SURFACE HARDNESS AND SHOD CONDITIONS EFFECTS ON BIOMECHANICS FOOT RESPONSE DURING RUNNING

by

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LIST OF ABBREVIATION

BF	Barefoot Running
HS	Heeled Running Shoe
MS	Minimally Running Shoe
MLA	Medial Longitudinal Arch
PFS	Plantar Fascia Strain
GRF	Ground Reaction Force
ISB	International Society of Biomechanics
3D	Three-dimensional
RMS	Root Mean Square
ROM	Range of Motion
BMI	Body Mass Index
QTM	Qualysis Track Motion
SPSS	Statistical Package of Social Science
UV	Ultraviolet
ASTM	American Society for Testing Material
AOI	Angle of Incidence
MFS	Mid-foot Strike
FFS	Forefoot Strike
RFS	Rearfoot Strike

KESAN-KESAN KEKERASAN PERMUKAAN DAN KEADAAN BERKASUT TERHADAP RESPON BIOMEKANIK KAKI SEMASA BERLARI

ABSTRAK

Berlari merupakan aktiviti yang sama ada boleh memberi pelbagai faedah klinikal atau menyebabkan kecederaan. Kekerasan permukaan dan keadaan berkasut boleh dianggap sebagai faktor utama yang mempengaruhi prestasi larian. Pemahaman tentang biomekanik yang dipengaruhi oleh permukaan larian dan keadaan berkasut mungkin membolehkan kecederaan dapat dielakkan dan meningkatkan faedah aktiviti larian ini. Tesis ini membincangkan analisa experimental terhadap kesan kekerasan permukaan larian dan keadaan berkasut kepada respon biomekanik kaki semasa berlari. Parameter-parameter ini dikaji ketika fasa 'stance' oleh sepuluh subjek lelaki dalam populasi universiti yang berlari dalam tiga keadaan (berkaki ayam, berkasut larian bertumit dan berkasut larian minimal) di atas permukaan yang berbeza dengan tiga tahap kekerasan (getah, rumput buatan dan konkrit). Proses pemeriksaan dijalankan dengan mengenalpasti jenis jejakan kaki dikalangan subjek untuk menyingkirkan pengaruh jejakan kaki kepada respon biomekanik. Hanya data jejakan tumit sahaja yang diambil kira untuk dianalisa kerana majoriti subjek menjejak dengan jejakan tumit. Perbezaan ketara pada parameter kinematik dapat dilihat dalam analisis putaran sendi semasa fasa 'mid-stance' dalam fasa 'stance' ketika larian berkaki ayam, walaupun corak putaran sendi tersebut hampir sama dalam setiap keadaan larian di atas semua kekerasan permukaan dalam keseluruhan fasa 'stance'. Perbezaan ketara juga dilihat dalam parameter masa ketika berlari dengan kasut larian bertumit dan kasut larian minimal. Parameter masa juga mempunyai kaitan yang kuat dengan kekerasan permukaan. Tetapi, parameter kinetik menunjukkan kaitan yang lemah antara kekerasan permukaan larian untuk kedua-dua parameter kinetic; daya reaksi permukaan dan ketegangan 'plantar fascia'. Kajian ini menambahbaik pandangan mengenai hubungan diantara parameter kinematik dan kinetik yang menjadi tambahan kepada parameter masa semasa berlari di atas permukaan dengan kekerasan yang berbeza.

SURFACE HARDNESS AND SHOD CONDITIONS EFFECTS ON BIOMECHANICS FOOT RESPONSE DURING RUNNING

ABSTRACT

Running activities can be either beneficial or caused chronic injuries among runners. Surface hardness and shod condition can be considered as the major factors that influenced the running performance. Understanding the biomechanics affected by running surface and shod conditions might prevent injury and enhance the benefits of running activity. This thesis discuss the experimental analysis on the effect of surface hardness and shod condition on the biomechanical foot responses. The parameters were investigated experimentally during the stance phase of ten male subjects that running with three different shod conditions; barefoot (BF), heeled running shoe (HS), and minimally running shoe (MS) on three types of running surface with different hardness level (i.e. concrete, artificial grass and rubber). Screening process was conducted by evaluating the foot strike pattern among the subjects in order to eliminate the influence of foot strike on biomechanics responses. Only heel strikers' data was analyzed since most of the subjects performed heel strike during the experiment. The significant difference on kinematic parameter was found in investigation of joint rotation during mid-stance of stance in BF running, although the pattern of joint rotations on all surfaces in each shod condition is almost similar in overall stance phase. The significant difference was also found in the temporal parameter during HS and MS running and the stance time was found to have a strong correlation relationship with surface hardness. However, kinetic parameters show poor correlation relationship with running surface for both GRF and PFS as the results are varied as the surface hardness was changed. This study could provide additional insight on relationships between kinematic and kinetic parameters in addition to temporal parameters when running on different surface hardness.

