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THE EFFECT OF FOOTWEAR CONDITION ON MUSCLE ARCHITECTURE DURING WALKING

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ABSTRACT

Previous literature has examined the effects of footwear on economy of locomotion, but it has been limited to conditions of running. Much of this research has shown a marked difference in economy between shod conditions and minimally shod or barefoot conditions through the utilization of elastic energy storage and return. Minimally shod or barefoot conditions of running required less energy expenditure than during shod conditions. As much research on economy has focused on running performance, it is of interest to see if these or similar energy expenditure requirements would be present during walking in a barefoot condition compared to a shod condition. The present study aimed to determine muscle fascicle length changes in the muscles of the *triceps surae* during walking in barefoot and shod trials. Fourteen healthy subjects walked on a treadmill with natural cadence during the two conditions. *In vivo* techniques were used to image real-time muscle fascicle behavior of the *triceps surae* in order to determine the extent to which elastic energy is utilized during walking. The results of the ultrasound data suggest that there was no significant difference of muscle architecture of the medial gastrocnemius (MG) and lateral gastrocnemius (LG) muscles during shod and barefoot walking. The study design limited the ability to determine efficiency of conditions accurately. Although direct measurements of efficiency were inconclusive, inferences were made that showed a non-significant difference of muscle fascicle length between the conditions of walking and ultimately no difference in elastic energy utilization. This data may be a validation for the lack of elastic energy storage and return that occurs during walking but more studies need to be done to confirm this.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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Chapter 1

Introduction

1.1 General Introduction

As humans, we possess the capability to produce movement in various fashions, one of which is locomotion. Locomotion is a vital aspect of everyday human life lending itself to be studied frequently by researchers. It is of interest to researchers not only to provide insight into the mechanisms underlying human locomotion but more specifically how locomotion can be utilized economically. The measurement and understanding of these mechanisms can have significant implications on the human population as a whole and provide a new understanding on how humans are able to produce maximum locomotor efficiency during everyday life. Knowledge of the conditions that produce efficiency during locomotion has the ability to influence the way in which humans choose to move as well as the methods used in rehabilitation of lower limb injuries.

Locomotion of the human body can occur in multiple forms from walking to running and from hopping to jumping. The production of locomotion can be conveyed by various mechanisms, whether it is by muscular work or by the conservation and utilization of energy. In order to understand the potential for energy saving techniques during locomotion, it should first be understood how energy is used to produce said locomotion. Muscles require metabolic energy in order to contract. Muscles perform various degrees of work under different conditions. Muscles are said to do ‘positive work’ during concentric contractions, ‘negative work,’ during eccentric contractions, and no work during isometric contractions. This concept of work is based on defining work as the application of a force through a distance; however, metabolic energy is expended during all contraction types. Although muscles play a vital role in producing movement they do not act alone. Tendons not only serve as a mechanism for locomotion but can serve to enhance the efficiency of locomotion by reducing the demand of the muscles during force production. This action by the tendon is important as a means of saving energy. It has been proposed by Alexander (1991) that mammals exhibit energy-saving mechanisms in regards to locomotion in many different ways. He investigated how these mechanisms work and the extent to which mammals use them. He found that tendons appear to serve as springs and are vital in reducing the negative (eccentric) and positive (concentric) work required by the muscle in each step during locomotion. Tendons do not reduce the amount of work required to perform any type of gait but rather do some of the work, therefore requiring less work to be done by the muscle. It was argued that lost kinetic and potential energy during contact with the ground could be stored as elastic strain energy and returned by elastic recoil, ultimately reducing the length changes that the muscle fibers have to make.

Locomotion in the realm of hopping, jumping, and running exhibit energy conservation by way of a spring-like bouncing mechanism (Ishikawa et al., 2005). This mechanism of energy conservation occurs when mechanical energy is compressed and stored upon the first half of the stance phase during the step cycle and is immediately returned upon the latter half. During this stance phase a stretch and recoil of the tendon occurs, generating what is referred to as elastic strain energy, as previously stated, or elasticity (Fukunaga et al., 2001). Elasticity is the mechanism that allows an object to spring back to its original shape after it has been deformed

(Alexander, 1988). The more a muscle shortens, the more the tendon is stretched and deformed, yielding more elastic energy to be recovered on the recoil.

In comparison to running, walking is characterized by a having a smaller braking force and a longer contact phase between brake and push-off (Ishikawa et al., 2005). The differences between the two forms of gait have prompted researchers to examine the mechanisms responsible for the storage and utilization of elastic energy during walking. Ishikawa et al. hypothesized that locomotion in the form of walking exhibits the utilization of elastic energy in a catapult action mechanism rather than a spring-like bouncing mechanism as seen in running. In walking, there is a slow stretch followed by rapid recoil of the tendinous tissue during the ground contact of walking, allowing for the amplification of muscle power production. The interactions between the muscle fascicles and the tendinous tissue are important in the process of the storage and recovery of elastic energy during locomotion. As walking and running are the most prevalent forms of human locomotion it would be pragmatic to investigate and understand the mechanics of elastic energy that exist in each form of gait. Furthermore, the relation of elastic energy and subsequent energy expenditure of the muscle is important when comparing different modes and conditions of locomotion.

During different conditions of locomotion, muscles are either required to produce mechanical work or must absorb it (Lichtwark & Wilson, 2006). As previously mentioned, muscles that produce work require metabolic energy in order to shorten and develop the force needed for movement. Additionally, if the kinetic and gravitational potential energy can be stored briefly as elastic energy and returned as elastic recoil, very little work from the muscles would be needed. In both walking and running gait cycles it is thought that elastic energy is stored within the elastic tissues of the muscle tendon unit (Fukunaga et al, 2001; Ker et al., 1987). This storage of elastic energy has the ability to contribute to overall efficiency of locomotion to different extents, where running has been seen to have greater efficiency than walking (Cavagna & Kaneko 1977). The greater efficiency during running is said to be promoted by mechanics, in which kinetic and potential energy enter the muscles to be restored immediately after, during shortening. The mechanics that occur during walking do not allow this same type of interaction but rather an exchange of potential and kinetic energy during the stretch and shortening cycles.

