Biomechanical characteristics of medial tibial stress syndrome based on traction-induced theory

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Biomechanical characteristics of medial tibial stress syndrome based on traction-induced theory

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Biomechanical characteristics of medial tibial stress syndrome based on traction-induced theory

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INTRODUCTION

General Introduction

This study focused on medial tibial stress syndrome (MTSS) which is a common cause of running related injuries. Mubarak et al. [1982] defined MTSS as “as a symptom complex seen in athletes who complain of exercise induced pain along the distal posterior-medial aspect of the tibia”. Clanton and Solcher [1994] reported that MTSS is one of the most common causes of exercise-induced leg pain during running.

Numerous previous studies have addressed the traction-induced theory for MTSS [Devas, 1958; Bouche and Johnson, 2007], and in order to verify this theory, we focused on two factors affecting the development of MTSS: foot pronation and plantar flexor abnormality. We hypothesize that these two factors may cause traction force on the tibial periosteum.

The first factor, increased foot pronation [Yates and White, 2004; Raissi et al., 2009; Reshef and Guelich, 2012], was selected from several intrinsic risk factors of MTSS, as increased foot pronation may cause traction force during running. Traction force in connective tissues could be generated by strong muscle activations or forces during sports activities that involve running [Devas, 1958; Reshef and Guelich, 2012]. Thus, structural deformation of longitudinal arches during running was investigated by fluoroscopy in Chapter 2.

In addition, Stickley et al. [2009] noted that soleus muscle activities apply traction forces to the tibial periosteum through the soleal aponeurosis. Thus, in Chapter 3-1 and 3-2 we investigated plantar flexor activations and forces as provision factors of traction force directly on connective tissues during running. However, the etiology of MTSS is still being debated. Therefore, it is necessary to determine how the traction-induced theory of MTSS occurred.

For this reason, we firstly aimed to verify structural deformation of the foot during running using fluoroscopy as muscle abnormality inducing factor in MTSS. Next, we verified plantar flexor activations and forces using SIMM during running. We hope to determine which muscle affects the development of MTSS, and how. Finally, the path of traction force should also be determined because MTSS is caused by musculotendon stress.

1. Running related injuries

1-1. Incidence rates of running related injuries

The popularity of running grew dramatically in the 1970s in many countries [van Mechelen, 1992]. However, running related injuries also frequently occurred in accordance with the increased running population [Wen, 2007]. Several studies reported that incidence of lower extremity running related injuries ranged from 19.4% to 79.3% [Wen et al., 1998; Taunton et al., 2003; Lun et al., 2004].

The most common running related injuries are as follows: patellofemoral pain syndrome (PFPS), Achilles tendinitis, hamstring injuries, plantar fasciitis, iliotibial band syndrome (ITBS), stress fracture, and medial tibial stress syndrome (MTSS) [Aschwanden, 2011]. Taunton et al. [2002] showed incidence rates of lower leg injuries indicate MTSS (4.9%), Achilles tendinitis (4.8%), Tibial stress fracture (3.3%), and Gastrocnemius/soleus strains/tears (1.3%) in runners.

Incidence rates indicated that MTSS is one of the most frequently occurring running related injuries in the lower extremity. Additionally, numerous runners interrupted training in response to development of MTSS, as well as experienced pain. Thus, study regarding MTSS is necessary to help prevent running related injuries.

1-2. Incidence rates of medial tibial stress syndrome

Among running related injuries, MTSS is one of the most common injuries experienced by running athletes [Clanton and Solcher, 1994]. The incidence rate of this injury varied from 4% to 35% in physically active populations [Clanton and Solcher, 1994; Bennett et al., 2001]. Especially, the incidence rates of MTSS in runners happened more frequently. Plisky et al. [2007] reported that MTSS occurred 2.8 times per 1000 athletic exposures.

2. Medial Tibial Stress Syndrome

2-1. Definition of medial tibial stress syndrome

Prior to the definition of MTSS, we should consider several types of MTSS. Detmer [1986] classified MTSS into 3 types as follows:

- Type 1 — the primary problem is a tibial bone stress reaction or cortical fracture
- Type 2 — the symptoms are typically noted perisotalgia from chronic avulsion of the periosteum at the periosteal fascial junction
- Type 3 — the symptoms are localized over the distal and deep posterior compartment syndrome

Our current study was based on Type 2 of MTSS which is commonly caused by overuse in athletes who participate in running. However, how MTSS mechanisms cause inflammation on the tibial site [Mubarak et al., 1982] remains controversial.

In 1966, the American Medical Association defined MTSS as “pain and discomfort in the leg from repetitive running on hard surfaces or forcible excessive use of the foot flexors; diagnosis should be limited to musculotendinous inflammations, excluding fatigue fracture or ischemic disorder”. ‘Shin splint’ is the most popular name, but it is also called medial tibial stress syndrome, tibial stress syndrome, posterior tibial syndrome, and soleus syndrome. These names have derived from the site of pain which appears in the posteromedial aspect of the tibia caused by exercise or running movements. Palpation pain is present along the posteromedial border of the tibia for at least 5 cm for at least 2 weeks [Yates and White, 2004]. The definition of MTSS is clear but its etiology is still debated.

2-2. Etiology of medial tibial stress syndrome

The first of etiology of MTSS was published by Devas in the 1950s, and it was he who introduced the traction-induced theory. Devas [1958] asserted that traction forces could occur in the periosteum of the tibia due to strong calf muscles in MTSS. After this study, numerous theories for the cause have been put forward, such as in response to pressure by the intersection point of the tibialis posterior and flexor hallucis longus [Saxena et al., 1990], repetitive stress on the distal tibial cortex [Gaeta et al., 2006], decreased bone density [Magnusson et al., 2003], and also involved repetitive bending loads (by microdamage) in the tibia [Frost, 2001; 2004]. However, these theories (aside from the traction-induced theory) are fairly, but not entirely, persuasive for the explanation of the onset of MTSS. In addition, there is not enough anatomical evidence to support these theories.

Recently, a study conducted dissection on cadaveric specimens. Traction forces were applied on the tibial periosteum though the soleal aponeurosis by soleus muscle activity [Stickley et al., 2009], and traction to connective tissues by soleus, tibialis posterior, and flexor digitorum longus [Bouche and Johnson, 2007]. However, as mentioned above, the etiology of MTSS is still under debate. It is necessary to further establish the etiology of MTSS clearly in accordance with the influential claims of the traction-induced theory.

There is also a lack of consensus for the etiology of MTSS which is caused during sports movement such as running. Hence, we should understand running to understand the onset of MTSS. In addition, we should understand running based on anatomical structures for understanding biomechanical evidence regarding ‘how to run safety and comfortably’, ‘why MTSS occurs’ and also to enhance running performance.