CHAPTER 1

INTRODUCTION

1.1 Background

Running is a popular activity which had been connected to various clinical benefits (Hillman, Erickson, & Kramer, 2008). However, based on etiology analyses completed, running is associated with the increment of most chronic injuries' risk among runners (Van Gent et al., 2007). Specifically, running on different surface characteristics requires a certain adaptation of the foot in order to avoid or reduce injury risk. Surface characteristics can be categorized as irregularity, hardness, roughness, slope and inclination. Running surfaces that commonly used in leisure running activities are concrete, asphalt, rubber, treadmill, grass and trails (Tillman, Fiolkowski, Bauer, & Reisinger, 2002).

In the framework of running gait cycle which involve the stance and swing phase, initial contact or foot strike of the stance phase is one of major phase that can cause injury. Foot contact with the surface and misalignment of the foot segment during stance phase enable several of physical injuries to occur. Instead of initial contact of the stance phase, mid-stance which is another sub-phase of stance phase also have a role in the occurrence of injury. The injury might occur due to the full body weight supported by the foot in this phase (Hardin, van den Bogert, & Hamill, 2004).

Mechanism used to relate running surface and shod condition with injury is biomechanics of the lower extremity. The biomechanics of lower extremity are involving kinematic and kinetic parameters in addition to temporal parameter. Dynamic modelling was implemented to investigate 3D-segments of foot, using either single rigid body or multi-segment analysis. Basically, characteristics of running surface contribute to various adaptations or alteration of the lower extremity which might lead to injury.

1.2 Problem Statement

Running in various conditions lead to different alteration on the foot movement in order to suit comfort ability and avoid injury. Adaptation of the foot during running can be characterized in terms of kinematics and kinetics measures. Running surface and shod condition generally contribute to major influence on this adaptation or alteration. It is important to investigate the effect of running condition (i.e. running surface and shod condition), because running surface and shod condition might contribute to foot injury. This injury could be predicted by analyzing the kinematics and kinetics responses. Although some studies had been conducted to examine the effect of running condition (i.e. running surface and shod condition) on kinematic and kinetic responses, these studies are limited to single-rigid segment foot model. Since this model might not produce adequate information as it is limited to a single segment of the foot, multi-segment foot model could be beneficial to investigate the foot kinematics response in multiple foot segment.

1.3 Objective

The principle aim of this research is to investigate the effect of surface hardness on the biomechanical response of foot during running with different shod conditions that may lead to injury. The task was divided into three specific objectives as follows:

i. To determine the effect running surface hardness on joint rotation of multi-segment foot kinematics.

ii. To analyze the influence of running surface hardness on temporal parameter and kinetic responses (i.e. plantar fascia strain and ground reaction force).

iii. To determine the correlation of kinematic and kinetic responses during running on different surface hardness in different shod conditions (i.e. barefoot (BF) heeled running shoe (HS) and minimally running shoe (MS)).

iv. To understand etiology of plantar fasciitis which one of common injury risk to runners.

1.4 Scope of study

This study were involving ten male subjects within university population. This study was done to investigate the biomechanical responses of foot during running on three different surfaces with different hardness level, (rubber (soft), artificial grass (medium) and concrete (hard)) in three shod conditions (BF, HS and MS).

The experimental study was focusing on kinematic and kinetic of foot response by highlighting the multi-segment foot model during running in recreational mode.

1.5 Thesis Organization

Chapter 1: This chapter begins with the introduction about the running and factors related to common foot injury occurrence. This chapter will also cover the problem statement, objectives, and scopes of this study.

Chapter 2: This chapter covers the literature review of running gait that includes the important notes about subtopic that related to this study as well as past research on similar topic of this study.