As previously mentioned, the elastic tissues that comprise the muscle tendon unit are thought to store elastic energy during locomotion. In order to understand the extent of work required by the muscle during locomotion, the contributions of the muscle must be distinguished from that of the tendinous tissue. Measuring length changes of the muscle's contractile parts (muscle fascicles) has been shown to be useful in understanding the dynamics of locomotion. Previous studies conducted by Griffiths (1987,1991) utilized sonomicrometry to measure muscle fascicle length changes in animal subjects. These studies have shown that tendons can store and release elastic energy, allowing muscle fascicles to act almost isometrically. This release of energy by the tendon aids in supplying the increased demand of energy during force production. This characteristic of tendons reduces the energy requirements of the muscle during force production. More recent measures of muscle fascicle length changes in human subjects will be detailed in Chapter 2.

Muscle length changes are not the only factor of interest when determining the degree of elastic energy utilization in locomotion. The various forms of footwear, or lack of, have been of recent concern when examining locomotion. Recent anthropological evidence has suggested that footwear began being worn about 40,000 years ago (Trinkaus & Shang, 2008). During this span, footwear design has evolved from basic open-toed sandals with minimal support and cushion to the more complex design seen today. Modern shoes are often elevated and contain some level of cushioning at the heel and throughout the sole. The cushioning of footwear and other aspects of shoe design can significantly affect the economy of locomotion (Frederick, 1984). Footwear is designed in an ergonomic manner such as to provide the wearer protection and optimal performance by way of efficient locomotion. These advances in footwear design have raised the question as to the usefulness and applicability of footwear during walking and running.

Much research on locomotion to date has focused on running performance and efficiency as a result of footwear condition. In previous studies, such as that conducted by Divert et al., it was found that mechanical differences existed between barefoot running and shod running (2005). These mechanical differences in barefoot running are displayed in lower contact and flight time, lower passive peak, higher braking and pushing impulses, and higher pre-activation of *triceps surae* muscles in comparison to shod running. When performed on a sufficient amount of steps, barefoot running allowed for a reduction of impact peak and ultimately enhanced storage and return of elastic energy when compared to shod running. The mechanical differences that are present between shod and barefoot running pose the question of whether these or similar differences in elastic energy utilization are present during the condition of walking.

1.2 Purpose of Study

The aim of this research is to expand upon previous studies displaying muscle length changes during walking and its relation to elastic energy storage and return. This study will be measuring muscle length changes in the human *triceps surae* muscles during conditions of shod and barefoot walking via treadmill. Subjects will be instructed to walk on a treadmill in both conditions (shod and unshod) with an ultrasound probe attached securely to the calf in order to measure and compare the muscle length changes that occur and determine the role of elastic energy in either condition. A validation of this study could add to current literature on the effects of footwear on muscle energy requirements and, consequently, the cost of transport.

1.3 Hypotheses

H_1: There will be a significant difference in muscle length changes during shod walking compared to barefoot walking.

H_0: There will be no significant difference in muscle length changes during shod walking compared to barefoot walking.

1.4 Specific Aims

The specific aims of this study are as follows:

1. To measure the muscle length changes exhibited by the *triceps surae* during conditions of shod and barefoot walking using ultrasound.
2. To compare the muscle length changes between shod and barefoot conditions in MATLAB using a custom written algorithm.
3. To estimate elastic energy differences between shod and barefoot conditions as a result of muscle length changes in the *triceps surae*.
4. To determine the energy expenditure requirements of shod and barefoot conditions and which is more economical.

1.5 Overview of Study

Using ultrasound measures, muscles of the *triceps surae* will be recorded during shod and barefoot conditions of walking on a treadmill. Muscles of the *triceps surae* include the lateral gastrocnemius, medial gastrocnemius, and the soleus. Measurement of these muscles will take place in two separate trials. In one trial of walking, the lateral gastrocnemius and soleus will be measured during shod and barefoot walking. In another trial, the medial gastrocnemius and soleus will be measured during both conditions of walking. Muscle length changes will be recorded for each instance and compared between shod and barefoot conditions.

1.6 Thesis Structure

Chapter 2 contains the review of literature. Chapter 3 discusses the methods of the study. Chapter 4 introduces the results of the experiment. Chapter 5 includes the discussion of the results and the conclusion of the study.

Chapter 2

Review of Literature

2.1 Overview

This chapter is a review of literature detailing the role of elastic energy storage and return in locomotion as introduced in Chapter 1. This chapter will further examine the function of structures involved in the energy saving process and the techniques implemented to measure this process. Section 2.2 discusses the mechanical properties of tendon and its role in locomotion. Section 2.3 reviews research concerning the characteristics and capacity of tendons in promoting locomotor efficiency. Section 2.4 describes the relationship of muscle fibers and tendon and how it contributes as a component of force generation. Section 2.5 introduces the technique of measuring muscle length changes and how this behavior allows for economy in human locomotion. Section 2.6 discusses the previous research examining the effects of footwear on the mechanics and energetics of locomotion.

2.2 Mechanical Properties & Role of Tendon in Locomotion

When discussing human locomotion it is important to note the mechanisms that make locomotion possible. In the case of walking, as in other forms of locomotion, the properties of tendons are critical for yielding efficient locomotion. Tendons, as well as muscle, contain elastic elements that allow for enhanced muscle versatility. The compliance of tendon contributes to SEE (series elastic element) compliance, which allows muscle to operate with greater efficiency in certain conditions. The study by Wilson and Lichtwark (2011) aimed to determine how the properties of tendon, as well as muscle, contribute to locomotor performance in different conditions. They examined the effects of changing the frequency of contraction on muscle power output in muscles with varying SEE compliance. The model force-length and force-velocity properties were set to represent a mixed fiber-type mammalian muscle while series elastic compliance was varied. The increase in tendon compliance showed to have a positive influence on muscle power output during frequencies below 3Hz. Tendons of increased stiffness required a greater volume of muscle to be activated and in turn increased metabolic energy by the muscle. Very compliant tendons also require muscle fascicles to shorten at high velocities. It is apparent that the stiffness of tendons is tuned to allow for the minimization of muscle activation and enhance muscle efficiency during locomotion.