3. Analysis of Running Biomechanics

3-1. Classification of running gait cycle

Classification of the running gait cycle involves two main phases according to movement: the stance and swing phases. These events are further subdivided into three sub-phases as follows: foot strike (initial contact), mid-support, and toe-off (propulsion). Running gait cycle is the foot contact with the ground that begins foot strike to end of toe off as shown figure 1-1 [Puleo and Milroy, 2009]. Each running related injury occurs in different running phases. Previous study reported that MTSS occurs due to increased stress on medial soleus insertion on the tibia in the stance phase [Kortebein et al., 2000]. Therefore, it is necessary to determine whether running gait has a key to resolve the traction-induced theory of MTSS.

Additionally, foot strike pattern was defined by Cavanagh and Lafortune [1980] as forefoot striking (FFS) and rearfoot striking (RFS) in response to the point of initial contact of the foot with the supporting surface. In the study of MTSS, it is necessary to consider including foot strike patterns because they can affect the development of MTSS. In addition, the literature regarding MTSS in response to foot strike patterns is not seen.

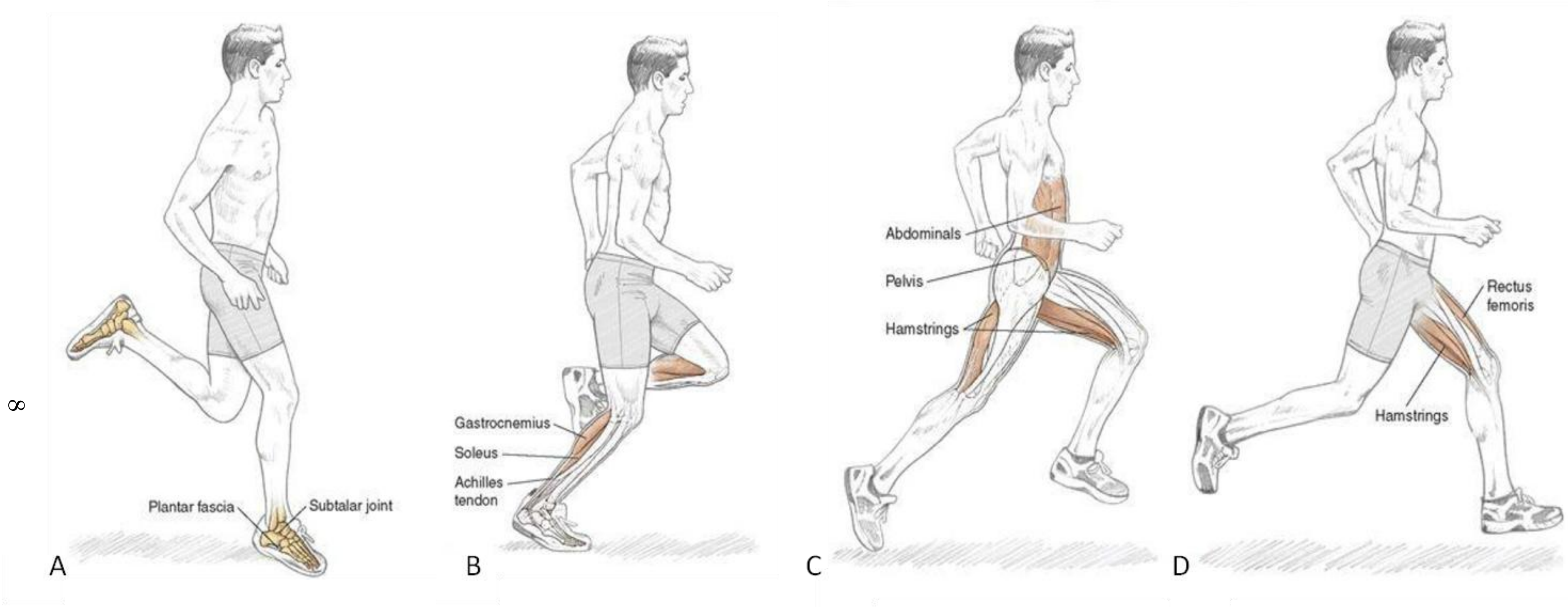

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Figure 1-1. Running gait cycle [© Human Kinetics].
A: Foot strike; B: Mid-support; C: Toe off; D: Swing phase.

3-2. Kinematics on running

In the RFS pattern, activation of the plantar flexor rapidly increases from heel strike to mid-support [Mann et al., 1986]. In addition, the hip and knee joints are slightly flexed, and the ankle joint is dorsiflexed and slightly inverted. The anterior tibialis works eccentrically and the gastrocnemius concentrically to control the foot as it strikes the ground. After foot strike, the ankle joint begins to plantarflex, however, the longitudinal arches are not still loaded. As the plantar flexes, the forefoot comes down. With the whole foot on the ground, longitudinal arches begin to stretch and flatten.

The FFS kinematics is similar to the RFS pattern with flexed position of the hip and knee joints. In contrast, the ankle is in a plantar flexed position (toes point slightly down) and then begin to dorsiflex. At this point, a higher pre-activation of triceps surae muscles before the mid-support has been shown. The longitudinal arches are loaded and begin to stretch and flatten immediately. As the ankle dorsiflexes, the heel comes down, controled by calf muscles which are eccentrically contracted.

Foot evertor muscles activity, as with the peroneal muscles, begins with the forefoot loading at the end of the mid-support and show peak activity at the toe-off. Finally, the ankle joint plantar flexes bringing the heel off and then running gait occurs with toe off in both foot strike patterns [Perry, 1992; Reilly and Williams, 2003; Divert et al., 2005; Lieberman et al., 2010]. Perry [1992] demonstrated EMG activity of the soleus during walking. The soleus muscle indicates an EMG activity of 25% MVC in the mid-support, and 75% MVC in the toe-off. It was hypothesized that the higher soleus activation might contribute to running.

Hence, mechanical factors affecting development of MTSS can be changed by foot strike pattern. Therefore, study of running related injuries is needed to determine the various running conditions that can cause running related injuries such as MTSS.

This process occurs during running, however, we might hypothesize that running related injuries such as MTSS could be caused by an abnormality in the body during the running process. Thus, analysis using the biomechanics of running techniques is necessary because not enough literature exists regarding the traction-induced theory of MTSS. Therefore, in this study (in Chapter 3-1, 3-2) we analyzed the characteristics of plantar flexor activations of MTSS during running using a musculoskeletal model.