Chapter 3: This chapter elaborates about the methodology of this study. This chapter is including the subject criteria, equipment used, experimental procedure and data analysis.

Chapter 4: This chapter presents the result obtained and discussion on the remarkable findings that focusing on joint rotation angles of foot segment as well as peak medial longitudinal arch (MLA) angle in addition to temporal parameter, plantar fascia strain (PFS) and ground reaction force (GRF).

Chapter 5: This chapter summarizes and concludes the overall project as well as discuss on the improvement and recommendation for future study.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This section describes several previous research works related to this study that investigating the effect of surface during running on kinematic and kinetic parameters particularly. This chapter also provides basic knowledge and fundamental input to readers in order to understand the overview of this thesis. This research purposes is to investigate the effect of running surface on foot that might contribute to injury. The parameters that could describe the injuries of the foot can be represented by obtaining the foot joint rotations, plantar fascia strain (PFS), medial longitudinal arch (MLA) angle and ground reaction force (GRF).

2.2 Foot structure

Foot is well-known as a complex structure which composed of 26 uniquely shaped bones, 30 joints, more than 100 ligaments and 23 extrinsic and intrinsic muscles (Hamill & Knutzen, 2006). The articulating bones are presented in Figure 2.1. These bones and joints of the foot provide a foundation support for the upright body and assist it to adapt the irregular surface and absorb shock.

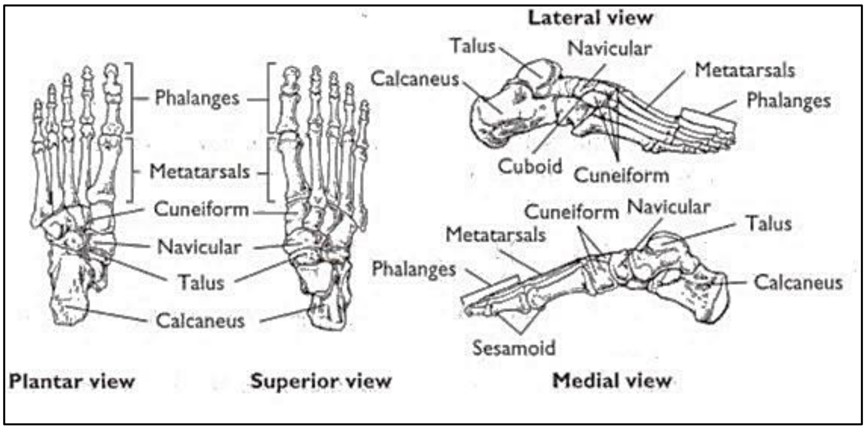


Figure 2.1 Bones of foot (Hall, 2011)

MLA is an important arch in foot geometry which made up by calcaneus, talus, navicular, three cuneiforms (medial, intermediate, and lateral), and first, second, and third metatarsals as shown in Figure 2.2. The navicular is assumed as the foundation of MLA (Hamill & Knutzen, 2006). MLA contribute a major role in gait and standing up position as it is involved in the impact absorption and transportation of ground reaction force (Zuil-Escobar, Martinez-Cepa, Martin-Urrialde, & Gomez-Conesa, 2015). The function of MLA are also to provide stability, absorb or store energy as well as generate and transfer energy. The stability of MLA is provided by the arch shape and alignment of the tarsal bones, with multiple ligaments and aponeuroses (Boyer, Ward, & Derrick, 2014).

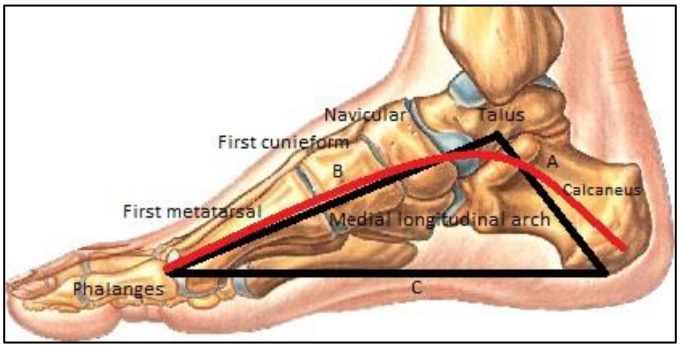


Figure 2.2 Triangulation of plantar fascia and medial longitudinal arch [edited from (“Foot Education,” 2016)]

Foot and its ligaments also can be defined as an arch-like triangular structure or truss (Hicks, 1954) which made up of metatarsal, mid-tarsal joint and calcaneus as shown in Figure 2.2. Plantar fascia is represented by the hypotenuse (line C) and MLA is represented by the other two lines (line A and B). The red arch indicate the arch shape of MLA.