The ability of tendons to promote power output while minimizing energy expenditure is dependent upon factors of the muscle tendon unit (Lichtwark & Barclay, 2010). The capability of the muscle to produce force, and the matching tendon compliance during movement, are important determinants of power output. In order to test the idea that efficiency of the muscle and power output can be affected by tendon compliance, they developed a method to test the outcomes of varying tendon compliance. The soleus muscle of adult, male rats were dissected and muscle fiber bundles were extracted for further examination. To test the effects of series compliance on muscle energetics, latex strips of various levels of compliance were placed between the muscle fiber bundle and the motor. The rat soleus was subject to cyclic contractions at 2Hz. It was found that compliant tendons altered the muscle fiber velocities to that in which power and efficiency is maximized. Shortening velocities for the most compliant tendons were closest to the optimal velocity for maximizing power output and efficiency. Lichtwark and Barclay demonstrated not only the importance of compliant tendons on producing efficiency but the overall influence of tendon structure during locomotion.

2.3 Role of Tendon in Elastic Energy

To understand how the elements of tendinous tissue contribute as an elastic component a study was conducted by Muramatsu et al. (2001) to examine the strain distribution along the tendon and aponeurosis. Previously, studies examining mechanical properties of the elastic component had been done on animal subjects or human cadavers, limiting their applicability to humans *in vivo*. Additionally, no previous studies estimated strain distribution along the aponeurosis and tendon separately. They used ultrasound for *in vivo* measurements of aponeurosis and tendinous tissue displacement of the Achilles tendon and medial gastrocnemius during varying levels of torque production. A myometer was used to detect the torque at the varying degrees of maximum voluntary contraction (MVC). Measurements were also made during a condition of passive range of motion at the ankle and during a plantar flexed condition. Strain in the Achilles tendon and the MG aponeurosis were similar and lacked significant heterogeneity suggesting that both possess elasticity and strain as a result of muscle force production. The significant strain of both the tendon and aponeurosis indicate the contribution of tendinous tissues as an elastic component of movement. These results imply that efficiency of locomotion can be achieved as a result of these properties as the MG and Achilles tendon are vital for carrying out human locomotion. The researchers proposed that methodological errors may have been present during the scanning of the muscle-tendon junction, which may have contributed to the lack of statistical significance in displacement.

2.4 Muscle Tendon Complex

Human movement is carried out by contractions of muscle fibers connected to tendons (Fukunaga et al. 2002). [This relationship is referred to as the muscle tendon complex (MTC)]. To understand the functional characteristics of muscle fiber and tendon during human movement, they measured *in vivo* the arrangement and interaction of muscle fibers and tendinous tissues. Architecture of the MTC for leg muscles (vastus lateralis, VL; gastrocnemius medialis, MG; tibialis anterior, TA) was estimated *in vivo* using ultrasound. More specifically, the lengths of fascicle and tendon as well as the pennation angle were measured. Changes in the fascicle lengths of the MG were shorter and had longer tendinous tissues compared to the VL and TA suggesting greater potential for elastic energy storage in the MG. Furthermore, they measured changes in fascicle lengths and tendinous tissues *in vivo* using ultrasound for MG during an ankle-bending exercise, jumping, walking, and bicycle peddling. The results indicated that tendinous tissues are compliant and that different muscles elicit different elasticity. During all movements, muscle fiber contractions occurred at a nearly constant length, while the tendon underwent a stretch-shorten cycle. These results suggest that the MTC is useful in matching the capacity of the muscle in generating force, meaning that its properties may be useful in eliciting economical locomotion. Furthermore, the abilities of the MTC far outweigh the abilities of the muscle contractile components alone.

Another study by Arampatzis et al., (2006) was done to assess the mechanical and morphological properties of the muscle-tendon unit (MTU) among runners with different running economies. They assessed VO_2 consumption and kinematics of the leg of subjects during treadmill running at velocities of 3.0, 3.5, and 4.0m/s. Based on their VO_2 economy, subjects were placed into one of three groups; high running economy, moderate running economy, and low running economy. Furthermore, measures of isometric maximal voluntary plantarflexion and knee extension contractions at eleven MTU lengths were assessed on a dynamometer and imaged by ultrasound. The results of this study showed that the most economical runners had higher contractile strength of the *triceps surae* MTU, higher energy storage capacity during MVC in the *triceps surae*, and no differences in muscle architecture of the GM. Important mechanical properties of the *triceps surae* MTUs showed differing values among the most economical runners. The authors suggest that these differences may affect the muscle properties for force and energy production and be an important factor for running economy.

2.5 Measurement of Muscle Length Changes

Measuring muscle fascicle length changes has been seen as a useful tool in determining efficiency during locomotion. Lichtwark, Bougoulias, and Wilson (2007) examined the length changes of muscle fascicles of the MG along the length of the muscle during treadmill walking and running. Furthermore, they examined how muscle fascicles function along the muscle throughout the gait cycle of both walking and running and how it relates to the action of the series elastic element (SEE)(Achilles tendon and aponeurosis). Ultrasonography was used to examine muscle fascicle length and pennation angles changes along the length of the MG for 6 healthy volunteers. During each trial they measured joint kinematics to determine the events of the stride cycle by the use of LED markers. Muscle architecture of the MG was examined using a PC-based ultrasound system through the use of a flat probe imaging the transverse section of the leg at each of the three positions (distal, midbelly, and proximal). From this, both muscle fascicle length and pennation angle were further examined along with the whole muscle-tendon length to estimate SEE elongation. This too was estimated at each of the three locations along the muscle, which was then combined to find an approximate tendon length change. The results show that the function of the muscle fascicles is similar at each position but different during walking and running. During walking, the results showed that small difference occurred in muscle fascicle length at the stance phase but the fascicles acted almost isometrically at all sites along the muscle. During running muscle fascicles shortened more than during walking at the stance phase, allowing for a greater production of work that is required during running. They imply that this production of force is a result of the compliance of the SEE. This compliance allows the shortening of the muscle fascicles at a slower speed, which is optimal for power output and efficiency. The authors acknowledge that further investigation needs to be done for better understanding of the nature the SEE stretch, where it occurs, and the danger of high strains, as they had to estimate this information in the study. Furthermore, it was concluded that in both walking and running trials, the midbelly positioning of the probe provided the best approximation of the entire muscle during the gait cycle.

In the study by Fukunaga et al. (2000) muscle fiber length changes of the human gastrocnemius medialis (MG) muscle were measured *in vivo* during barefoot walking by way of ultrasound. Additionally, electromyographical (EMG) activity, joint kinematics, and ground reaction forces were taken. Average values for pennation angle and fascicular length were taken from ultrasound images during several phases in the step cycle. They found that muscle fascicle of the MG follow a different displacement pattern than those of the muscle tendon complex and tendon during the step cycle. They also showed that muscle fascicles remained at a near constant length during muscle activity and that the tendon stretches during part of the stance phase and recoils during push-off. These findings suggest locomotor economy by way of tendon yielding elastic strain energy during stretch and recoil and lack of mechanical work required by the contractile component of the muscle.