4. Modeling of the musculoskeletal system

4-1. Software for interactive musculoskeletal modeling

In order to verify the hypothesized plantar flexor abnormality, this study analyzed plantar flexor activation and force following tools, using software for interactive musculoskeletal modeling (SIMM) [Delp and Loan, 1995]. Mechanical stress or load in the body can be calculated by SIMM with demonstrated human movement. SIMM has high expandability features such as changeable addition of muscles, origin and insertion of muscles, characteristics of musculotendons, and joints with degrees of freedom [Hase, 2010].

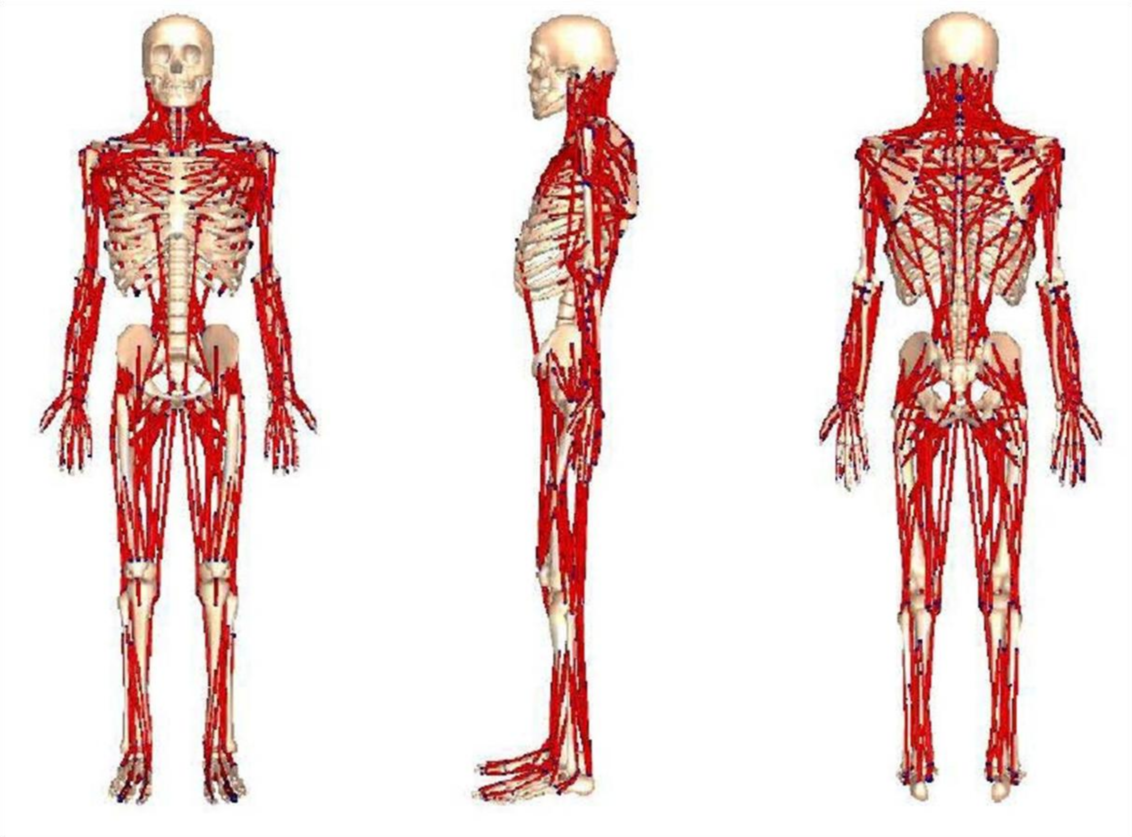

Figure 1-2. The musculoskeletal model [© Ishii, 2011].

Several studies applied SIMM to determine injuries. Besier et al. [2009] performed a study which evaluated knee muscle forces during walking and running in patients with patellofemoral pain. They found that patellofemoral pain patients had greater normalized muscle forces during walking. SIMM was also applied to the hamstring and psoas length during crouch gait for comparison of patients with cerebral palsy and controls [Rhie et al., 2013] and female runners strain rate for comparison of patients with iliotibial band syndrome and controls [Hamill et al., 2008].

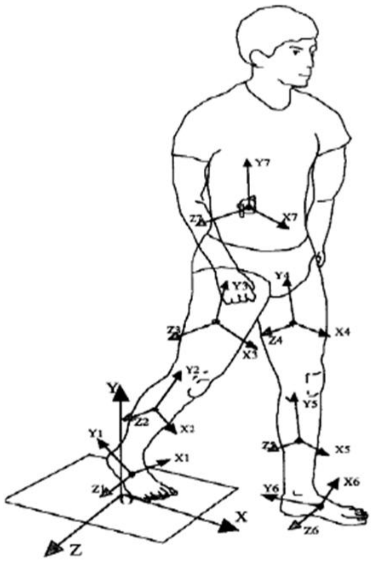

Figure 1-3. Local reference frame and joint coordinates system
by ISB recommendation [© Wu et al., 1995].

In addition to these studies, other research has also reported that muscle abnormalities as inducing factor of injuries were evaluated by SIMM. However, literature with analysis using SIMM for the traction-induced theory is not available. Thus, it is necessary to determine muscle abnormalities during running using SIMM in order to clearly verify the traction-induced theory of MTSS.