Plantar fascia is defined as a thick and fibrous layer of connective tissue (aponeurosis) that adheres to the plantar surface of metatarsophalangeal joints which come from the medial tubercle of the calcaneus embedded into the deep soft tissue of the forefoot (Aquino & Payne, 1999) as shown in Figure 2.3. Anatomical attachment of the plantar fascia has displayed its various functional and structural function. Main responsibility of plantar fascia is to support the arch of the foot during loading (Crary, Hollis, & Manoli, 2003) and it remains the most important arch stabilizing structure. Plantar fascia elongates with increasing loads, and stores this elastic energy, serving as a shock absorber (Wright & Rennels, 1964). These mechanical properties are linked with the manner of its insertion into the medial calcaneus. Eventually, the plantar fascia has a vital role in re-supination of the foot during the propulsive period of the stance phase of gait (Bartold, 2004).

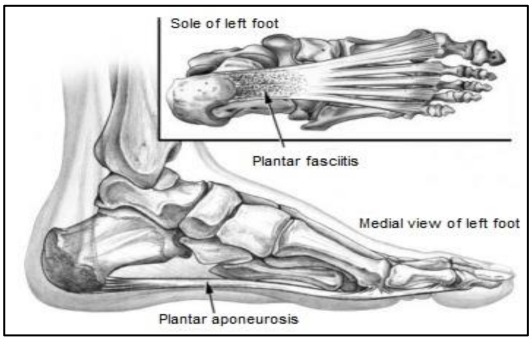


Figure 2.3 Plantar fascia/aponeurosis originates from calcaneus to phalanges (Bolgla & Malone, 2004)

Excessive plantar fascia elongation may lead to injury due to the abnormal foot motion during walking or running. This elongation can be analyzed and investigated as strain. The plantar fascia strain, ε_{PF} is computed using Equation (2.1). In general, strain is defined as a complete deformation of a material body where the force is being applied and commonly expressed as a dimension changes percentage. While, muscular strain is described as eccentric stretch of muscle fibers (Knudson, 2013) .

$$\varepsilon_{PF} = \frac{l_1 - l_0}{l_0} \tag{2.1}$$

Where,
$l_1 = change\ of\ length\ in\ plantar\ fascia$
$l_0 = original\ length\ in\ plantar\ fascia$

Typical injury of plantar fascia is plantar fasciitis. Plantar fasciitis occurred when plantar fascia is in an inflammatory state (Yucel, Yazici, Degirmenci, Erdogmus, & Dogan, 2009) and lead to muscular strain. Plantar fasciitis is the major contributor to inferior heel pain, however, with poorly understanding of etiology and complicated terminology (Sabir, Demirlenk, Yagci, Karabulut, & Cubukcu, 2005) due to various contributing factors such as poor biomechanics strategy, overexertion, activity that related to occupation, weight gain and improper shoes selection (Roxas, 2005) might lead to difficult treatment to be applied. Furthermore, plantar fasciitis is believed because of the persistent overload either from lifestyle or exercise (Schwartz & Su, 2014) and affects both inactive and athletic people. Risk factors for generating plantar fasciitis can be categorized into anatomic, biomechanical, and environment as listed in Table 2.1 (Dyck & Boyajian-O’Neill, 2004). The most important independent risk had been found due to the limit of ankle dorsiflexion motion (≤10°) (Riddle, Pulisic, Pidcoe, & Johnson, 2003). Surface hardness is included as one of the risk factor of plantar fasciitis.