In order to better understand the interaction of the muscle tendon unit and fascicle behavior during locomotion, Cronin et al., (2011) suggested the use of automated techniques. Past studies examining muscle fascicle length changes during locomotion have been performed manually. This technique is time consuming and prone to error. Automated techniques have been used in measuring muscle fascicle length and tendinous tissue length changes but have been limited during actual locomotion. Cronin et al., aimed to assess the validity and reliability of automated tracking in comparison to manual tracking. Eight healthy subjects were instructed to walk and jog on a treadmill at various speeds while ultrasound images of the medial gastrocnemius were collected. Ultrasound data was analyzed in MATLAB through use of an automated algorithm as well as through manual analysis for comparison. Muscle fascicle length changes of the GM were analyzed five times for each participant at each speed in order to assess repeatability. Assessment of the results revealed close agreement between the automated tracking algorithm and the conventional manual approach at all speeds. Furthermore, the automated algorithm was found to be highly repeatable. The findings of this study indicate that automated fascicle tracking is a viable and time-efficient alternative to manual analysis. A similar automated technique will be used in this study, which is detailed in Chapter 3.

2.6 Effects of Footwear on Economy of Locomotion

To understand the role of footwear Perl, Daoud, and Lieberman (2012) examined the effects of minimal and standard running shoes on running economy. In this study, minimal shoes were used in place of barefoot running in order to prevent injury from treadmill running. Previous research by Lieberman et al., (2010) and Squadrone & Gallozi (2009) has shown minimal shoes to have no significant effect on the economy or kinematics of barefoot running, prompting the researchers of this study to use minimal shoes to mimic barefoot conditions. Biomechanics and economy of 15 healthy subjects (13 men, 2 women), all experienced in barefoot or minimally shod running, were measured. Each subject ran in standard running shoes (elevated, cushioned heal, arch supports, and a stiff sole) as well as minimal shoes (lacking features of standard shoe) using both fore foot strike (FFS) and rear foot strike (RFS) gait patterns. No significant difference was seen between running economy of FFS and RFS in regards to footwear condition but a significant difference was seen on economy within strike types. During both FFS and RFS, subjects were significantly more economical in the minimally shod condition. Plantar flexor force output was also significantly higher in minimally shod condition as well as in the forefoot strike pattern. After accounting for the effects of shoe mass, strike type, habitual footwear, and stride frequency this study has shown that minimally shod runners are slightly but significantly more economical than runners in traditional shoes. The authors proposed that the likely difference is due to the greater amount of elastic energy storage and release in the lower extremity during the minimally shod condition but it is not something they examined in the current study. Furthermore, they proposed future studies to investigate elastic energy storage and utilization as well as the strain of the Achilles tendon during both barefoot and shod footwear conditions.

Previous studies examining footwear in relation to walking economy has been limited. The recent changes in footwear, as previously discussed, have prompted many studies to examine the advantages of certain footwear in regards to running economy, but very little to that of walking. A study conducted by Divert et al. (2005) found that mechanical differences exist between barefoot running and shod running. These mechanical differences in barefoot running are displayed in lower contact and flight time, lower passive peak, higher braking and pushing impulses, and higher pre-activation of *triceps surae* muscles when compared to shod running. When performed on a sufficient amount of steps, barefoot running allows for a reduction of impact peak and ultimately enhanced storage and return of elastic energy when compared to shod running. These findings on the mechanical differences present between shod and barefoot running pose the question of whether these or similar differences are present during the condition of walking.

2.7 Summary

The storage and return of elastic energy is an important energy saving technique that allows for the enhancement of locomotor economy. Elastic elements of the muscle and tendon allow for this energy to be absorbed and redistributed during the propulsion phase of locomotion. Ultrasound imaging has been used to effectively assess the muscle fascicle length changes that occur during various conditions of locomotion. The degree of muscle length change is useful in determining the level of work required by the muscle in different activities, such as walking and running. Greater efficiency has been seen in barefoot trials of running when compared to shod conditions. Similar patterns may exist during trials of walking.

Chapter 3

Methods

3.1 Overview

This chapter discusses the methods implemented to determine muscle length changes along the MG, LG, and soleus muscle during two conditions of walking. Section 3.2 details the subjects recruited to this study. Section 3.3 explains the ultrasound technique and equipment used to examine the muscle(s) of interest for each subject. Section 3.4 describes the instruction given to the participants in order to carry out each condition of walking. Section 3.5 presents the software used and the technique used by the examiner in determining pennation angles of the muscles. Section 3.6 details the tests used in order to determine significance of muscle length changes between shod and unshod walking.

3.2 Subjects

Fourteen healthy subjects (Males N=5, Females N=9), average age 25±4.64 years, height 168±9 cm, and weight 76±26 kg, were recruited to this study. All subjects were enrolled students or staff at Penn State University Berks Campus at the time of experimentation. All potential participants were approached outside of classes for recruitment into the study. Subjects were excluded if they suffered an orthopedic injury to their lower extremities in the previous 18 months, if they displayed abnormal joint mechanics, or if they were not between the ages of 18 and 40 years old.

All experimentation was conducted in the Biomechanics Laboratory at Penn State Berks. Prior to beginning the experiment all participants gave verbal consent to their participation in the study, which was approved through The Pennsylvania State University's Institutional Review Board.

3.3 Ultrasound Measures

A personal computer-based ultrasound system (EchoBlaster 128, Telemed Inc., Lithuania) was used with a 7.5 MHz linear probe to image the medial gastrocnemius (MG), lateral gastrocnemius (LG), and the soleus *in vivo*. The software used during imaging was Echo Wave II (Telemed Inc., Lithuania). A sampling frequency of (8MHz) was used to image the muscle fascicles during all conditions. The probe was first aligned to the midline of the lateral gastrocnemius muscle at the midbelly position of the muscle as described in previous work (Lichtwark, Bougoulias, & Wilson, 2007) (Figure 3.1A). The probe was attached to the calf such that it imaged the sagittal section of the muscle. A non-allergenic gel was used in order to enhance the ultrasound image. This process was repeated with the medial gastrocnemius during the second set of recordings (Figure 3.1B).