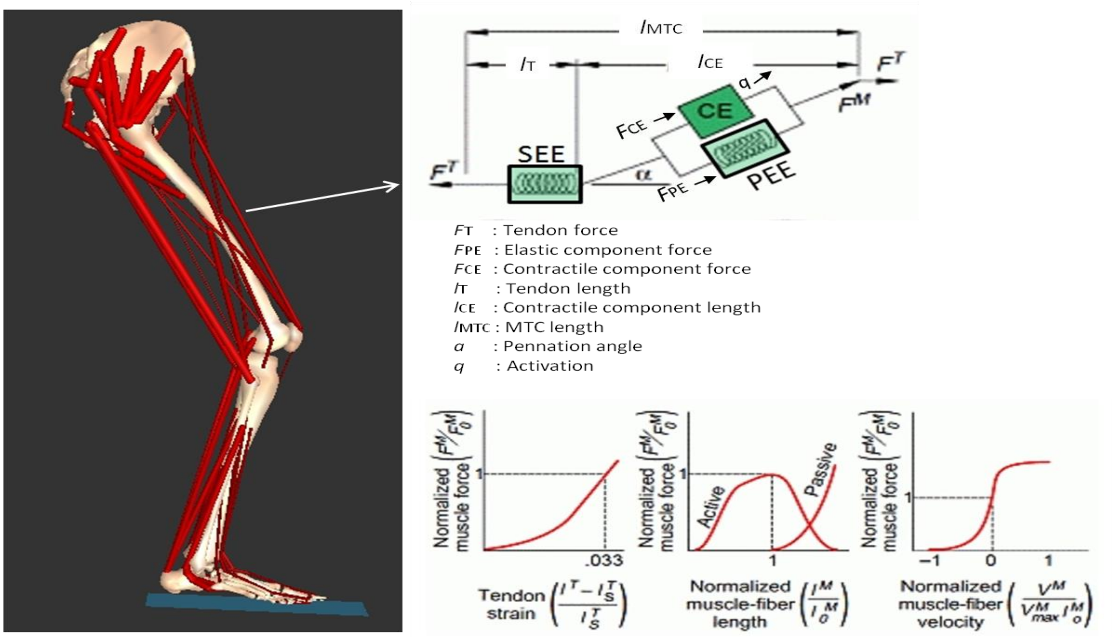

Figure 1-4. The musculotendon actuator model (Hill-model) [© Delp, 1990].

4-2. Structure of the musculoskeletal model

As mentioned above this musculoskeletal model (Figure 1-2) consists of body segments (bones) connected by joints with degrees of freedom and spanned by muscles and ligaments with origins, insertions and pathways of each muscle [Delp et al., 1990; Hoy et al., 1990; Damsgaard et al., 2006]. It is also possible for muscle and ligament forces to be calculated from muscle activation by optimization [Crowninshield, 1978; Crowninshield and Brand, 1981; Dul et al., 1984a; Dul et al., 1984b; Praagman et al., 2006; Erdemir et al., 2007]. Inertia parameters, segment mass, center of mass, and muscle characteristics data have been extracted from cadaveric study of male adults (Figure 1-3) [Wu et al., 1995; de Leva, 1996].

Each muscle based on the Hill-model consists of contractile element (CE), parallel elastic element (PEE), and series elastic element (SEE) (figure 1-5). CE converts the simulation of the nervous system into a force and reflects the shortening and lengthening of the muscle and inclined to α of pennation angle. PEE represents the passive properties of the muscle. SEE is a nonlinearly elastic structure, and represents primarily tendon [Rezgui, 2012]. Normalized muscle force is calculated to consider relationships with muscle force-tendon strain of SEE, muscle force-fiber length of CE, and muscle force-fiber shortening velocity of CE (figure 1-4) [Zajac, 1989; Delp and Loan, 1995]. Therefore, individual muscle activations and forces during movement can be calculated by this musculoskeletal model with optimization tools.

4-3. Optimization process in the musculoskeletal model

There are two main types of modeling used in biomechanical analysis: forward dynamics and inverse dynamics. Forward dynamics is compute segment motions (kinematics) from moments of forces (torques) and applied forces. Forward dynamics has a disadvantage as input parameters may be difficult to estimate (e.g., muscle properties). In contrast, inverse dynamics is computed forces and moments of force from segment motions. It allows estimate of net muscle moments acting at joints from experimental data [Anderson and Pandy, 2001b]. Thus, this study used inverse dynamics for calculation of muscle activations and forces.

Inverse kinematics is used to compute joint angles by experimentally measured marker positions. Next, calculated joint angles are used to solve the net reaction forces and net moments at each joint by inverse dynamics with angular velocities, angular accelerations, and ground reaction forces. Finally, estimation of muscle activations by maximum isometric forces and forces are used for the static optimization tool. In the static optimization approach, the dynamic equations are solved to calculate the muscle forces, the net forces and moments at the joints from experimental kinematics measurement, called inverse dynamic simulations (Figure 1-5) [Anderson and Pandy, 2001a; Pandy, 2003].

Simulated muscle activation indicates similar %MVC (Maximum Voluntary Contraction) of EMG and invigoration rates of the motor unit in muscular physiology. However, simulated activations are defined to be between 0 (no activation) and 1 (full activation) because of a concept applied by robotics [Ishii, 2011]. The estimated muscle activation was computed by optimization, with the goal of minimizing the sum of the squared difference by determining the maximum isometric muscle force (objective function) within constraint condition. The static optimization tool is estimated muscle force by minimizing the sum of the square of muscle excitations while computing for muscle activation, length, and shortening velocity [Zajac, 1989].