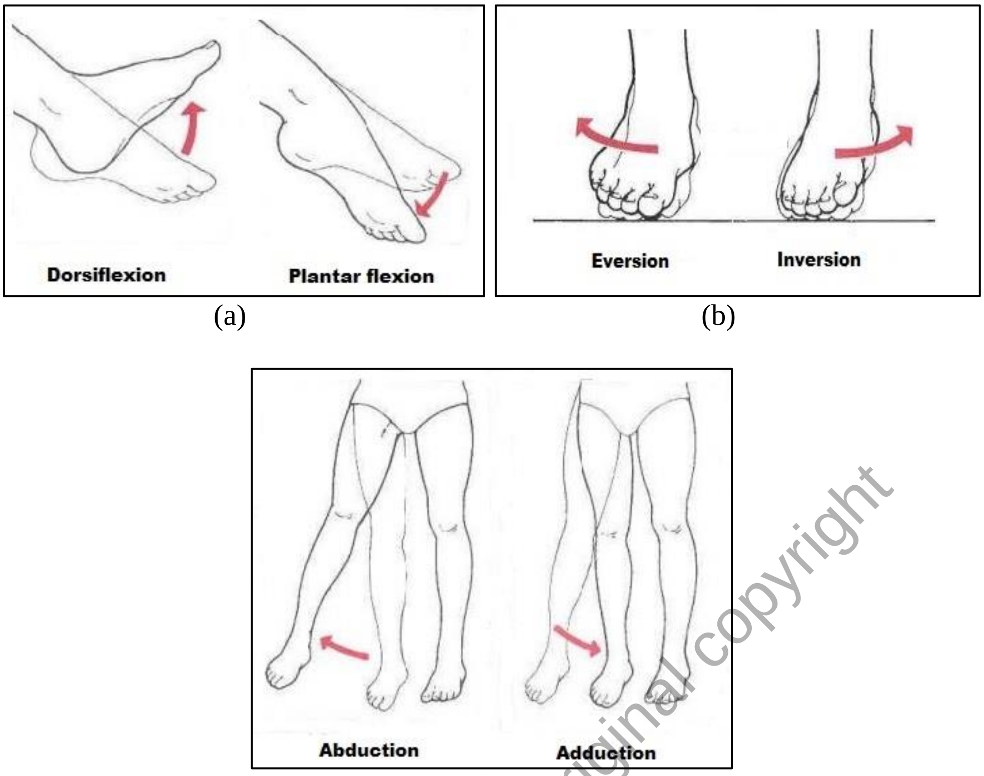
Table 2.1 Risk factor of plantar fasciitis

Anatomical	Biomechanical	Environmental
• Pes planus • Pes cavus • Obesity • Tarsal coalition • Leg length discrepancy • Fat pad atrophy • Shortened Achilles tendon	• Weak plantar flexor muscles • Weak intrinsic muscle of the foot • Excessive subtalar joint pronation • Poor footwear • Limited ankle dorsiflexion	• Trauma • Deconditioning • Hard surfaces • Walking barefoot • Prolonged weight-bearing • Inadequate stretching

2.3 Foot joint rotations

Joint angle is defined as relative rotation between two segments which one of the segment act as reference and considered to be non-moving (Chizewski & Chiu, 2012). Basically, joint angle is reported according to the rotation of the joint. In the present study, joint rotations of foot segments were evaluated in reference to International Society of Biomechanics (ISB) recommendations (Wu et al., 2002) which are plantar- or dorsi-flexion as the rotation about the z-axis of the proximal segment (Figure 2.4(a)), abduction or adduction about the y-axis of the distal segment (Figure 2.4(b)) and eversion or inversion about the axis orthogonal to the medio-lateral and vertical axis (Figure 2.4(c)).

These movement commonly described in sagittal, frontal/coronal and transverse plane. Each joints rotation has a predominant plane that allows the rotation to be perpendicular to the axis. The body plane is illustrated in Figure 2.5.