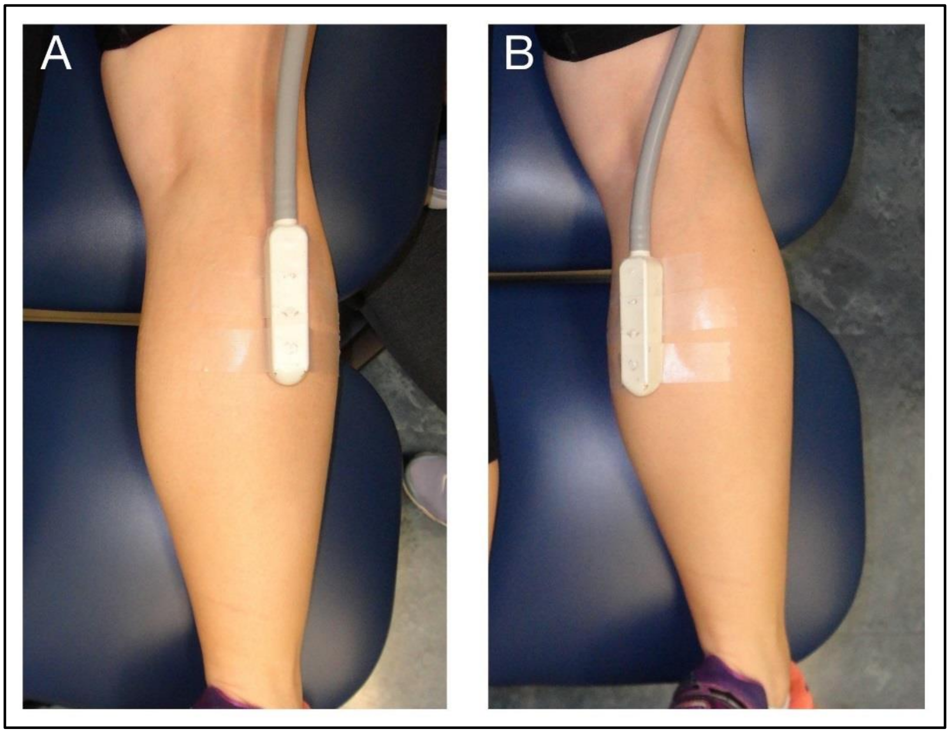

Figure 3.1 Placement of ultrasound probe over MG and LG.

(A) Picture of the flat ultrasound probe secured over the lateral gastrocnemius. The ultrasound probe imaged the muscle in the sagittal plane. (B). Picture of the ultrasound probe secured over the medial gastrocnemius of the subject.

The probe was secured to the surface of the skin using an adhesive, hypoallergenic medical tape. An elastic bandage was used to further secure the probe to the area of interest and prevent any rotation during the walking trials. The probe's flat surface design also aided in minimizing rotation of the probe about the skin. The transducer cord was secured to the waist of the subject using an elastic bandage, allowing the subjects to walk without being disrupted by the hanging cord and to prevent any detachment of the probe (Figure 3.2).

Figure 3.2 Attachment of probe and transducer cord to subject.

Subject with flat probe secured to calf with elastic bandage. Transducer cord secured to waist using elastic bandage.

3.4 Gait Measures

Subjects were instructed to walk with a natural cadence on the treadmill at 0.67m/s during each of the four conditions. Muscle fascicle behavior of the LG, MG, and soleus was measured during the conditions of gait. Subjects were instructed to walk in a shod condition with the probe secured over the lateral calf (lateral gastrocnemius, LG), and a barefoot condition immediately following. Prior to each recording, the subjects were directed to walk for one minute to serve as a warm up and to allow them to become familiarized with the new walking condition. Once participants were comfortable, video of the muscle was recorded using the ultrasound machine during 5 cycles of gait. The same procedure was done for measurements of the medial calf (medial gastrocnemius, MG) in which the subject walked for one minute prior to recording in shod and barefoot conditions. Muscle fascicle measures of the Soleus were obtained from ultrasound data collected during measurements of the lateral calf (LG).

3.5 Analysis of Ultrasound Data

Automated processing of the ultrasound data was conducted in MATLAB using a custom written algorithm. The examiner manually selected the area of interest in the first frame of the video sequence (Figure 3.3).

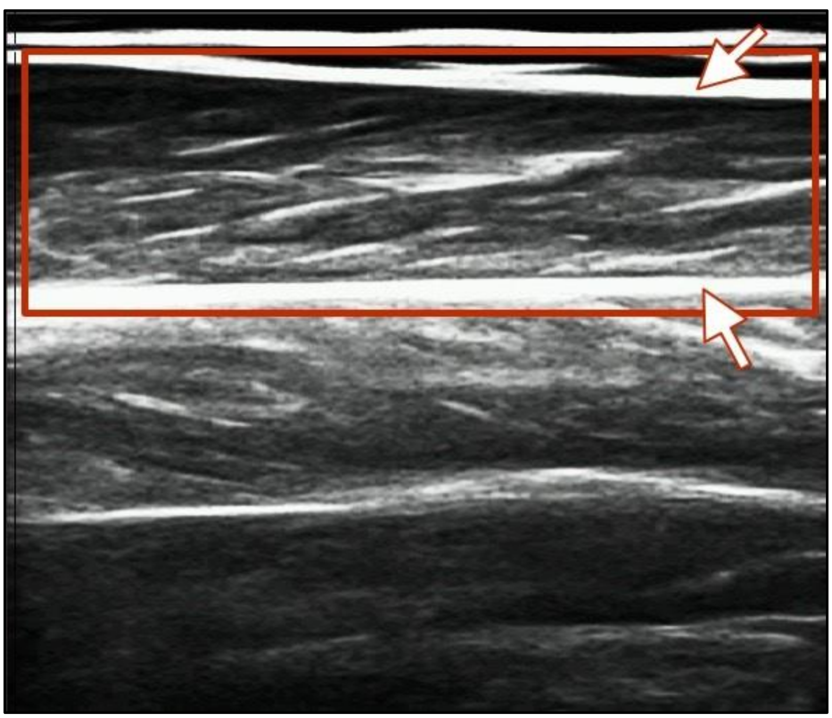

Figure 3.3 Selection of muscle of interest.

Outline illustrates selected area of interest of the gastrocnemius muscle. Arrows indicate the superficial and deep aponeurosis.

