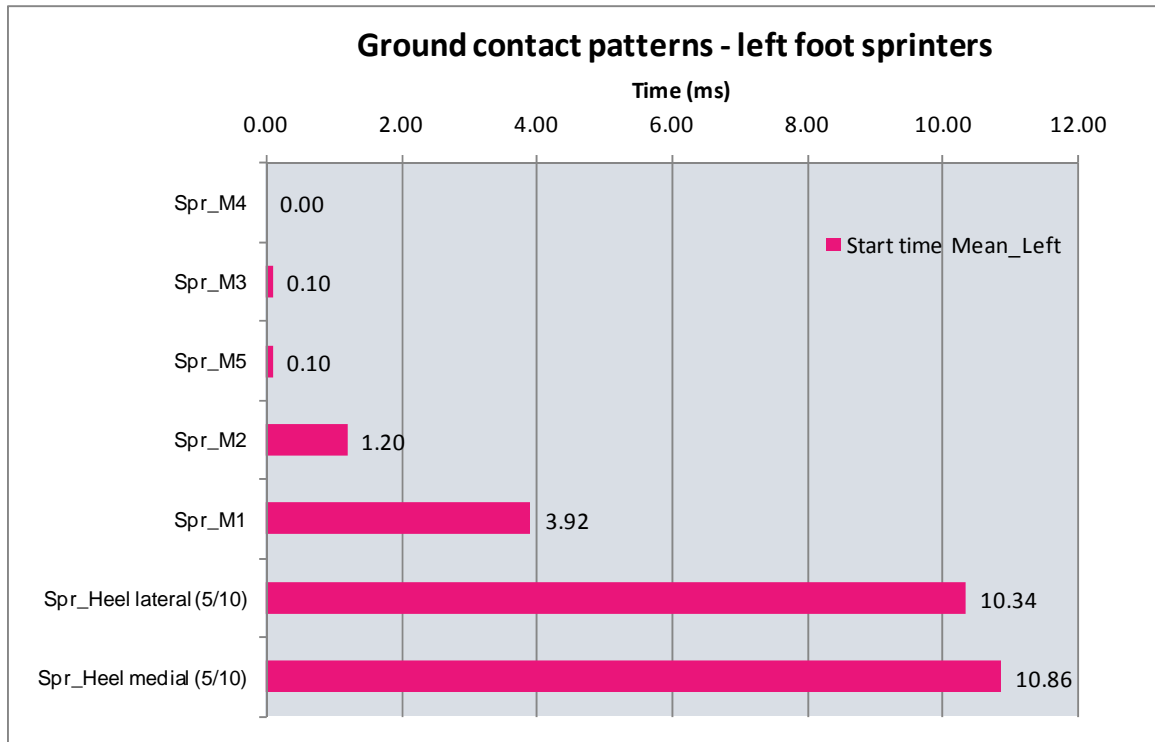


Figure 4.8: Plantar pressure area patterns of the left foot of sprinters during barefoot sprinting.

Figure 4.8 illustrates the foot contact pattern of the sprinters' left foot. The data indicates the contact pattern of the foot during the contact phase of sprinting. The amount of milliseconds spent on each sub-area of the foot is also indicated as per foot contact only.

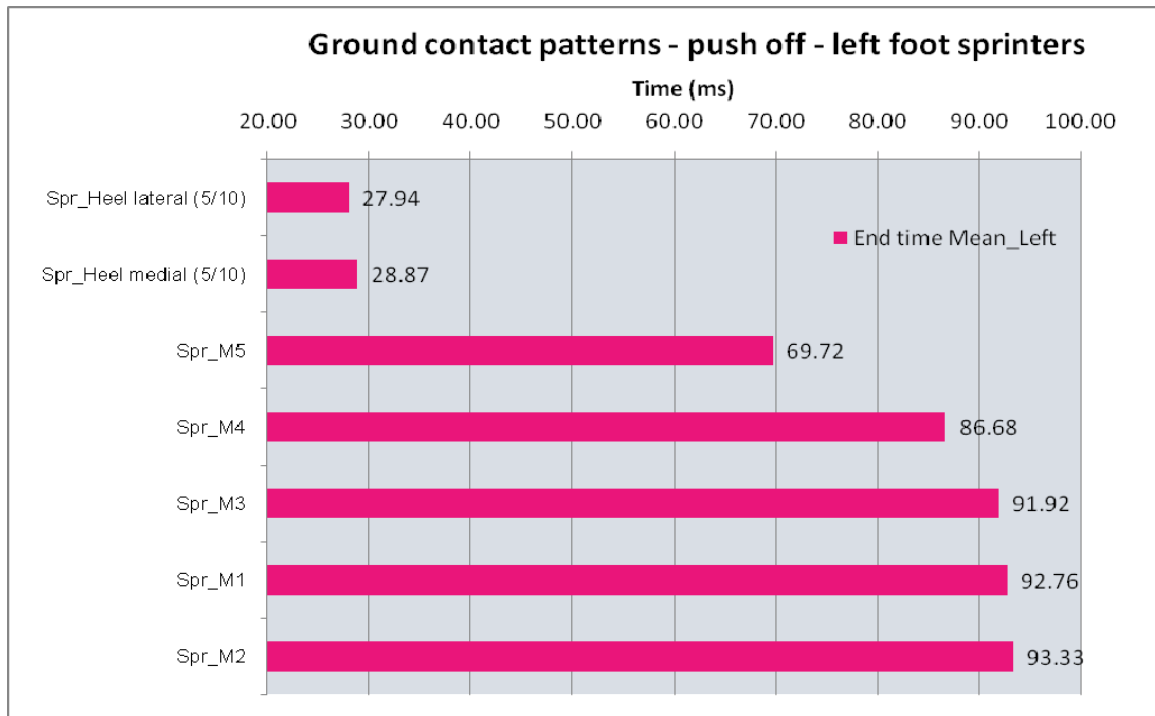


Figure 4.9: Plantar pressure area patterns for push-off of the left foot of sprinters during barefoot sprinting.

Figure 4.9 illustrates the foot contact pattern of the sprinters left foot. The data indicates the contract pattern of the foot during the push-off phase of sprinting. The amount of milliseconds spent on each sub-area of the foot during push-off is indicated as per foot push-off only.

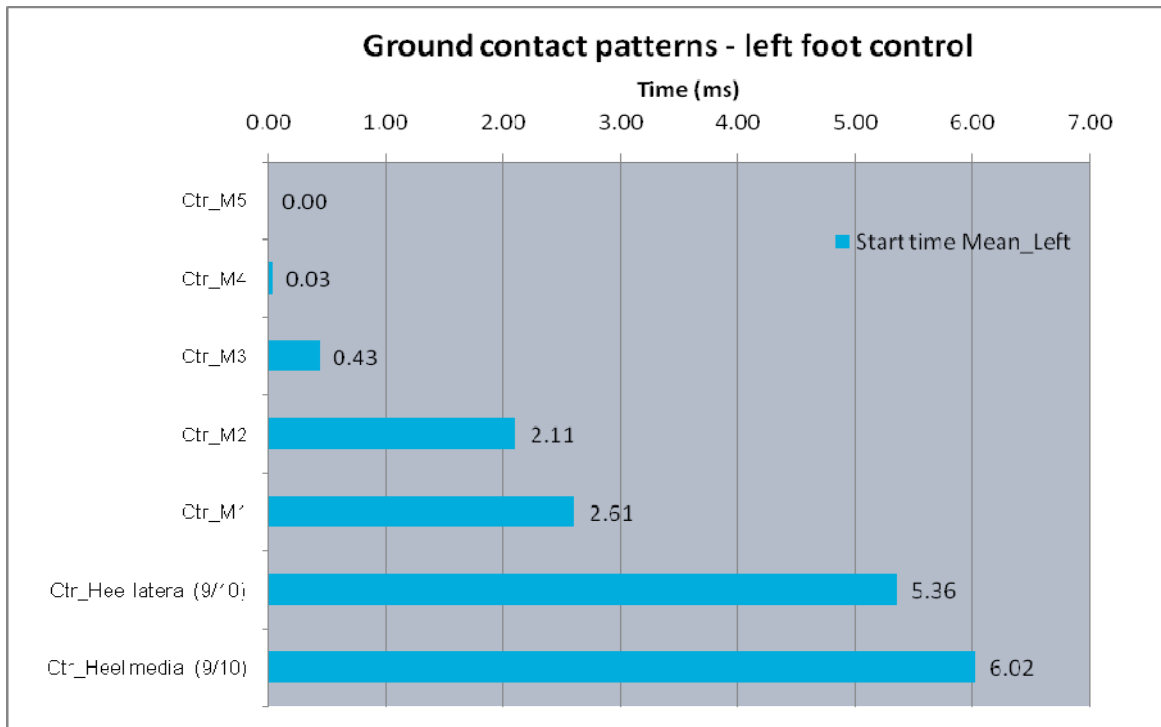


Figure 4.10: Plantar pressure area patterns of the left foot of the control group during barefoot sprinting.