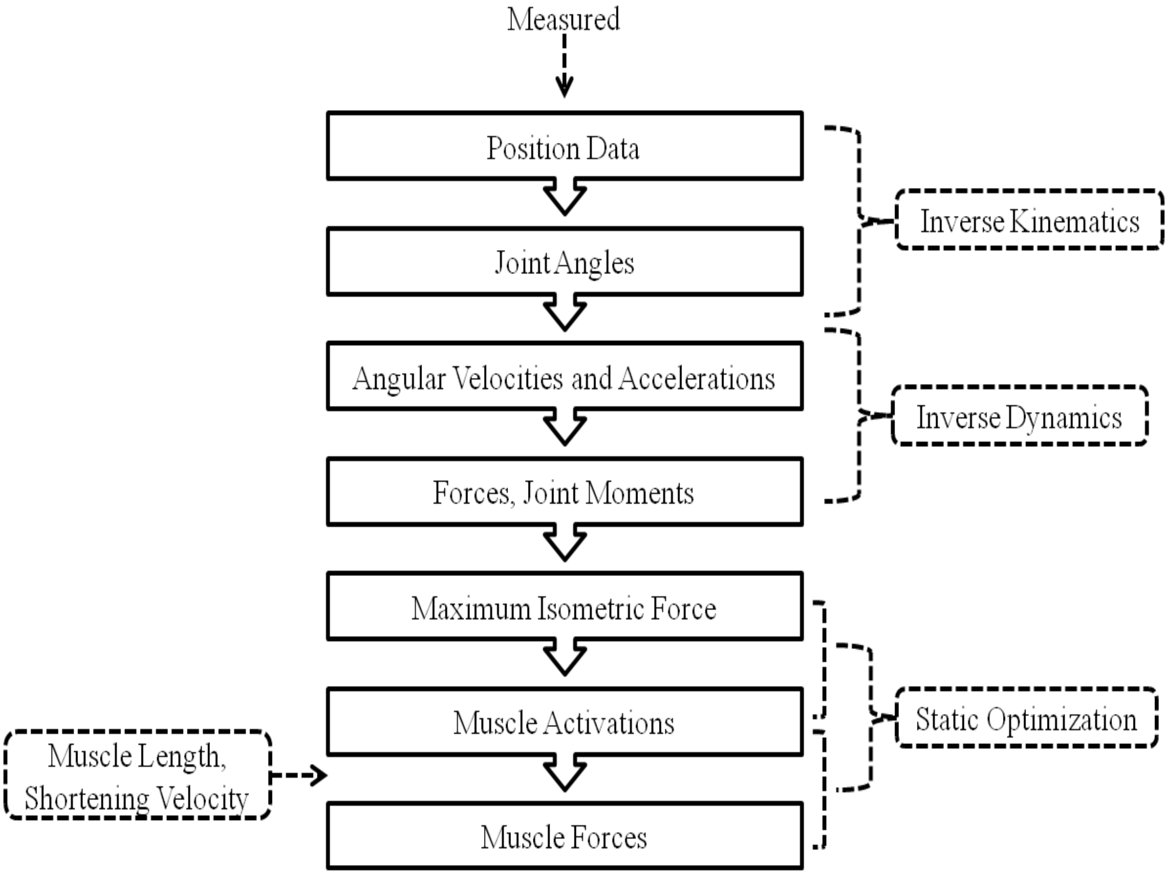

Figure 1-5. Flow of computing algorithm.

Final Goals of the Dissertation

This series of studies will establish development of MTSS in response to traction-induced theory during running. Foot pronation has been addressed as one of the risk factors for MTSS [Yates and White, 2004; Raissi et al., 2009; Reshef and Guelich, 2012]. Thus, Chapter 2 of this study compared athletes with MTSS and uninjured controls for verification of structural deformation of the foot such as angular change of the longitudinal arches and translational motion during running. However, results of structural deformation of the foot are not sufficient to determine the cause of MTSS in response to traction-induced theory. For this reason, we produced a musculoskeletal model using SIMM to verify the traction-induced theory of MTSS. This model will determine changes in plantar flexor activation during barefoot or shod running for comparison of athletes with MTSS and uninjured controls as previous studies have concluded that the higher muscle activities during running could induce injury due to a greater load on muscles [McClay, 2000; Shih et al., 2013]. In addition, previous studies also have found that MTSS was caused by a comparatively greater plantar flexor tension (or force) during running [Detmer, 1986; Bouche and Johnson, 2007]. Therefore, this study also calculates plantar flexor forces with those derived from mechanical factors during running with different strike patterns. This study also compares running with and without shoes and foot strike patterns during running. Recently, previous studies regarding barefoot running with the FFS pattern found a reduction of running related injuries compared to shod running with the RFS pattern [Lieberman et al., 2010; Daoud et al., 2012]. However, a few studies have reported an increasing number of injuries due to barefoot running with the FFS pattern [Giuliani et al., 2011; Salzler et al., 2012; Olin and Gutierrez, 2013]. Hence, Chapter 3-1 and 3-2 of this study determines how different foot strike patterns and with and without shoes conditions affect the development of MTSS.

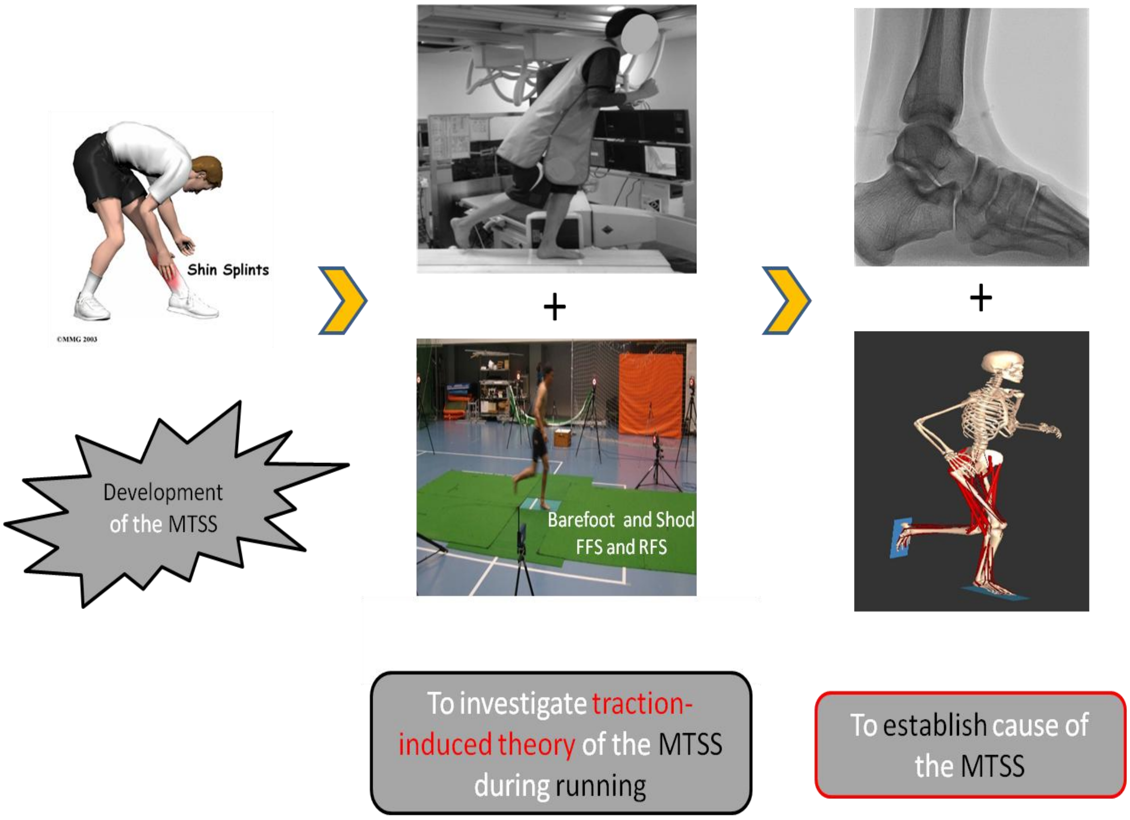

Figure 1-6. Flow of overall goals in this study.

Research Questions and Hypotheses

This study tested these hypotheses to verify each chapter of this study:

1. During running, subjects with MTSS would show significantly different structural deformation of the foot from that of control subjects.

2. Plantar flexor activity would be higher in subjects with MTSS than in the controls (without MTSS) during running. We also expected that higher plantar flexor activity depended on whether running was done barefoot with the FFS pattern or shod with the RFS pattern.

3. Plantar flexor forces would be greater in subjects with MTSS than in non-MTSS during running. We also expected that the greater plantar flexor forces depended on whether running was done in the FFS pattern or the RFS pattern.