This area of interest was defined to include the area from the superficial to deep aponeurosis of the given muscle. This was done separately for the LG, MG, and soleus muscles for each condition of walking. The algorithm used object detection to identify fascicle structures and aponeurosis in order to determine pennation angle of the muscle (Figure 3.4). Previous algorithms have focused on a single muscle fascicle (Cronin et al., 2011), which causes difficulty when the object moves in and out of the imaging frame.

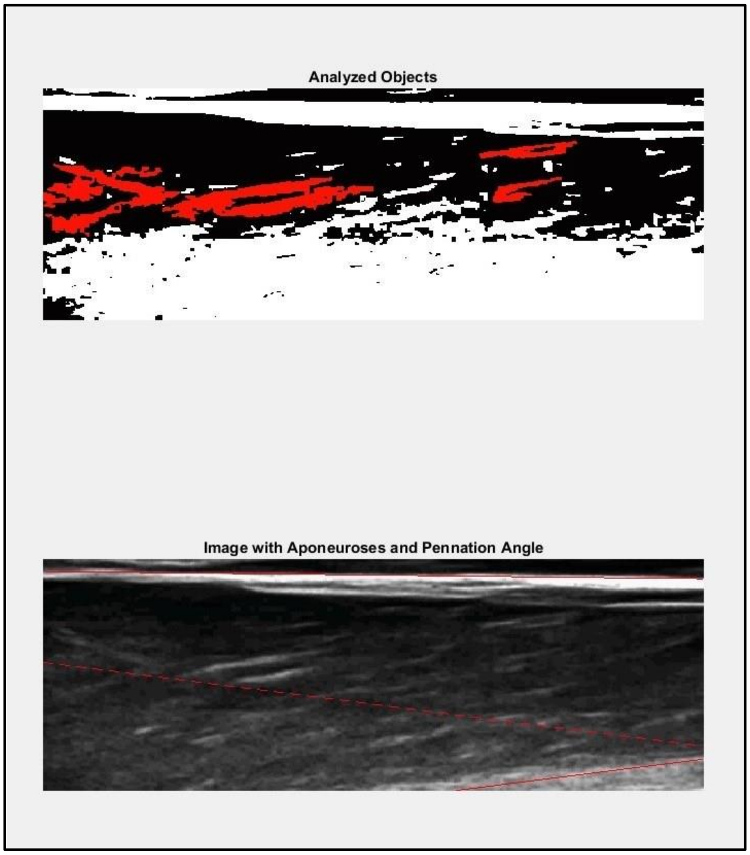

Figure 3.4 MATLAB analysis of pennation angles.

Highlighted (red) areas indicate multiple muscle fascicles depicted using object identification in MATLAB to assess pennation angle.

3.6 Statistical Analysis

Values computed from MATLAB pertaining mean, minimum, and range of pennation angles for LG and MG muscles during each condition were analyzed. Since there was a lack of quality ultrasound data for the soleus, its values were not used for comparison. The means for these values of LG and MG were compared between shod and barefoot conditions using a t-test.

3.7 Summary

Measurements of the *triceps surae* muscles were taken by ultrasound imaging of 14 healthy subjects. Subjects walked on a treadmill during shod and barefoot conditions with the ultrasound probe attached over the muscle of interest. Ultrasound videos of the muscles were analyzed using automated techniques in MATLAB. Using this software, pennation angles of each muscle were determined for each condition. These values were compared between conditions for the LG and the MG by t-test.

Chapter 4

Results

4.1 Overview

A comparison between the average pennation angles of the MG during shod and barefoot conditions showed no significance ($P > .05$). There was also no significant difference between the average pennation angles of the LG during both conditions ($P > .05$). Furthermore, there was no significant difference between walking conditions of minimum pennation angle or pennation angle range in the MG and LG. Figure 4.1 represents the average values of pennation angle mean, range, and minimum of shod and barefoot conditions.

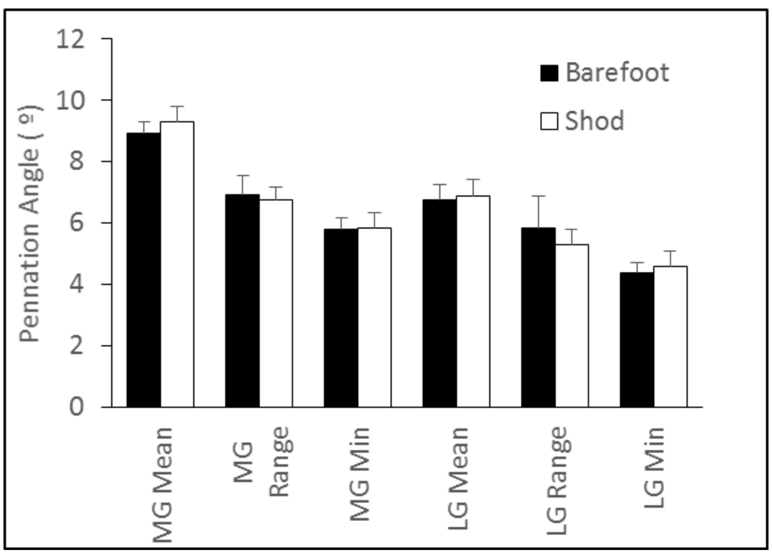

Figure 4.1 Average pennation angle values of LG & MG.

The average pennation angle (±SEM) of the MG was 8.91±0.411° during barefoot walking and 9.30±0.520° during shod walking. The mean range of pennation angles of the MG was 6.94±0.613° during barefoot walking and 6.77±0.402° during shod walking. The average of the minimum pennation angle values of the MG during barefoot walking was 5.79±0.368° and 5.85±0.484° during shod walking. Measurements of the LG showed an average pennation angle of 6.75±0.518° during barefoot conditions and 6.90±0.506° during shod conditions. The mean range of pennation angles of the LG for barefoot conditions was 5.82±0.518° and 5.27±0.502° during shod conditions. Lastly, the average for minimum pennation angle values of the LG was 4.37±0.360° for barefoot conditions and 4.58±0.491° for shod conditions of walking.

Table 4.1 Mean pennation angles (°) of the MG during shod and barefoot conditions.