Figure 4.10 illustrates the foot contact pattern of the control group's left foot. The data indicates the contact pattern of the foot during the contact phase of sprinting. The amount of milliseconds spent on each sub-area of the foot is also indicated as per foot contact only.

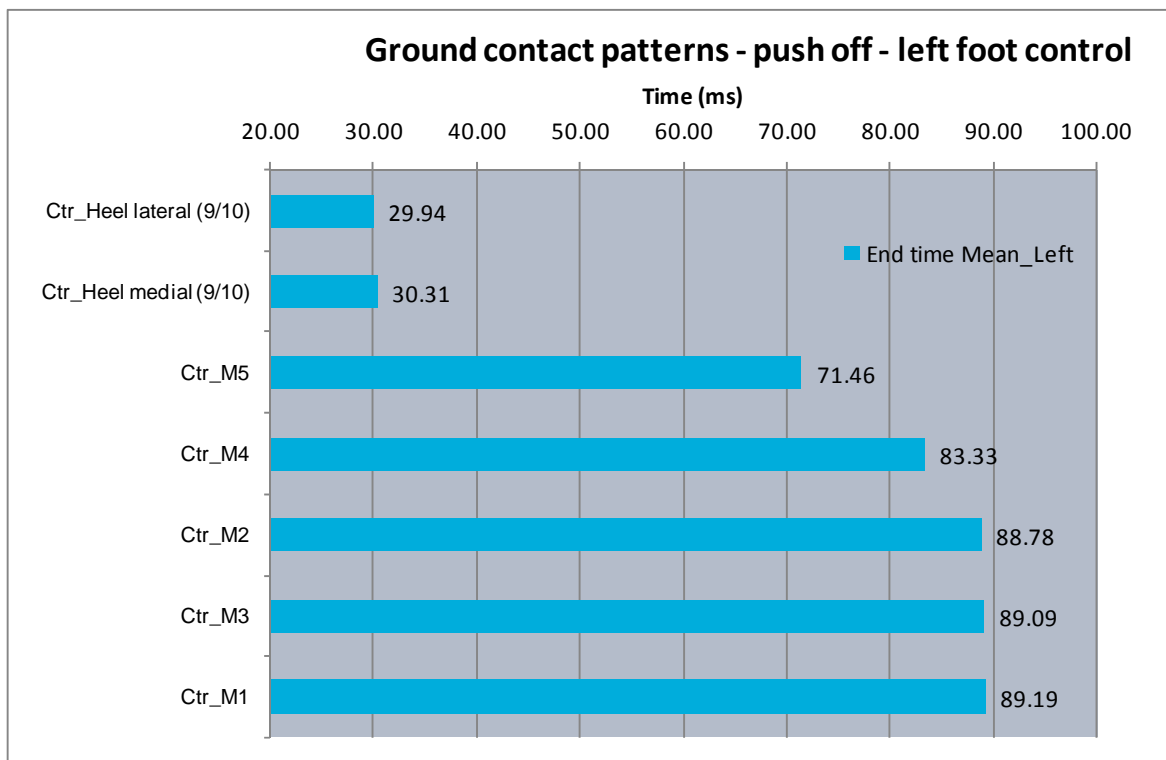


Figure 4.11: Plantar pressure area patterns for push-off of the left foot of the control group during barefoot sprinting.

Figure 4.11 illustrates the foot contact pattern of the control group's left foot. The data indicates the contact pattern of the foot during the push-off phase of sprinting. The amount of milliseconds spent on each sub-area of the foot during push-off is indicated as per foot push-off only.

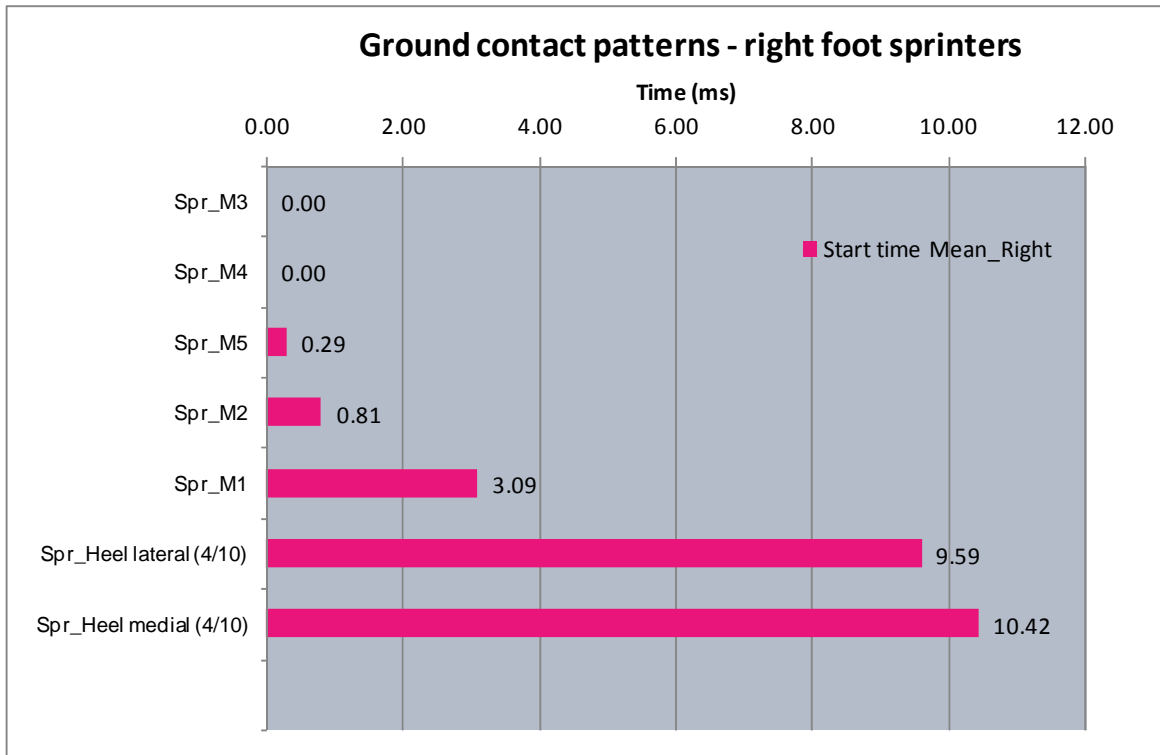


Figure 4.12: Plantar pressure area patterns of the right foot of sprinters during barefoot sprinting.

Figure 4.12 illustrates the foot contact pattern of the sprinters' right foot. The data indicates the contact pattern of the foot during the contact phase of sprinting. The amount of milliseconds spent on each sub-area of the foot is also indicated as per foot contact only.

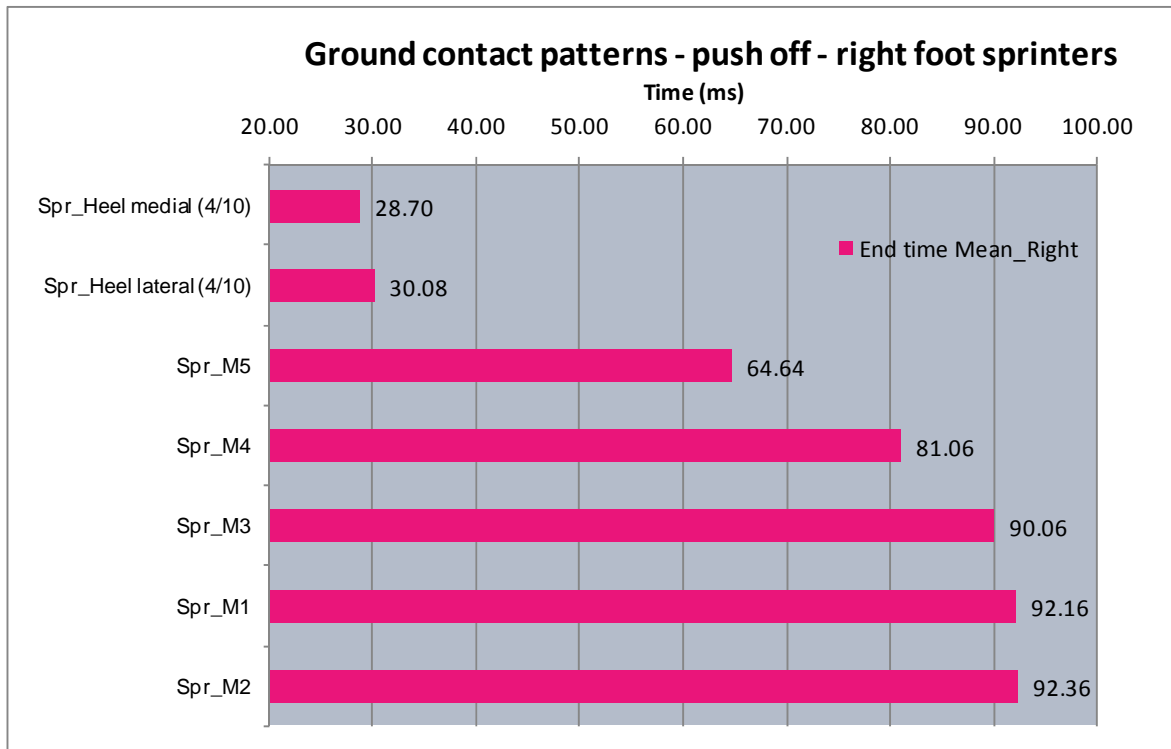


Figure 4.13 Plantar pressure area patterns for push-off of the right foot of sprinters during barefoot sprinting.