(a) (b)

(c)

Figure 2.4 Foot motion illustration (a) Dorsi-/Plantar flexion of foot (b) Abduction/Adduction of leg (c) Eversion/Inversion of foot (Hall, 2011)

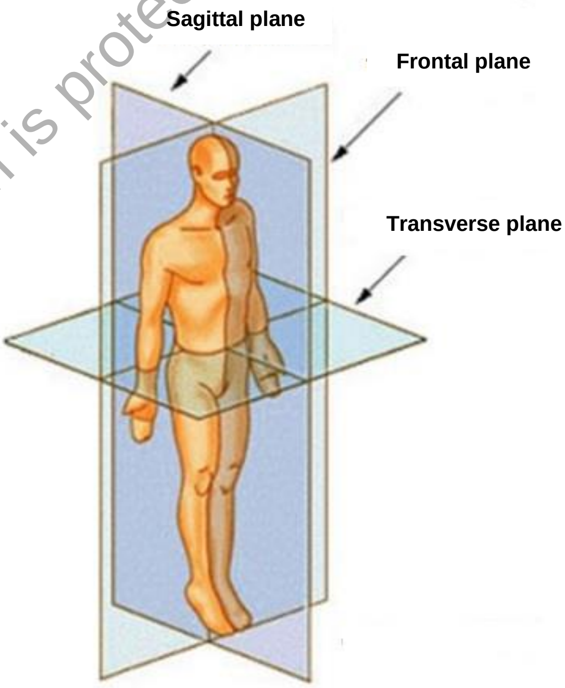


Figure 2.5 Body plane (Hall, 2011)

In running investigation, joint rotations are the favorite kinematic parameters to be studied and analyzed by researchers due to its major contribution on running performance. Joint rotations which one of kinematic parameters is always known able to explain the running injuries. Previously, various research groups evaluate the joint rotations response during running on different surface characteristics (Alcaraz, Palao, Elvira, & Linthorne, 2011; P. C. Dixon, Tisseyre, Damavandi, & Pearsall, 2011; W. Fu et al., 2015; Hébert-Losier, Mourot, & Holmberg, 2015; Kim, Tan, Veloso, Vleck, & Voloshin, 2011; Müller, Grimmer, & Blickhan, 2010; Nicholas Stergiou & Bates, 1997; Tenbroek, 2011; Tessutti, Ribeiro, Trombini-Souza, & Sacco, 2012). These previous studies generally investigated the joint rotations as a single rigid segment.

Moreover, an individual consistently has to undergo kinematic strategy alterations in adapting and effectively negotiate each of the running surface. The alterations might produces different kinetic response and reduce risk of injury. Several investigations of running on different surfaces revealed that individuals altered the joint rotations during movement over surfaces with different mechanical properties. According to the result identified by previous studies on surface hardness effect, the relationship of surface hardness and kinematic parameter i.e. joint rotation remain unclear because the findings on kinematics response to the surface changing reported by previous studies were in disagreement (S. J. Dixon, Collop, & Batt, 2000; Ferris, Liang, & Farley, 1999; Kerdok, Biewener, McMahon, Weyand, & Herr, 2002). Dixon et al. (2000) found that there was no significant different of the magnitude of kinematic variables response during running on different surface. Instead of that, Ferris et al. (1999) and Kerdok et al. (2002) found kinematic changes of subjects during running in adapting to the different surfaces.

2.4 Foot Modelling

Mechanic of the foot become a frequent measurement investigated due to the increasing of the accuracy of motion analysis measuring system. In gait analysis, optical tracking equipment that investigate motion is shown as an effective method of measuring three-dimensional kinematics and kinetics of the human body in term of dynamic modelling (Jenkyn, Anas, & Nichol, 2009). Dynamic modelling was utilized to define the segments of body parts. These body parts can be analyzed as single rigid body or multi-segment. Clinical biomechanical models in gait analysis commonly represent foot as a single rigid vector where only foot progression angle and net dorsiflexion or plantar-flexion can be identified. (Carson, Harrington, Thompson, O'Connor, & Theologis, 2001). Resolution of a camera that detects reflective markers during early development of clinical gait analysis on marker placement was limited. Thus, a single rigid segment was used with two reflective markers positioned on the heel and toe. The ankle motion of normal foot was accurately measured, however, the measurement of pathologic foot is questionable as motion distal to the ankle is assigned to the ankle joint (Saraswat, MacWilliams, Davis, & D'Astous, 2014).

The complexity of foot structure caused difficulty in achieving a standard and valid method of dynamic in vivo measurement (Carson et al., 2001). Previously, there were research groups introducing multi-segment foot model which varied in number of segments and marker placement (Helm, 2014). In order to overcome the limitation of single rigid segment model, a few studies had been done to improve the model into a multi-segment model. This non-invasive approach that use skin-mounted markers was applied in order to replace the use of invasive intracortical bone pins. The invasive