Structure of the Dissertation

This dissertation is produced in a journal format. The individual research issues described in Chapter 2~4 include co-authored materials and individual manuscripts which have been submitted and prepared for submission to sports journals. Chapter 2 examines structural deformation of the foot during running in athletes with MTSS compared with uninjured controls using a template method using fluoroscopy. Chapter 3-1 and 3-2 will verify plantar flexor muscles abnormalities which might be induced by structural deformation of the foot as shown in Chapter 2. Therefore, plantar flexor activations and forces in Chapter 3-1 and 3-2 are estimated by a musculoskeletal model using the same running experiment comparing MTSS and uninjured controls. Additionally, these Chapters involve running trials with and without shoes and different foot strike patterns. Finally, Chapter 4 presents conclusions and suggestions for further research.

CHAPTER 2

STRUCTURAL DEFORMATION OF LONGITUDINAL ARCHES DURING RUNNING IN MEDIAL TIBIAL STRESS SYNDROME

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Introduction

In 1982, Mubarak et al. defined medial tibial stress syndrome (MTSS) as "as a symptom complex seen in athletes who complain of exercise induced pain along the distal posterior-medial aspect of the tibia". Clanton and Solcher [1994] reported that MTSS is one of the most common causes of exercise-induced leg pain during running. The incidence rate of this injury is 5-15%, and approximately 60% of reports of injuries to the lower extremity describe the development of MTSS in patients [Bates, 1985]. In runners, MTSS accounts for an overall injury rate of 2.8 per 1000 Athlete Exposures [Plisky et al., 2007].

Numerous theories for the development of MTSS have been founded on the functional anatomy of the lower limb and the onset of pathological biomechanics. The traction-induced theory suggests that traction to the periosteum can be caused by any strong force exerted by the flexor digitorum longus, tibialis posterior and soleus through connective tissues [Devas, 1958; Reshef and Guelich, 2012]. Because the flexor digitorum longus, tibialis posterior and soleus muscles originate from the medial left tibia, these muscles cross the medial aspect of the ankle and run along the plantar surface of the foot [Behnke, 2006; Stickley et al., 2009]. Therefore, these muscles become overloaded because of excessive movement of the foot, which, in turn, can lead to development of MTSS during sports activities.

A number of studies have addressed the intrinsic and extrinsic risk factors for the onset of MTSS. In particular, increased foot pronation during quiet standing [Yates and White, 2004] and malalignment of the lower extremity during weight bearing can result in excessive navicular drop [Moen et al., 2012]. The longitudinal arches support the body and play a critical role in human bipedal locomotion during landing in running, as they facilitate shock absorption against the ground [Fukano and Fukubayashi, 2009]. However, the foot consists of two arches: the longitudinal arch and the transverse arch; the longitudinal arch comprises medial and lateral components. Indeed, Fukano and Fukubayashi [2009] recently showed that the lateral longitudinal arch (LLA) provides the same function as the medial longitudinal arch (MLA). In the past, many studies have classified the foot based predominantly on the shape of the arch, such that, to date, the MLA has been reported as the primary source of variability, and there is little information regarding the function of the LLA.

Previous studies have shown that it is difficult to measure the movement of these longitudinal arches. However, in recent years, fluoroscopy has been used for motion analysis as well as to evaluate alterations to the connective tissue structures during gait changes [Gefen et al., 2000; Gefen, 2003]. Several studies have shown that the development of MTSS is related to structural deformation of the longitudinal arches during standing and sports activities [Raissi et al., 2009; Moen et al., 2012]. Therefore, it is necessary to consider the function of the arch, including both the MLA and the LLA, under dynamic conditions and to investigate structural deformation to these longitudinal arches during running.

Fluoroscopy studies have shown gender-based differences in the functional deformation of the MLA and LLA during landing, and have evaluated the effects of step-up exercises in anterior cruciate ligament deficiency [Fukano and Fukubayashi, 2009, 2012; Kozanek et al., 2011]. These studies demonstrated a method to evaluate movement of the bones in the sagittal plane. However, only a few published studies have included an assessment of the LLA, and have yet to establish its role in injury. Fluoroscopy could be used to analyze the relationship between lower extremity injuries and kinematics of bony movement during sport. Therefore, knowledge of the angular changes that occur in the longitudinal arches and the translational motion of the bones during running can be used to develop prevention and treatment strategies for patients with MTSS.

The purpose of this study was to compare the angular change and the translational motion of the MLA and LLA between MTSS and non-MTSS subjects during simulated running. This study considered the relevance of structural deformation that occurs during the RFS, which is observed in 74.9% of all analyzed runners [Hasegawa et al., 2007]. We hypothesized that, during running, subjects with MTSS would show significantly different structural deformation of the foot from that of control subjects.

Methods

Subjects and data acquisition

Ten university soccer players volunteered to participate in the study. The MTSS group consisted of 5 male soccer players with MTSS [(age, 21.4 ± 2.3 years; height, 1.75 ± 0.06 m; body mass, 71.0 ± 5.3 kg) (table 2-1)]. Subjects in the MTSS group had been diagnosed with MTSS within a period of 6 months by an experienced orthopedic surgeon. The MTSS was defined as exercise-induced pain in the posteromedial aspect of the tibia, and pain in the posteromedial tibia on palpation of at least 5 cm. Patients had experienced symptoms for at least 2 weeks [Yates and White, 2004]. However, the MTSS group included participants who currently have no any pain and symptoms. The non-MTSS group (control group) consisted of 5 male soccer players without pain in the posteromedial aspect of the tibia (age, 19.0 ± 1.0 years; height, 1.77 ± 0.05 m; body mass, 68.8 ± 4.7 kg). All subjects were university soccer players recruited through advertising and gave their informed consent. Natural forefoot strikers were excluded from the study. This study was approved by the Ethics Committee of the Graduate School of Comprehensive Human Sciences, University of Tsukuba, Japan.

The testing apparatus was equipped with a C-arm fluoroscopic imaging system (Infinix Celeve-I INFX-8000C, Toshiba Medical Systems, Tochigi, Japan) with a 200-mm (8-inch) image intensifier. Fluoroscopy data was collected at a rate of 60 Hz sampling rate, using a radiation exposure equivalent to 200 mA (1 ms) with an intensity of 50 kV.

Each subject completed three trials of barefoot running on customized platform (size: length 200 × height 100 × width 70 cm) for which a single trial was collected by fluoroscopy for analysis (Figure 2-1). Prior to the trials, subjects were imaged during quiet standing with the right foot on the platform. For the dynamic measurements, the subjects performed running with the RFS. To minimize the effects of foot pronation, lines to guide the foot placement of the subjects were placed at a distance of 10 cm parallel to the image intensifier. The subjects were instructed to land with the center of their foot, contacting lines to guide the foot placement with their second toe and the center of their heel along the running platform at a low speed of 150 beats per minute (bpm) with metronome. Verbal or visual instruction of the RFS technique during running was given prior to testing and subjects were required to practice the technique before the trials were captured for analysis.