Figure 4.13 illustrates the foot contact pattern of the sprinters' right foot. The data indicates the contact pattern of the foot during the push-off phase of sprinting. The amount of milliseconds spent on each sub-area of the foot during push-off is indicated as per foot push-off only.

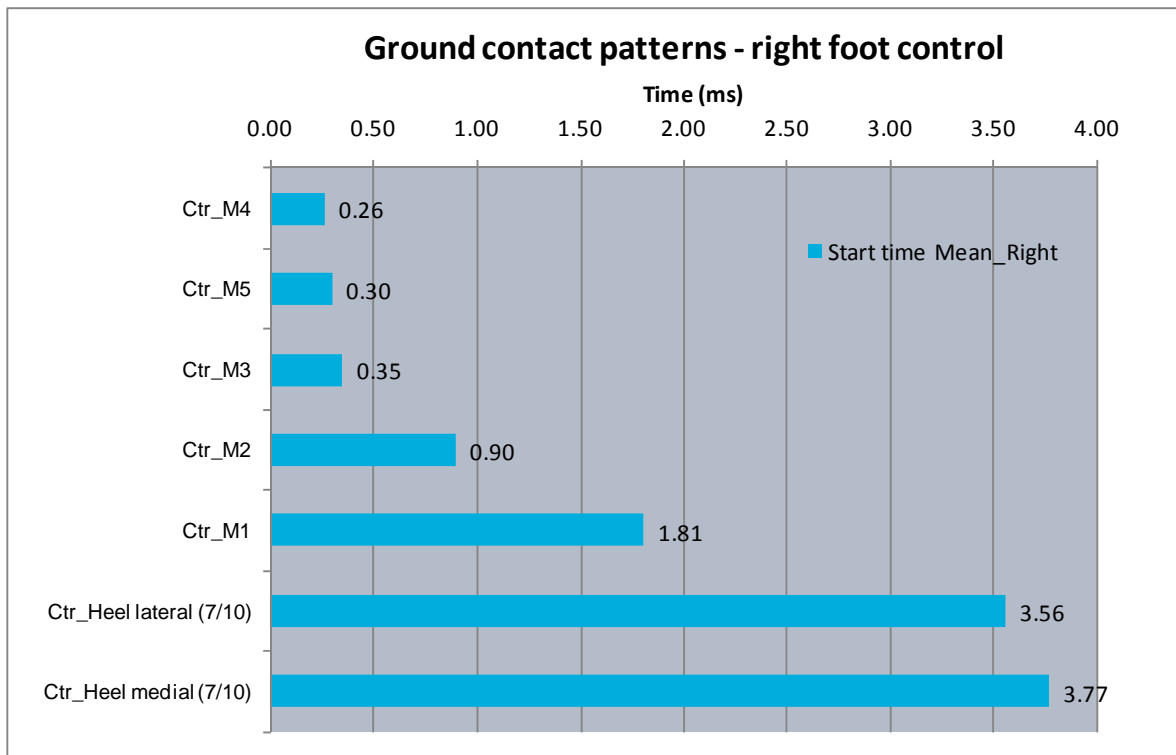


Figure 4.14: Plantar pressure area patterns of the right foot of the control group during barefoot sprinting.

Figure 4.14 illustrates the foot contact pattern of the control group's right foot. The data indicates the contact pattern of the foot during the contact phase of sprinting. The amount of milliseconds spent on each sub-area of the foot is also indicated as per foot contact only.

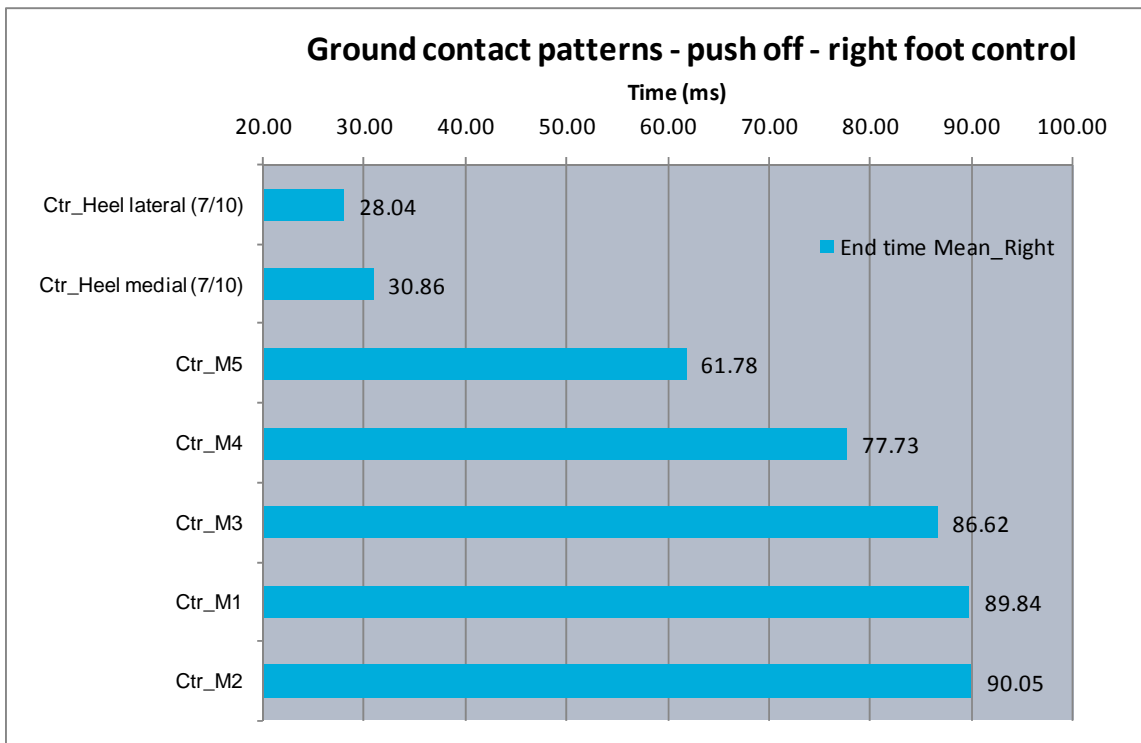


Figure 4.15: Plantar pressure area patterns for push-off of the right foot of sprinters during barefoot sprinting.

Figure 4.15 illustrates the foot contact pattern of the control group's right foot. The data indicates the contact pattern of the foot during the push-off phase of sprinting. The amount of milliseconds spent on each sub-area of the foot during push-off is indicated as per foot push-off only.

4.2.3 Under-foot peak pressures.

Table 4.11: Newton readings of the relative regional pressures in the different sub-areas of the foot: sprinters versus control group - left foot.

LEFT SIDE					
Sub areas	N=10		Control vs. Sprinter	N=10	
	Control			Sprinter	
	Mean	Std	<i>p</i> -value	Mean	Std
Heel Lateral	327.69	356.22	0.0285	33.58	48.94
Heel medial	434.08	472.70	0.0291	45.26	71.39
Meta 1	441.07	244.91	0.0030	129.91	99.75
Meta 2	362.62	156.58	0.0119	178.72	136.53
Meta 3	271.08	92.31	0.0097	139.82	109.86
Meta 4	177.27	96.37	0.0695	101.78	77.51
Meta 5	206.47	199.89	0.0974	85.73	66.67
Midfoot	174.32	126.75	0.0966	279.95	142.29
Toe 1	227.32	137.45	0.3274	175.02	89.95
Toe 2-5	65.91	39.27	0.6309	76.32	54.67