Subject	1	2	3	4	5	6	7	8	9	10	11	12	13	14
MG Barefoot	11.6	6.82	7.59	7.75	9.25	10.3	10.3	9.98	10.3	8.81	7.28	8.47	9.78	6.54
MG Shod	11.7	7.16	8.04	7.21	8.02	11.5	11.0	9.80	13.0	9.03	7.86	9.18	9.84	6.76

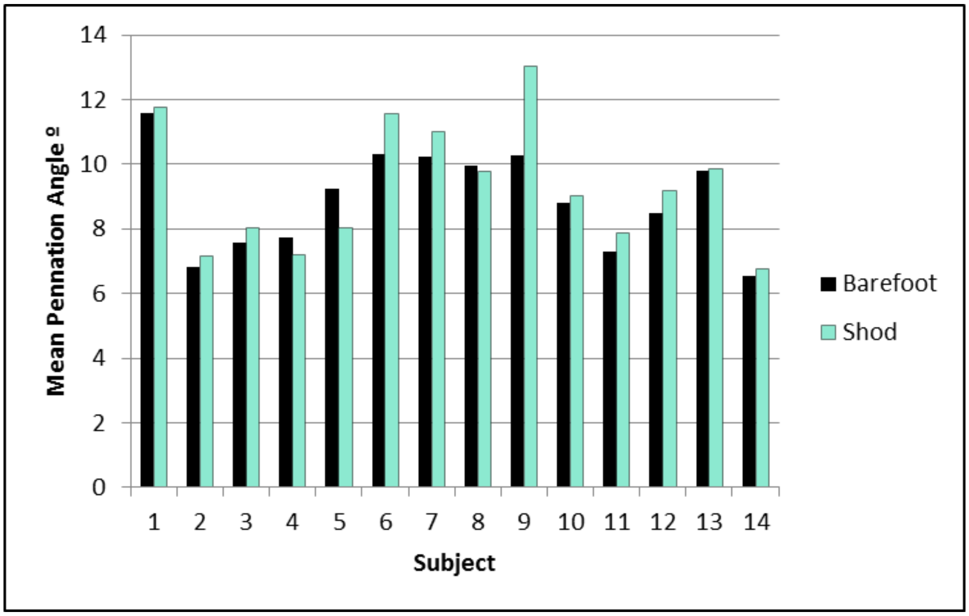

Figure 4.2 Mean pennation angle values of shod and barefoot conditions of the MG.

Table 4.1 displays the mean values of pennation angle of the MG during shod and barefoot conditions. Figure 4.2 represents the individual values of mean pennation angles of the MG for each subject compared during both conditions of walking. The mean pennation angles were different between conditions for each subject, with a majority showing higher values during shod conditions. Although these differences did exist they were not consistent across all subjects and furthermore not significant as a result of the t-test (P>.05).

Table 4.2 Mean pennation angles (°) of the LG during shod and barefoot conditions.

Subject	1	2	3	4	5	6	7	8	9	10	11	12	13	14
LG Barefoot	7.84	4.08	7.84	6.07	7.82	N/A	10.1	6.23	N/A	7.42	6.57	4.42	8.06	4.55
LG Shod	8.96	4.19	6.15	5.95	7.93	N/A	9.87	6.62	N/A	7.65	7.33	4.84	8.33	4.95

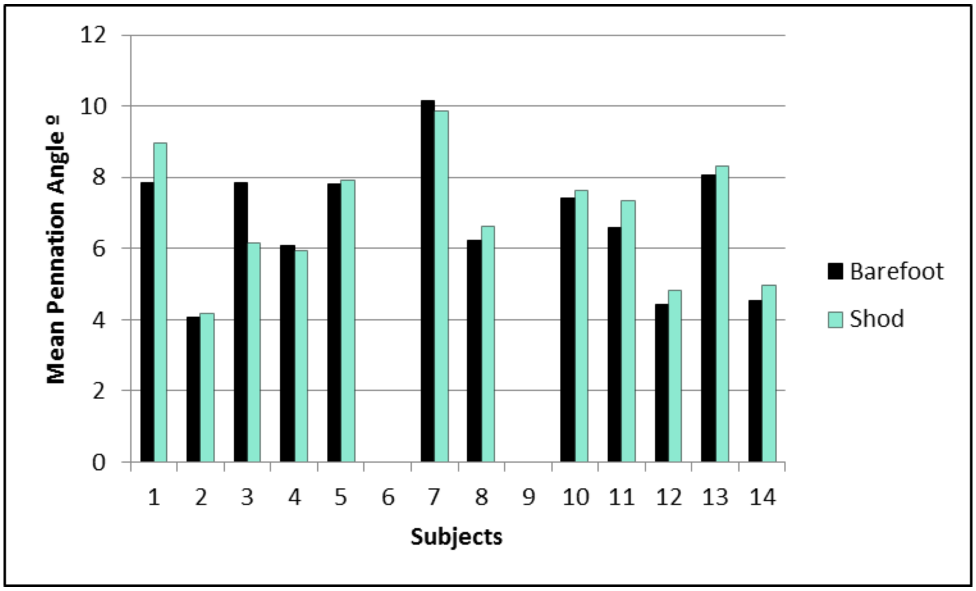

Figure 4.3 Mean Pennation angle values of shod and barefoot conditions of the LG.

Table 4.2 displays the mean values of pennation angle of the LG for all subjects excluding 6 and 9. Figure 4.3 presents the subjects' mean pennation angles of the LG of barefoot and shod conditions. Video sequences from subjects 6 and 9 were unable to be processed by MATLAB, eliminating them from further comparison. As mentioned earlier in this chapter there was no significant difference between pennation angles of the LG during shod and barefoot walking. Similar to the characteristics of the MG pennation angles, the LG pennation angles displayed no consistent pattern across subjects. Although there were differences in mean pennation angles of barefoot and shod conditions for the subjects, this behavior was not constant for participants.

4.3 Summary

The results of this study were presented in Table 4.1 and 4.2. Mean pennation angles of the MG (Figure 4.2) and LG (Figure 4.3), as determined by ultrasound, of 14 subjects were compared between shod and barefoot conditions. Figure 4.1 displayed the average values of minimum, mean, and range of pennation angles of the LG and MG muscles compared between conditions. These results indicate that there was no significant difference in muscle behavior of the MG and LG between walking conditions.

Chapter 5

Discussion

5.1 Overview

The results of the present study were inconclusive in determining the muscle length change that occurs during the conditions of walking but suggestive that no significant difference will be seen under the current parameters. Section 5.2 includes a discussion of the results and their implications for the understanding of elastic energy involvement during walking. Section 5.3 details the limitations of the current study and proposes future studies. Section 5.4 contains the conclusions to this study.