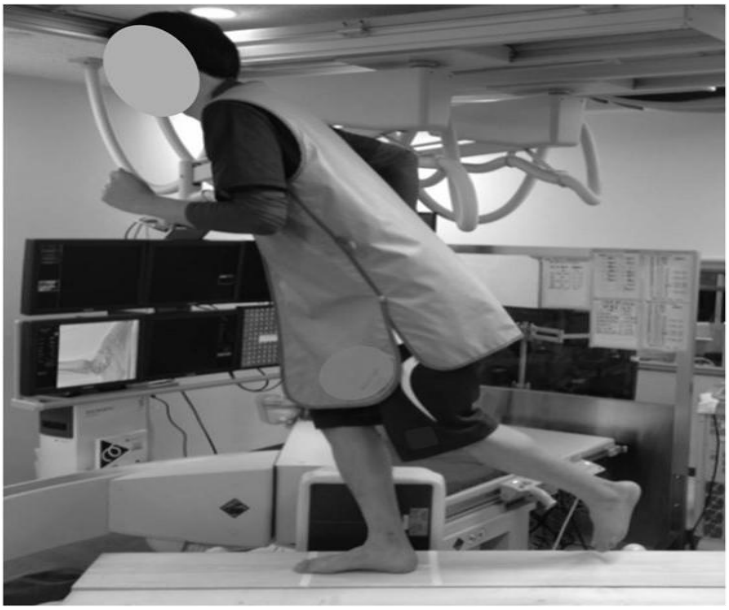

Figure 2-1. Experimental set-up during data acquisition by fluoroscopic imaging. Each subject is performing running on the platform measurement field.

Data management and analysis

All fluoroscopic images were imported into graphics software (CANVAS™ X, ADC System, Miami, FL, USA) and open source software (Image-J, National Institutes of Health, NIH, Bethesda, MD, USA) and manually digitized to dotting points of bony landmarks along the longitudinal arches. The two-dimensional x- and y-coordinates within the image frame of reference were recorded using a rectilinear calibration grid, which consisted of 16 metal points placed 5 cm apart in a rectangular grid pattern on an acrylic board.

The complete imaging sequences of three trials were collected for analysis, selecting imaging sequences with the clearest osseous contour. We confirmed the interclass correlation coefficient (ICC) of the three trials in advance. The ICC of the kinematics data was $r > 0.85$.

We used a template method that consisted of the calcaneus, first metatarsal and fifth metatarsal bones. This template method, arch angular change and translational motion were defined with reference to the anatomical parameters reported by Fukano and Fukubayashi [2009]. Movements of the longitudinal arches in the sagittal plane were established as the angular change and translational motion observed after the foot strike (Figure 2-2). The section of footage analyzed encompassed the angular change of the longitudinal arches from right foot strike to right toe-off with 20 frames and the translational motion of the longitudinal arches, with 10 frames within the mid-support during running. Especially, each frame recorded to coordinate bone position of M1c and M5c for calculate translational motion distance and direction. Calculated coordinate bone position of M1c and M5c were defined x-coordinates as anterior/posterior displacement and y-coordinated as superior/inferior displacement. Furthermore, to evaluate the extent of the activities of the first and fifth metatarsals for the control point, we evaluated the translational displacement of the M1 (d1) and M5 (d2) for the calcaneus using the same analysis section of the translational motion by below an equation of distance between two points.

[An equation of d1]

$$\mathbf{d1 = r2(M1c) - r1(Cc)}$$

$$= (x2, y2) - (x1, y2)$$

$$= (x2 - x1, y2 - y1)$$

$$d1 = \sqrt{(x2 - x1)^2 + (y2 - y1)^2}$$

[An equation of d2]

$$\mathbf{d2 = r2(M5c) - r1(Cc)}$$

$$= (x2, y2) - (x1, y2)$$

$$= (x2 - x1, y2 - y1)$$

$$d2 = \sqrt{(x2 - x1)^2 + (y2 - y1)^2}$$

Statistical analysis

A Mann-Whitney U test (non-parametric) was performed to compare the values between the groups regarding to change of the MLA and LLA (angular change and translational motion included d1 and d2 displacements). A two tailed test was used to test the null hypotheses. The level of significance was set at $p < 0.05$.