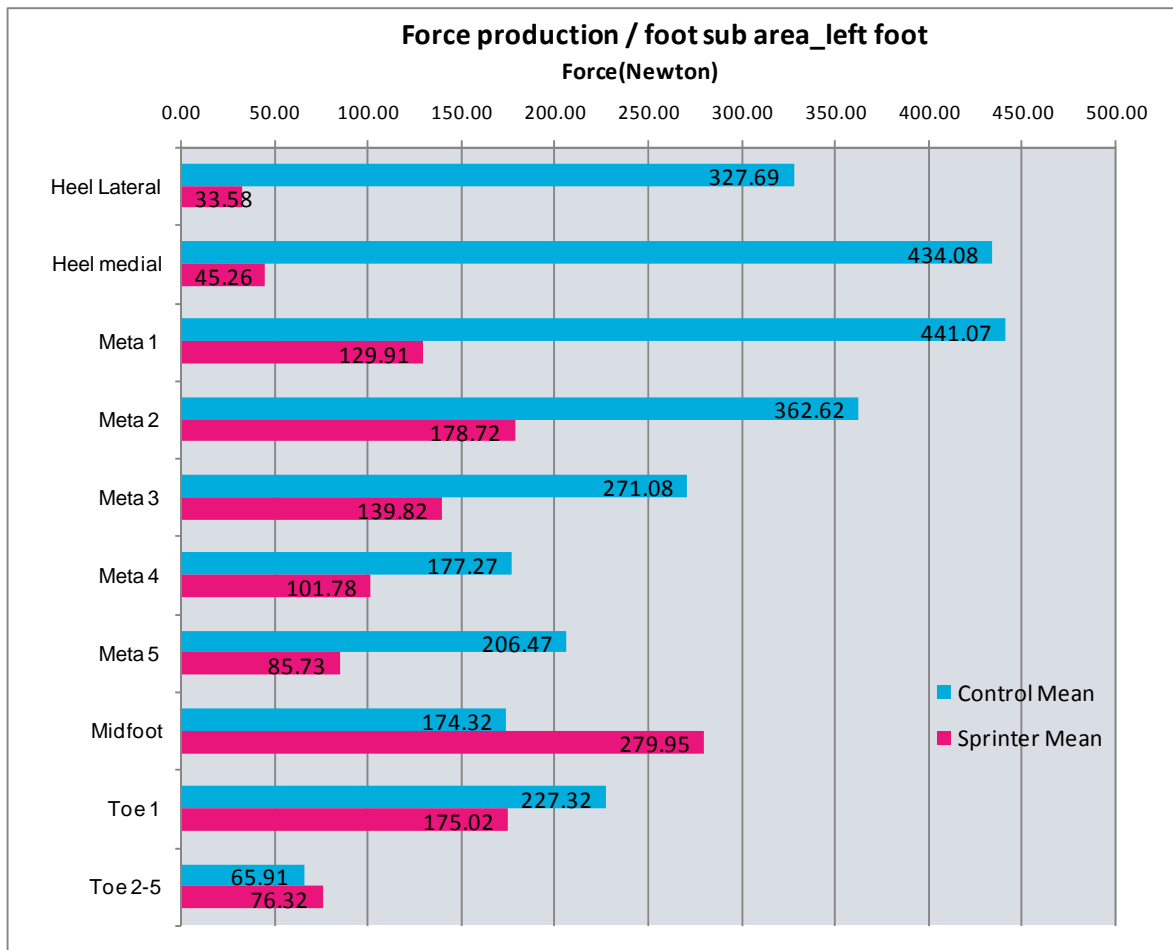


Figure 4.16: Newton readings of the relative regional pressures in the different sub-areas of the foot: sprinters versus control group - left foot.

Figure 4.16 derived from **Table 4.11** demonstrates the Newton readings during ground contact for the left foot of the control group and the sprinters. The control group's Newton readings were higher than that of the sprinters in all the sub-areas except for that of the mid-foot.

Table 4.12: Newton readings of the relative regional pressures in the different sub-areas of the foot: sprinters versus control group - right foot.

Sub areas	RIGHT SIDE				
	N=10		Control vs. Sprinter	N=10	
	Control			Sprinter	
Mean	Std	<i>p</i> -value	Mean	Std	
Heel Lateral	351.44	428.08	0.0374	21.05	25.66
Heel medial	423.19	449.74	0.0213	27.10	34.68
Meta 1	485.47	166.86	0.0017	176.30	206.86
Meta 2	355.30	146.06	0.0009	115.25	124.73
Meta 3	178.07	72.02	0.0085	77.69	79.66
Meta 4	129.82	100.06	0.1310	67.63	73.74
Meta 5	120.60	140.85	0.1644	50.36	49.52
Midfoot	201.72	162.86	0.1399	324.97	192.42
Toe 1	307.90	163.60	0.0131	145.07	67.70
Toe 2-5	63.56	32.25	0.1256	71.23	55.16

Figure 4.17 derived from **Table 4.12** demonstrates the Newton readings during ground contact for the right foot of the control group and the sprinters. The Newton readings of the control group are higher than that of the sprinters in all the sub-areas except for that of the mid-foot.

As indicated in **Table 4.12**, significant differences ($p < 0.05$) were found at the pressure sub-areas: HL (left, $p = 0.0285$; right, $p = 0.0374$), HM (left, $p = 0.0291$; right, $p = 0.0213$), M1 (left, $p = 0.0030$; right, $p = 0.0017$), M2 (left, $p = 0.0119$; right, $p = 0.0009$), M3 (left, $p = 0.0097$; right, $p = 0.0085$) of both the left and right foot peak pressure of the sprinter and control group. A significant difference was also found at the T1 (right, $p = 0.0131$).

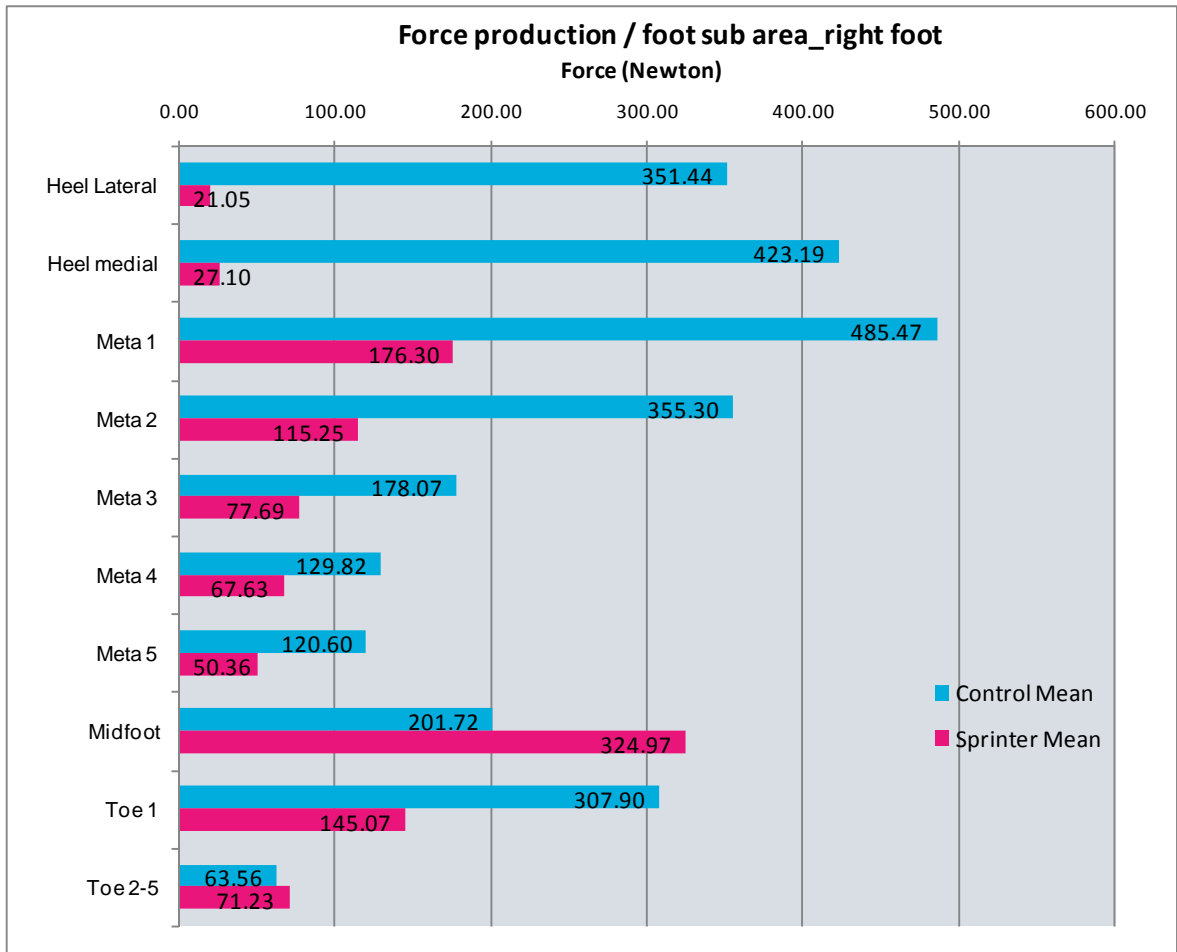


Figure 4.17: Newton readings of the relative regional pressures in the different sub-areas of the foot: sprinters versus control group - right foot.

CHAPTER 5

INTERPRETATION AND DISCUSSION OF RESULTS

5.1 INTRODUCTION

The purpose of this research is to provide sprinting coaches and sprinters with valuable guidelines when identifying possible talented sprinters. The methodology used in this research is based on the hypothesis of using sprinter athletes and finding possible relationship between a sprinter and a specific foot type, using the RSscan as measurement tool.

5.2 INTEGRATED DISCUSSION OF RESULTS

The objective of this study was to compare sprinters and non-sprinters (the control group). Sprinting speed and ground contact were tested over 20 meters and all of the participants were barefoot during the testing.

The aim of this study was:

- To determine the ground contact time of the different foot types.
- To investigate the effects of roll-over action of the foot during ground contact time.
- To measure under foot peak pressures to determine if there are differences with regard to different foot types, with a possible specific foot type being dominant amongst sprinters.