5.2 Determination of Muscle Length Changes During Walking

The aim of this study was to investigate the *in vivo* behavior of the *triceps surae* muscles during shod and barefoot conditions of walking and determine the difference in elastic energy utilization between the two. Ultrasound techniques were employed in order to test the hypothesis that significant differences in muscle length change exist between the two conditions of walking. The muscle behavior determined by MATLAB analysis showed insignificant differences among pennation angle between shod and barefoot conditions of MG and LG, supporting the null hypothesis. Measurements of muscle thickness were unable to be made, therefore muscle fascicle length and subsequent change in length could not be determined directly. Although the proper data was not collected in order to directly determine muscle fascicle length change, inferences could still be made based on the planimetric muscle model. This model assumes that 1) the aponeuroses act as rigid bodies that run parallel to one another, and 2) muscle fibers run straight between aponeuroses (Maganaris & Baltzopoulos, 1999). According to this model, muscle thickness (*t*) is assumed constant and can therefore be used to determine muscle fascicle length (*l*) by use of the pennation angle measurement (θ) (Figure 5.1). Simple geometric equations reveal that muscle fascicle length is proportional to the pennation angle. A change in pennation angle results in a change in muscle fascicle length of the same proportion. Using this assumption it can be inferred that a non-significant change in pennation angle between conditions would result in a non-significant change in muscle fascicle length between the conditions. Furthermore, it can be said with relative certainty that changes in pennation angle found in the current study would not have produced a significant change in fascicle length and therefore no difference of elastic energy utilization exists between conditions.

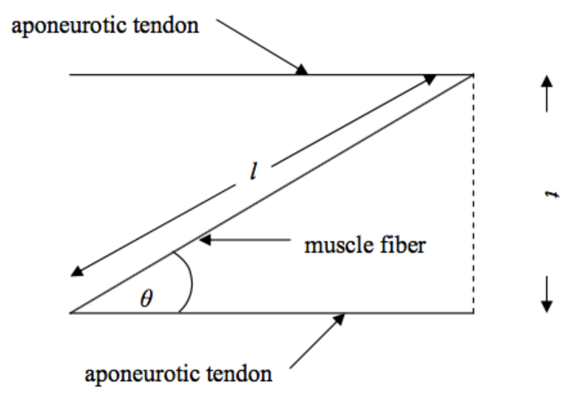

Figure 5.1 Relationship between pennation angle (θ), distance between aponeuroses (*t*), and muscle fiber length (*l*).

Image from Infantolino and Challis (2010).

The results of the current study, and the subsequent assumptions made about muscle fascicle length changes, are suggestive that walking does not elicit the utilization of elastic energy differently between conditions. These results may fall in agreement with Alexander's (1991) proposal that the energy saving techniques, like those evident in running, are ineffective in walking. The lack of energy saving is said to be due to the inconsistency of force along the stance phase of walking. There is less force being exerted during the stance phase in comparison to the force that is exerted during foot strike and push-off. Alexander argues that the lack of force during the mid-stance phase of walking does not allow for the elastic energy gained during initial impact to be retained and further power the push-off. Although measures in this study were limited in determining the timing of events and the extent of elastic energy, the results may suggest that these walking speeds are too slow for the storage and return of elastic energy.

5.3 Limitations & Future Studies

A major limitation in this study was the lack of measurements, specifically in determining muscle thickness. As this measure is used to calculate muscle fascicle length changes, it is important to have an accurate measurement in order to make correct calculations. Along with the inability to directly measure muscle thickness, the timing of events during the walking cycle was unable to be determined, limiting the applicability of the data. To better assess these values, more measures should be implemented in future studies. Along with the ultrasound imaging used in the present study, motion analysis techniques should be used in order to further assess the behavior of the muscles during the conditions of walking. Lichtwark & Wilson (2009) employed ultrasound imaging along with motion analysis measures to assess length changes of the fascicles and determine the timing of events during the walking cycle. Motion analysis allowed them to define foot contact and swing phase as well as the time in which the foot was in these phases during conditions of walking and running. Having this data would provide a better representation of how the muscles respond during the conditions of walking and ultimately allow for a more accurate analysis of elastic energy storage and return.

As mentioned in Section 5.2 the walking speed used in this study (0.67m/s) may have been too slow for the storage and return of elastic energy. Slower walking speeds lead to increased time during the transition from foot strike to push-off leading to the dissipation of energy and ultimately the inability to effectively store and return elastic energy. Sasaki and Neptune (2005) investigated elastic energy utilization during walking and running at speeds above and below the preferred walk-run transition speed (PTS). The average PTS was 4.4mph. Walking speeds of 80% and 120% of the PTS were employed. Speeds of 120% PTS produced greater series elastic element (SEE) utilization in comparison to walking at 80% PTS. In the future, studies should implement various walking speeds in order to determine the threshold at which elastic energy utilization occurs and the extent to which it is used between shod and barefoot conditions.

This study was conducted in order to compare the effects of footwear condition on economy of locomotion. The shoes used in this study were not standardized as in other studies (Perl, Daoud, & Lieberman, 2012). Instead, the subjects were instructed to wear a standard running shoe that was defined as having an elevated, cushioned heel. The study by Perl et al., used the same brand and model shoe for each participant in order to ensure that contributions made by the shoe were consistent across all subjects. Future studies should implement a standardized shoe in order to obtain a better representation of the effects of footwear on elastic energy in walking.

5.5 Conclusions

As research on elastic energy during walking is limited, the ultimate goal of this study was to add insight to the degree in which it is utilized during walking conditions, if at all. The results of this study demonstrated that no significant difference in muscle behavior exists between shod and barefoot conditions of walking. The measurements utilized in this study were not optimal for obtaining the necessary data to determine elastic energy accurately, but inferences about muscle length changes allowed for further assessment. These assumptions suggested that elastic energy was not utilized differently between the two situations. Although no significant difference appeared to exist in the level of elastic energy storage and return, it is possible that these results are limited to the parameters used in this study. As previously mentioned, elastic energy is an important component of running, especially in comparison of shod and barefoot conditions, and may not be present in speeds so dissimilar to that of running. Walking speeds of 0.67m/s, as used in this study, may be too slow to initiate energy saving techniques to the degree observed in running. Future studies should further investigate the determinants of elastic energy storage and return, whether it is initiated by the speed of the movement or the pattern of gait.

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