The results obtained through this investigation and a comparison of results obtained from previous research regarding this subject, is discussed in this chapter.

5.2.1 Classification of the different foot types (barefoot walking)

Research indicated that runners have different types of feet, such as high-arch, normal or flat-foot (this is determined by the height of the arch), as illustrated in **Figure 4.1**. <http://www.nwhealth.edu>. In this study (**Table 4.1**) gait of the left and right foot were analysed separately. Gait is assumed to be symmetrical (Goble *et al.*, 2003:279), however, the results from this study indicate some differences for both sprinters and the control group between the left and right foot during gait.

Data was captured while walking barefoot over the RSscan plate and **Table 4.1** and **Figure 4.1** shows the different foot types of the Sprinters and Control groups' left and right feet respectively. **Figure 4.1** also shows that the control group dominantly has a high-arch foot type for both the left and right foot. The right foot readings of the sprinters are spread equally between the different foot types. The left feet of the sprinters are dominantly a normal foot type, followed by high and then low foot types.

If the data from the left foot type and right foot type are integrated, as illustrated in **Table 4.2**, it is interesting to note that sprinters predominantly have normal feet (eight out of 20), whereas the control group (15 out of 20) predominantly have high-arch feet.

5.2.2 Foot roll-over (barefoot sprinting)

Initial contact phase (ICP) starts with initial foot contact (IFC) and ends at initial metatarsal contact (IMC), which is the start of the forefoot contact phase (FFCP) and accounts for the following stance phases. During the first two phases, the foot makes contact with the ground until forefoot flat (FFF) is achieved. In the total foot contact (TFC) duration, the foot has a flat position throughout the foot flat phase (FFP). After heel-off (HO), the remaining part of total foot contact duration, is forefoot push-off- phase (FFPOP).

The dataset, as set out in **Table 4.3**, describes the temporal characteristic of the foot roll-over time during sprinting. Four functional phases (ICP, FFCP,

FFP, FFPOP) were proposed and were indirectly linked to functional foot movements. Besides temporal aspects, individual pressure amplitudes of sub-areas also provide information about the functional behaviour of the foot. There was a significant difference ($p < 0.05$) during the foot-flat phase (FFP) between the sprinters (mean left: 4.04ms, mean right: 4.34ms) and control group (mean left: 26.40ms, mean right: 24.46ms), left: $p=0.007$; right: $p=0.022$. This indicates, as expected, that the FFP time is significantly faster for the sprinter than for the control group.

It must be remembered that the results are based on the most common sub-areas to analyse pressure distributions underneath the sole of the foot which are; the rear-foot, mid-foot and forefoot. The rear-foot (heel) area is subdivided into two sub-areas (Hennig & Rosenbaum, 1991:307; Hennig *et al.*, 1994:39; De Cock, 2006:7) to differentiate between lateral and medial heel loading during gait. The forefoot area is divided into sub-areas covering one or more of the metatarsal heads, the hallux or the lesser toes (Hennig & Rosenbaum, 1991:308; Hughes *et al.*, 1993:515; Hennig *et al.*, 1994:39; Kernozek & LaMott, 1995:143; Walker & Fan, 1998:380; McPoil *et al.*, 1999:500; Bryant *et al.*, 1999:118; Bryant *et al.*, 2000:297; VanZant *et al.*, 2001:339; De Cock 2006:7).

The results of the 10 meter and 20 meter speed tests of the control group and sprinters are indicated in **Table 4.6**. There were significant differences ($p < 0.05$) between both the 10 meter and 20 meter times of sprinters and the control group. In the 10 meter sprint test, sprinters' mean left foot times were 1.85 seconds and the right foot 1.91 seconds. The control group's mean left foot time was 2.09 seconds and the right foot 2.10 seconds. In a comparison between the left and right foot indicators of the sprinters and control group, the following significant differences were found, left: $p=0.0007$ and right: $p=0.0016$.

5.2.2.1 Forefoot push-off

In **Table 4.3** it can also be seen that the forefoot push-off phase (FFPOP) percentage time spent on the ground is less for the sprinters than that of the

control group (sprinters vs. control group - left foot: 89.47% vs. 99.79%; right foot: 91.87% vs. 104.89%).

When differentiating between the different areas of the foot (**Table 4.4**), it is clear that the control group have a significantly ($p < 0.05$) higher percentage of time spent on the rear-foot than that of the sprinters (left: $p=0.0057$, right: $p=0.0268$). The reason for this difference may be that the running technique of the sprinters and the foot contact under the centre of gravity for sprinters differ from the control group subjects, who are not trained with regards to the correct technique for sprinting or foot-placing.

According to Hamilton *et al.*, (2008:479) when running, the foot hits the ground in front of the body's centre of gravity, however, not as far in front of the body as in walk. When running at a faster speed, the distance the foot hit the ground in front of the body decreases until the foot contact is almost directly under the body's centre of gravity, due to momentum. This position reduces the restraining part of the support phase and gives greater emphasis to the propulsive part.

At maximum speed, the restraining part disappears entirely. The use of the term 'driving phase' for the support phase in running, indicates its propulsive nature (Hamilton *et al.*, 2008:480).

It has been found that leg stiffness differs in individuals with different dynamic foot orientations during running. With a high-arched individual, an increased height of the medial longitudinal arch is often linked with a more supinated position of the foot, which is why the foot may show decreased pronation throughout the stance phase (Dorsey *et al.*, 2003:1).

5.2.2.2 The effects of roll-over action of the foot during ground contact time

Mean and standard deviation of temporal characteristics of the foot roll-over during barefoot sprinting are given in **Table 4.7 and 4.8**.

Reference data of the temporal foot roll-over during barefoot sprinting, relative to Start time, End time, Total time, Peak time as illustrated in **Table 4.7**, analyse differences of the various anatomical sub-areas of the left foot (heel medial, heel lateral, M1, M2, M3, M4 and M5), in timings between the four different contact times. No significant difference ($p < 0.05$) was found for the Start time and Total time between the sprinter and control groups' left foot roll-over for the following variables: Heel medial, heel lateral, M1, M2, M3, M4 and M5.

According to Dintiman & Ward (2003:232), the foot muscles of athletes are stronger in the area of M1 and as the athlete must push-off from the ball of the foot and not the toes, the athlete will have a better drive action.

Reference data of the temporal foot roll-over during barefoot sprinting relative to Start time, End time, Total time, Peak time as illustrated in **Table 4.8**, to analyse difference in timing between the four different contact times for the right foot. A normal distribution was found for the End time between the sprinter and control groups' right foot roll-over for the following variables: heel medial, heel lateral, M1, M2, M3, M4 and M5.

Previous studies showed that the foot contact in walking and running starts with a more lateral loading of the heel, followed by medial loading (Alexander *et al.*, 1990:156; Novacheck, 1998:79). The study of De Cock (2006:31) revealed the results that H_L and H_M could be considered as one single area making contact with the ground. No significant differences ($p < 0.05$) were found between the two heel areas with regard to time to peak pressure.

There are, however, some slight differences in the centre of pressure (COP), the geometric centre of the distribution of force applied by the foot to the ground. A rear-foot striker moves their COP from the rear lateral border of the foot to the midline within about 15 milliseconds of initial contact, and then continues along the midline to the centre of the forefoot, where it remains for most of the stance phase of gait. Mid-foot strikers have an initial COP at about 50% of shoe length, which then moves backwards until the rear part of

the shoe makes contact with the ground. After moving to the back of the foot, the COP then moves forward to the middle of the forefoot (to approximately the same place as for rear-foot running) and stays there until toe-off (Dintiman & Ward, 2003:233).

During the support phase, the foot makes initial contact with the ground on the outside edge of the ball of the foot (Dintiman & Ward, 2003:233), as the results show when analyzing the control group. With the sprinters, speed achievement is maximized the higher the contact point is on the ball of the foot. When the speed is slower, the contact point moves toward the rear of the foot between the arch and heel. The results of this study also support the findings of Dintiman & Ward, (2003:233), that the heel will make a brief, but definite contact with the ground. This can be seen in **Table 4.9**, when analyzing the different contact patterns. **Figure 4.8, 4.10, 4.12** and **4.14** also illustrates ground contact patterns.

Research has shown that the horizontal component of the touchdown velocity is significantly faster in barefoot running. As awareness of mechanical inputs and pain is well established in the foot sole, it is assumed that runners take on a flatter foot position in barefoot running, in an effort to limit the local pressure below the heel (De Wit *et al.*, 2000:273;275). There are, however, some subtle differences in the centre of pressure (COP), the geometric centre of the distribution of force applied by the foot to the ground. A rear-foot striker moves their COP from the rear lateral border of the foot to the midline within about 15 milliseconds of initial contact and then continues along the midline to the centre of the forefoot, where it remains for most of the stance phase of gait. Mid-foot strikers have an initial COP at about 50% of shoe length, which then moves backwards until the rear part of the shoe makes contact with the ground. After moving to the back of the foot, the COP then moves forward to the middle of the forefoot (to approximately the same place as for rear-foot running) and stays there until toe-off (Dintiman & Ward, 2003:233)

5.2.3 Under-foot peak pressures.

The foot pressure areas are color coded according to the amount of force applied in a specific point in time. Red indicates the highest pressure point and the blue the lowest pressure point. The centre of pressure (COP) is the instantaneous point of application of the ground reaction force and its location changes during the stance phase (De Cock, 2006:8; Miller, 1990:209,210) See **Figure 5.1**.

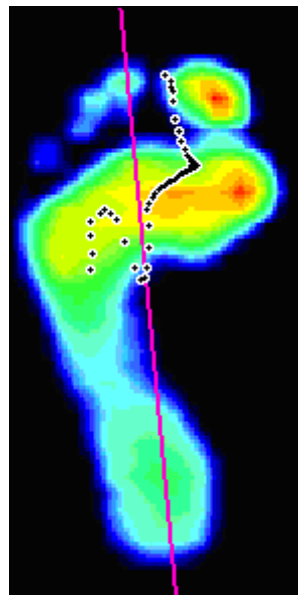


Figure 5.1 Color coded pressure areas during ground contact.

The location of the COP is mostly defined with respect to the foot y-axis, drawn from mid-heel to mid-forefoot and the x-axis perpendicular to the foot axis. Displacements in medial-lateral and anterior-posterior directions, together with the maximal distances and the range of displacement, are the most common variables used in the analysis of the COP. The velocity of the COP reflects the dynamics of the foot when making contact with the ground and may be a better indicator of foot function than displacement (De Cock, 2006:9).

Pressure-time curves underneath sub-areas reflect the pressure distribution over time during the stance phase. From these time-curves, instant of first contact, instant of last contact, instant of peak pressure and contact duration for a specific area are derived. Based on the timing variables, an image of the

foot roll-over can be reconstructed, which helps with the interpretation (Blanc *et al.*, 1999:102; De Cock, 2006:9).

During running, most athletes first hit the ground with the outside border of the shoe – some with the rear lateral part of the shoe (rear-foot strikers) and most others with the middle lateral region of the shoe (mid-foot strikers). Faster runners and elite sprinters spend much less time than 22% in the stance phase (Novacheck, 1998:78). Normally speed increases further and initial contact changes from being on the hind-foot to the forefoot. This typically marks the distinction between running and sprinting. Running is performed over longer distances and of these runners, approximately 80% are mostly referred to as rear-foot strikers (Novacheck, 1998:78). Most of the remainder is characterized as mid-foot strikers. Sprinting is done over shorter distances at faster speeds. Sprinters run with a forefoot initial contact and rarely make heel contact. When the one foot comes in contact with the ground and ends with contact of the same foot, it's called the gait cycle (Novacheck, 1998:78).

Foot landing distance is the horizontal displacement of the foot relative to the centre of gravity. A sprinter should minimize this distance, as large landing distances tend to increase the braking forces (forces decelerating the runner's forward velocity) that occur at foot strike. Over striding causes a significant deceleration in running velocity at foot strike (Novacheck, 1998:78).

The size of this deceleration can be minimized if the foot is moving slightly backward prior to foot strike. The main cause of excessive braking forces is making ground contact too far in front of the athlete's centre of mass (<http://www.HPCsport.com>). The more completely the horizontal force is directed straight backward, the greater its contribution to the forward motion of the body. Lateral motions are inefficient and detract from forward propulsion (Hamilton *et al.*,2008:483).

Cadence can be improved by maximizing the effort in removing the support foot from the ground. This maximized use of gravity should pull the runner forward. Stride frequency is the direct result of the athlete performing the

sprint cycle correctly. When the athlete can achieve this, the ground reaction time (this is the largest contributor to stride frequency) should become faster. It is known that almost all athletes spend approximately the same amount of time in the air during the sprint stride, so the big difference comes in the amount of time spent on the ground. Sprinters should try to spend as little time on the ground as possible (<http://www.gillathletics.com>).

Ten anatomical pressure sub-areas were identified on the peak pressure footprint to categorise the foot peak pressures during sprinting (**Figure 5.2** – location of the ten anatomical sub-areas of the peak pressure footprint – RSscan Int.). The sub-areas used are: heel lateral (HL), heel medial (HM), metatarsal 1 (M1) metatarsal 2 (M2) metatarsal 3 (M3) metatarsal 4 (M4) metatarsal 5 (M5), toe 1/ hallux (T1), toe 2-5 (T2-5).

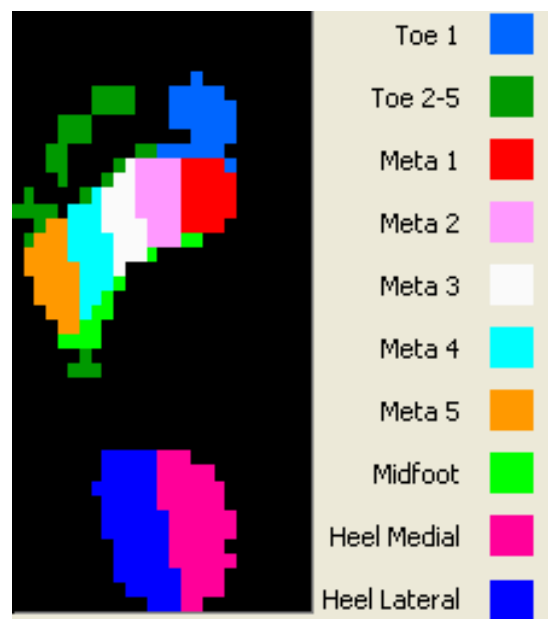


Figure 5.2 Plantar pressure sub-areas.

For each anatomical pressure sub-area, descriptive statistics (mean and standard deviation) were calculated by the RSscan International Footscan ® 7.x system to indicate peak pressure. The reference data set was calculated by averaging all four trials of all the individual athletes. Those results were averaged further between the sprinters and control group respectively.

Relative regional pressure sub-areas allow for a comparison between pressures of different foot areas of the sprinters and control group (**Table 10**).

As reflected in **Table 4.11** and **Table 4.12** the control group's peak plantar pressures are predominantly on the sub-areas of the heel (mean HL = Left: 327.69, right: 351.44; mean HM = Left: 434.08, right: 423.19) and M1, M2, M3, whereas the sprinters peak plantar pressures are predominantly on the sub-areas of the M1, M2, M3, mid-foot and T1. This confirms that sprinters predominantly have peak pressures on forefoot contact, whereas the control group predominantly has peak pressures on heel contact.

CHAPTER 6

SUMMARY AND CONCLUSION

6.1 INTRODUCTION

This chapter will summarise the trends seen in the analysed data and conclude the findings of this study. It will also discuss further recommendations concerning this particular subject matter.

6.2 SUMMARY

6.2.1 Foot type

Data suggested that athletes with a normal foot type can be seen as possible candidates for sprinting items and activities in general. It is, however, not conclusive to say that they will be sprinters, since several other physiological aspects have to be taken into consideration. It also does not state that a sprinter would not have high arch foot type, but rather that the majority of sprinters would have a normal foot type.

If comparisons are made between a foot type (**Table 4.1**) and the contact phase times (**Table 4.3**), a specific tendency can be identified, namely, a normal foot type has a faster forefoot contact than that of a high arch foot type. It is also clear that the control group with the high arch foot type, spends more time on the rear-foot than a normal foot type with rarely any rear-foot contact.

The results of this study also support the findings of research on foot types, that being flatfooted does not decrease foot speed, meaning that flat feet do not affect response to the plantar reflex test (Solomon *et al.*, 2005:243).

6.2.2 The effects of roll-over action of the foot during ground contact time

Gait is assumed to be symmetrical, however, the results from this study indicate some differences for both sprinters and the control group between the left and right feet during roll-over. Analysis should, however, always include

the foot roll-over of the left and right foot separately, as was done in this study. Although there are symmetrical differences between the left and right feet of all the test subjects, the foot roll-over differences between the sprinters and the control group is of specific relevance in this study and therefore emphasis will be based on the latter. A significant difference ($p < 0.05$) in foot roll-over was found between sprinters and the control group according to results presented in **Figure 4.6** and **Figure 4.7**. These results proved that the control group achieved more heel contact time than sprinters, resulting in a longer total foot roll-over time compared to that of the sprinters.

The results of this study support the findings of research (<http://www.nwhealth.edu>), that there are different types of foot strikes during ground contact; for example, a heel striker, a forefoot striker and a mid-foot striker. When comparing types of foot strike with the foot contact phases during sprinting, one can see why sprinters have a shorter FFP in relation to the control group.

6.2.3 Under-foot peak pressures

The results of the study provided a representative reference dataset for plantar pressures measured during sprinting underneath weight-bearing anatomical areas for barefoot sprinting. This reference dataset can be used for comparison of the load bearing function of foot pressure points of sprinter versus the control group. The peak pressure sub-areas for the sprinters and control groups' left and right foot, classified from highest to lowest, are indicated in **Table 4.5**.

Elite sprinters spend less time on the ground and this is because they produce greater forces. As a result, despite not moving their limbs significantly faster through the air, better sprinters tend to have greater stride frequency because they reduce the amount of time they spend on the ground. Cadence can be improved by maximizing the effort in removing the support foot from the ground. This maximized use of gravity should pull the runner forward.

The results of the foot type analysis were used to compare peak plantar pressure differences amongst the various foot types. It was found that sprinter participants predominantly have a normal foot type, whilst the control group participants predominantly have high arch feet. If the peak plantar pressures are taken in consideration with the foot types, it can be concluded that a normal foot type is more beneficial for sprinters as the peak pressures during sprinting were more dominant under the forefoot, which is a prerequisite for sprinting (Dintiman, & Ward, 2003:233).

6.3 CONCLUSION

6.3.1 There was no significant difference ($p < 0.05$) between the classification of foot types of the sprinters and control group. According to the research done, it seems that sprinters predominantly have a normal foot type.

6.3.2 The results of this study showed that sprinters will have a more predominant forefoot contact than that of the control group (non-sprinters) during sprinting; whereas the control group have a more predominant rear-foot strike than the sprinters during sprinting.

6.3.3 Lastly the research has shown that the sprinters' peak pressures during sprinting foot contact are the highest under the forefoot, whilst the peak pressures during sprinting foot contact of the control group is spread amongst the different sub-areas of the foot.

The main aim of this study was to determine if sprinters would have a specific foot classification (high, flat, normal). According to the results analysis, one can say that sprinters tend to have a normal foot type. Furthermore, it was evident that sprinters have the highest contact underneath the forefoot during sprinting which shortens the foot contact time during ground contact. The peak pressures under the forefoot of sprinters tends to be higher than that of the control group, which indicates a faster and more powerful foot contact, which establishes a better ground reaction force (Newton's third law).

6.4 LIMITATIONS

Despite the controlled design, certain limitations were experienced in this study. Not all items could be controlled, like the physical activity of the sprinters and control group a few days before the testing. Another limitation could be the restricted number of participants due to the unavailability of a bigger group of sprinters who qualified according to selection criteria.

All of the sprinters involved in this study normally compete wearing sprinting spikes. The test was, however, done barefoot to get each individual's unaltered biomechanical gait patterns. Barefoot versus spikes sprinting will differ due to the restrictions which the spikes might have on the foot. Another implication of using spikes might be the effects on the foot biomechanics due to different brandings (Nike, Adidas, etc), spike designs, spike length and the number of spikes used.

6.5 PRACTICAL RECOMMENDATIONS

It is recommended that a larger number of subjects, especially sprinters, should be involved in the study to provide more evidence to support the findings of the results. The results of such a study can also be improved by using more specific selection criteria with regards to the age, gender and ethnicity of the study subjects.

REFERENCES

Abboud, R.J. 2002. Relevant foot biomechanics. *Current Orthopedics*, 16:165-179.

Albaspectrum. (n.d). Training Speed – Acceleration. Available from: <http://www.albaspectrum.com/Recreation/200/086> (Accessed 13 February 2007).

Alcamo, I.E. 2003. Anatomy coloring workbook. *The Princeton Review 2nd ed*, 92-95.

Alexander, I.J., Chao E.Y.S. & Johnson, K.A. 1990. The assessment of dynamic foot-to-ground contact forces and plantar pressure distribution: a review of the evolution of current techniques and clinical application. *Foot & Ankle International*, 11 (3):152-167.

Arampatzis, A., Bruggeman, G.P. & Morey Klapsing, G. 2002. A three-dimensional shank-foot model to determine the foot motion during landings. *Medical Science Sports Exercise*, 34 (1):130-138.

Areblad, M., Nigg, B., Ekstrand, J., Olsson, K. & Ekstrom, H. 1990. Three-dimensional measurement of rear foot motion during running. *Journal of Biomechanics*, 23(9):933-940.

Benedetti, M., Catani, F., Leardini, A., Pignotti, E. & Giannini, S. 1998. Data management in gait analysis for clinical applications. *Clinical Biomechanics*, 13(3):204-215.

Bennett, P.J. & Duplock, L.R. 1993. Pressure distribution beneath the human foot. *Journal of the American Podiatric Medical Association*, 83 (12):674-678.

Blanc, Y., Blamer, C., Landis, T. & Vingerhoets, F. 1999. Temporal parameters and patterns of the foot roll over during walking: normative data for healthy adults. *Gait Posture*, 10:97-108.

Bobbert, M.F., Yeadon, M.R. & Nigg, B.M. 1992. Mechanical analysis of the landing phase in heel-toe running. *Journal of Biomechanics*, 25:223-234.

Borghese, N.A., Bianchi, L. & Lacquaniti, F. 1996. Kinematic determinants of human locomotion. *Journal of Physiology*, 494 (3):863-879.

Brugman, M., 2009. *lighterliving*. Available from: <http://www.lighterliving.com/pilates/article>. (Accessed 12 November 2010)

Brukner, P. Khan, K. 1993. Clinical Sports Medicine 2nd ed., The McGraw-Hill Companies, Inc, 43-59.

Bryant, A., Tinley, P. & Singer, K. 1999. Plantar pressure distribution in normal, hallux valgus and hallux limitus feet. *The Foot*, 9:115-119.

Bryant, A., Tinley, P. & Singer, K. 2000. Normal values of plantar pressure measurements determined using the Emd-SF system. *Journal of the American Podiatric Medical Association*, 90 (6):295-299.

Cappozzo, A. & Paul, J.P. 1997. Instrumental observation of human movement: historical development. Three-dimensional analysis of human locomotion. John Wiley & Sons Ltd., 1:1-25.

Carr, G. 1997. Mechanics of sport. United States of America. Human Kinetics, 88-102;159-164.

Carson, M.C., Harrington, M.E., Thompson, N., O'Connor J.J. & Theologis, T.N. 2001. Kinematic analysis of a multi-segment foot model for research and clinical applications: a repeatability analysis. *Journal of Biomechanics*, 34:1299-1307.

Cavanagh, P.R. 1990. The mechanics of distance running: a historical perspective. *Human Kinetics*, 1-34.

Cavanagh, P.R., Lafortune, M.A. 1980. Ground reaction force in distance running. *Journal of Biomechanics*, 13:397-406.

Cavanagh, P.R., Rodgers, M.M. & Liboshi, A. 1987. Pressure distribution under symptom-free feet during barefoot standing. *Foot Ankle*, 7: 262-276.

Clover, J. 2010. Sports Medicine Essentials, Core Concepts in Athletic training & fitness Instruction 2nd ed., *Cengage Learning USA*, 172-174.

Chai, H.M. 2005. *Biomechanics of Running*. Available from: <http://www.pt.ntu.tw/hmchai/Biomechanics/BMsports/Run> (Accessed 13 February 2007)

De Cock, A. 2006. The use and interpretation of plantar pressure measurements during running. Gent: Department of Movement Sport Science. 3-71.

De Cock, A., De Clercq, D., Willems, T. & Witvrouw, E. 2005. Temporal characteristics of foot roll-over during barefoot jogging: reference data for young adults. *Gait and Posture*, 21:432-439.

De Wit, B., De Clercq, D. & Aerts, P. 2000. Biomechanical analysis of the stance phase during barefoot and shod running. *Journal of Biomechanics*, 33:269-278.

Dintiman, G. & Ward, B. 2003. *Sports speed*. 3rd edition. United States of America: Human Kinetics Publishers Inc.

Dintiman, G., Ward, B. & Tellez, T. 1998. *Sports speed*. 2nd edition. United States of America: Human Kinetics Publishers Inc.

Dorsey, S.W., Davis, I.M., Scholz, J.P., Hamill, J. & Buchanan., T.S. 2003. High-arched runners exhibit increased leg stiffness compared to low-arched runners. *Gait and Posture*, 19:263-269.

Eng, J. & Winter, D. 1995. Kinetic analysis of the lower limbs during walking: what information can be gained from a three-dimensional model. *Journal of Biomechanics*, 28(6):753-758.

Foot Mechanics. (n.d.) Available from: <http://www.nwhealth.edu>. (Accessed 15 January 2006)

Giacomozzi, C., Macellari, V., Laerdini, A. & Bendetti, M.G. 2000. Integrated pressure-force kinematics measuring system for the characterisation of plantar foot loading during locomotion. *Medical. Biomechanics. Companies.*, 38:156-163.

Goble, D.J., Marino, G.W. & Potvin, J.R. 2003. The influence of horizontal velocity on interlimb symmetry in normal walking. *Human Movement Science*, 22:271-283.

Hagman, F. 2005. *Can plantar pressure predict foot motion?* Universiteitsdrukkerij, Technische Universiteit Eindhoven. 1-31.

Halleman, A., D'Aout, K., De Clercq, D. & Aerts, P. 2003. Pressure distribution patterns under the feet of new walkers: the first two month of independent walking. *Foot and Ankle International*, 24(5):444-453.

Hamilton, N. & Luttgens, K. 1997. *Kinesiology: Scientific basis of human motion*. 9th edition. New York: The McGraw-Hill Companies Inc. 218-236.

Hamilton, N., Weimar, W. & Luttgens, K. 2008. *Kinesiology: Scientific basis of human motion*. 11th edition. New York: The McGraw-Hill Companies Inc. 190-204; 467-483.

Harrison, A.J. & Folland, J.P. 1997. Investigation of gait protocols for plantar pressure measurement of non-pathological subjects using a dynamic pedobarograph. *Gait & Posture*, 6:50-55.

Hastings, M.K., Commean, P.K., Smith, K.E. & Pilgram, T.K. 2003. Aligning anatomical structure from spiral X-ray computed tomography with plantar pressure data. *Clinical Biomechanics*, 18: 877-882.

Hennig, E. & Rosenbaum, D. 1999. Pressure distribution patterns under the feet of children in comparison with adults. *Foot and Ankle*, 11 (5):306-311.

Hennig, E.M. & Lafortune, M.A. 1997. Technology and application of force, acceleration and pressure distribution measurements in biomechanics. Three-dimensional analysis of human locomotion. John Wiley & Sons Ltd. 6:109-127.

Hennig, E.M. & Rosenbaum, D. 1991. Pressure distribution patterns under the feet of children in comparison with adults. *Foot and Ankle* 12 (5):306-311.

Hennig, E.M., Staats, A. & Rosenbaum D. 1994. Plantar pressure distribution patterns of young school children in comparison to adults. *Foot and Ankle*, 15 (1):35-40.

Hintermann, B. & Nigg, B.M. 1998. Pronation in runners: implications for injuries. *Sports Medecine*, 26: 169-176.

Hoskisson, J.L. (n.d.). *Sprint Mechanics Revisited*. Available from: <http://www.gillathletics.com/articles/news120202>. (Accessed 6 March 2007)

Hughes, J., Clark, P., Linge, K. & Klenerman, L. 1993. A Comparison of two studies of the pressure distribution under the feet of normal subjects using different equipment. *Foot and Ankle*, 14 (9):514-519.

Hunt, A. & Smith, R. 2004. Mechanics and control of the flat versus normal foot during the stance phase of walking. *Clinical Biomechanics*, 19:391-397.

Hunt, A.E., Smith, R.M., Torode, M. & Keenan A.M. 2001. Inter-segment foot motion and ground reaction forces over the stance phase of walking. *Clinical Biomechanics*, 16:592-600.

IFPA. 2006. *Sprinting Form & Technique*. Available from: http://www.ifpa-fitness.com/Resources_Articles_SprintingForm.aspx (Accessed 13 February 2007).

Keller T.S, Weisberger A.M, Ray J.L, Hasan S.S. Shiavi R.G & Spengler D.M. 1996. Relationship between vertical ground reaction force and speed during walking, slow jogging and running. *Clinical Biomechanics*, 11:253-259.

Kernozek, T.W. & LaMott, E.E. 1995. Comparison of plantar pressure between the elderly and young adults. *Gait Posture*, 3:143-148.

Leardini, A., Benedetti, M.G., Catani, F., Simoncini, L. & Giannini, S. 1999. An anatomically based protocol for description of foot segment kinematics during gait. *Clinical Biomechanics*, 14:528-533.

MacWilliams, B.A., Cowley, M. & Nicholson, D.E. 2003. Foot kinematics and kinetics during adolescent gait. *Gait Posture*, 17:214-224.

McClay, I. 2000. The evolution of the study of the mechanics of running; relationship to injury. *Journal of the American Podiatric Medical Association*, 90(3):133-148.

McClay, I. & Manal, K. 1999. Three-dimensional kinetic analysis of running; significance of secondary planes of motion. *Medicine and Science in Sports and Exercise*, 31(11):1629-1639.

McPoil, T.G., Cornwall, M.W., Dupuis, L. & Cornwell, M. 1999. Variability of plantar pressure data, a comparison of the two-step and midgait methods. *Journal of the American Podiatric Medical Association*, 89 (10):495-501.

McRae, R. 2004. *Clinical orthopedic examination*. 5th edition. United Kingdom: Elsevier Limited. 271-306.

Medical MultiMEDIA Group. 2001. *A patient's guide to the anatomy of the foot*. Available from: <http://www.medicalmultimedigroup.com/pated/foot/anatomy> (Accessed 12 February 2007).

Miller, D.I. 1990. *Ground reaction forces in distance running*. *Biomechanics of distance running*. USA: Human kinetics books. 203-224.

Moore, K.L. & Dalley, A.F. 1999. *Clinically oriented anatomy*. 4th edition. Canada: Lippincott Williams & Wilkins. 632-646

Morag, E. & Cavanagh, P.R. 1999. Structural and functional predictors of regional peak pressure under the foot during walking. *Journal of Biomechanics*, 32:359-370.

Nigg, B.M., Cole, G.K. & Nachbauer, W. 1993. Effects of arch height of the foot on angular motion of the lower extremities in running. *Journal Biomechanics*, 26(8):909-916.

- Novacheck, T.F. 1998. The biomechanics of running. *Gait Posture*, 7:77-95.
- Orlin, M.N. & McPoil, T.G. 2000. Plantar pressure assessment. *Physical Therapy*, 80:399-409.
- Palastanga, N. Field, D. Soames, Rodger. 1989. Anatomy and Human movement structure and function 5th ed. *Elsevier*, 419-420.
- Pribut, S.M. 2005. Gait Biomechanics. *Dr. Stephen M. Pribut's sport pages*, 1-10.
- Prentice, W.E., 1999. *Rehabilitation techniques in sports medicine*. 3rd edition. USA: The McGraw-Hill Companies Inc. 490-509.
- Quinn, E. 2006. Lower leg anatomy. Available from: [attp://Sportsmedicine.about.com/cs/Leg_injuries](http://Sportsmedicine.about.com/cs/Leg_injuries) (Retrieved 20 January 2009).
- Reinschmidt, C. & Nigg, B. 1995. Influence of heel height on ankle joint moments in running. *Medicine and Science in Sports and Exercise*, 27(3):410-416.
- Rosenbaum, D., Hautmann, S., Gold, M. & Claes, L. 1994. Effects of walking speed on plantar pressure patterns and hind foot angular motion. *Gait Posture*, 2:191-197.
- Running mechanics. (n.d.). Available from: <http://www.icb.oxfordjournals.org>. (Accessed 15 January 2006).
- Seeley, R.R., Stephens, T.D. & Tate, P. 2006. *Anatomy & Physiology*. 7th edition. New York. 1-418

Solomon, L., Warwick, D.J. & Naygam, S. 2005. *Apley's concise system of orthopedics and fractures*. 3rd edition. London: Hodder Arnold. 238-254.

Soutas-Little, R., Beavis, G., Verstraete, M. & Markus, T. 1987. Analysis of foot motion during running using a joint co-ordinate system. *Medicine and Science in Sports and Exercise*, 19(3):285-293.

Stacoff, A., Kalin, X. & Segesser, E.S.B. 1989. The torsion of the foot in running. *Journal of Sport Biomechanics*, 5:375-389.

Strauch, B. Vasconez, L.O. Hall-Findlay, E.J. Lee, B.T. 2009. Grabb's Encyclopedia of Flaps, Torso, Pelvis, and Lower extremities 3rd ed. *Lippincott Williams & Wolters Kluwer Business*, 1500.

Team Oregon (n.d.). *Foot Motion in Running*. Available from: <http://www.teamoregon.com/publications/footmot> (Accessed 12 February 2007).

Thomas, R.B. & Roger, W.E. 2000. *Essentials of strength training and conditioning*. 2nd edition. 472-480

Titianova, E.B., Mateev, P.S. & Tarkka, I.M. 2004. Footprint analysis of gait using a pressure sensor system. *Journal Electromyograph Kines*, 14 (2):275-281.

VanZant, R.S., Mcpoil, T.G. & Cornwall, M.W. 2001. Symmetry of plantar pressures and vertical forces in healthy subjects during walking. *Journal of the American Podiatric Medical Association*, 91 (7):337-342.

Walker, M. & Fan, H.J. 1998. Relationship between foot pressure patterns and foot type. *Foot and Ankle*, 19 (6):379-383.

Wearing, S.C., Urry, S., Smeathers, J.E. & Battistutta, D. 1999. A comparison of gait initiation and termination methods for obtaining plantar foot pressures. *Gait Posture*, 10:255-263.

Wearing, S.C., Urry, S.R. & Smeathers, J.E. 2001. Ground reaction forces at discrete sites of the foot derived from pressure plate measurements. *Foot Ankle*, 22:653-661.

Williams, K.R. 2000. The dynamics of running. In: *Biomechanics in sport; performance enhancement and injury prevention*. Edited by Zatsiorsky, V.M. In: *The Encyclopaedia of Sports Medicine* (Vol. IX:161-183). Blackwell Science Ltd.

Young, M. 2006. *Maximal Velocity Sprint Mechanics*. Available from: <http://www.HPCsport.com>. (Accessed 5 January 2006).

Zatsiorsky, V.M., Werner, S.L. & Kaimin, M.A. 1994. Basic kinematics of walking: step length and step frequency, A review. *Journal of Sports Medicine and Physical Fitness*, 34:109-134.