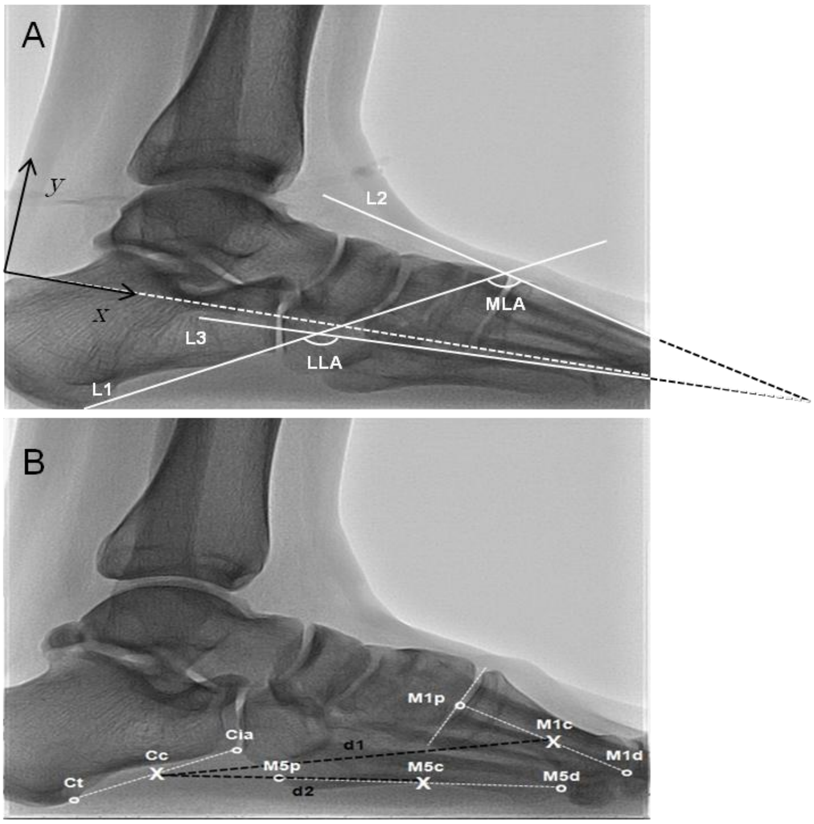

Figure 2-2. A) The definition of the MLA and LLA angular coordinates; L1 describes the line that connects the calcaneal anterior tubercle and the medial process of the calcaneal tuberosity. L2 describes the dorsal aspect of the first metatarsal bone shaft. L3 describes the dorsal aspect of the fifth metatarsal bone shaft. The MLA angle is defined as the obtuse angle appeared by L1 and L2. The LLA angle is defined as the obtuse angle appeared by L1 and L3. B) The definition of the MLA and LLA translational motion coordinates; Read the coordinates of the x - y axis that pointing anterior epiphyseal of the first metatarsal(M1d), fifth metatarsal(M5d) and calcaneus(Cia) and posterior epiphyseal of the first metatarsal(M1p), fifth metatarsal(M5p) and calcaneus(Ct). The bony coordinates of center of the calcaneus(M1c, M5c, Cc) calculated using coordinate averages of the M1p and M1d, M5p and M5d, Ct, and Cia. The d1 describes the line that connects the Cc and M1c. The d2 describes the line that connects the Cc and M5c. Each frame was recorded bony coordinates of the M1c, M5c, Cc, d1 and d2.

Results

MLA and LLA angular changes

The magnitude of the MLA angular changes that appeared at early stance phase of running occurred after about 80-145 ms (Figure 2-3A) and was significantly greater for subjects in the MTSS group compared with those in the non-MTSS group ($p < 0.05$). The LLA angular change, which appeared between 45 and 290 ms (Figure 2-3B), was also significantly greater for the MTSS group compared with the non-MTSS group ($p < 0.05$). The angular change of the MLA was 8.6 (1.9)° for subjects in the MTSS group and 6.2 (1.8)° for those in the non-MTSS group. The angular change of the LLA was 10.8 (2.0)° in the MTSS group and 7.0 (1.8)° in the non-MTSS group.

Table 2-1. Subjects' characteristics

Parameter	MTSS Mean (SD)	non-MTSS Mean (SD)
Age (yr)	19.8 (1.5)	19.6 (1.9)
Height (m)	1.73 (0.10)	1.69 (0.04)
Total body mass (kg)	63.8 (11.1)	62.3 (4.4)
BMI (kg/m²)	21.2 (1.2)	21.3 (1.1)

BMI - body mass index; SD - standard deviation; yr = year; MTSS - medial tibial stress syndrome.

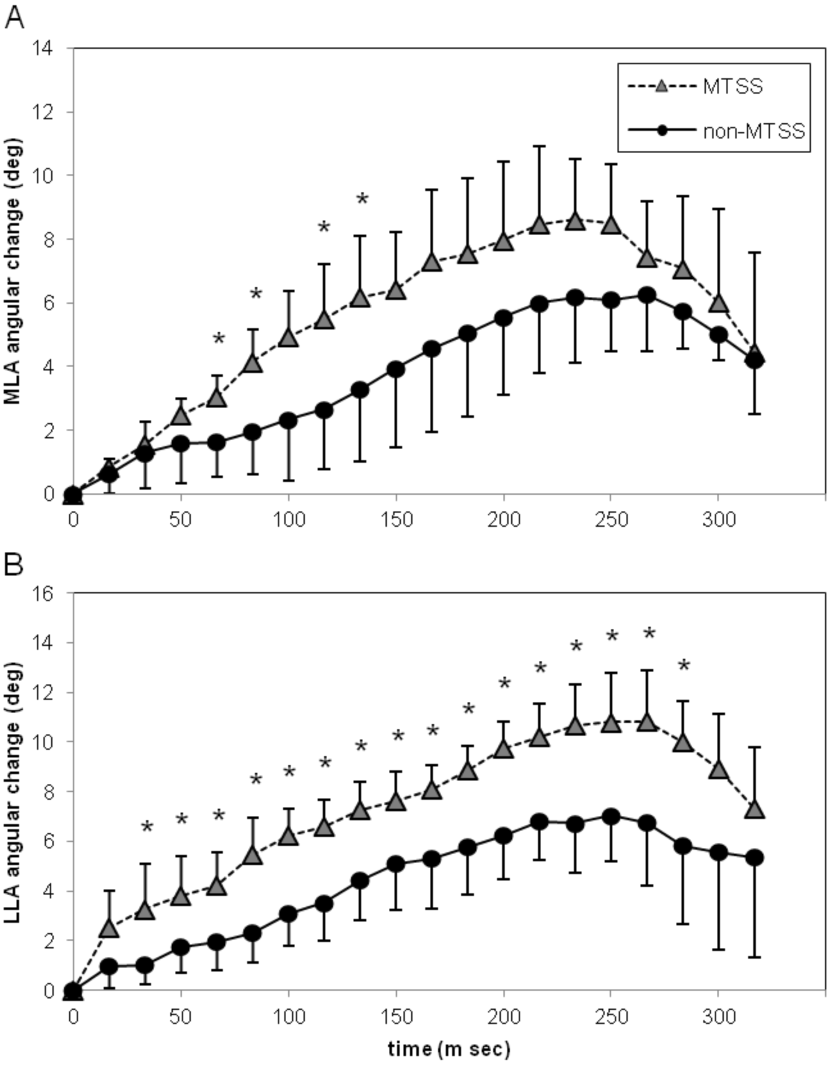

Figure 2-3. The medial and lateral longitudinal arches movements in the sagittal plane. The mean result of angular change of medial(A) and lateral(B) longitudinal arches of the MTSS and non-MTSS group during running. Asterisk denotes statistically significant difference between groups at $P<0.05$.

Translational motion

The maximal MLA (M1) translational motion occurred from 65 ms to 165 ms after foot strike and was significantly anteriorly displaced in subjects in the MTSS group [1.38 (0.44) cm] compared with those in the non-MTSS group [0.89 (0.43) cm] ($p < 0.05$; Figure 2-4A). The maximal MLA (M1) was also significantly inferiorly displaced after about 80 ms for subjects in the MTSS group [1.79 (0.69) cm] as compared with those in the non-MTSS group [0.76 (0.49) cm] ($p < 0.05$; Figure 2-4B).

The LLA (M5) translational motion was also significantly anteriorly displaced for the MTSS group [0.88 (0.35) cm] compared with the non-MTSS group [0.41 (0.25) cm] at 8-165 ms ($p < 0.05$; Figure 2-4C) and was significantly inferiorly displaced for the MTSS group (1.14 ± 0.38 cm) compared with the non-MTSS group [0.35 (0.33) cm] after about 65 ms ($p < 0.05$; Figure 2-4D).

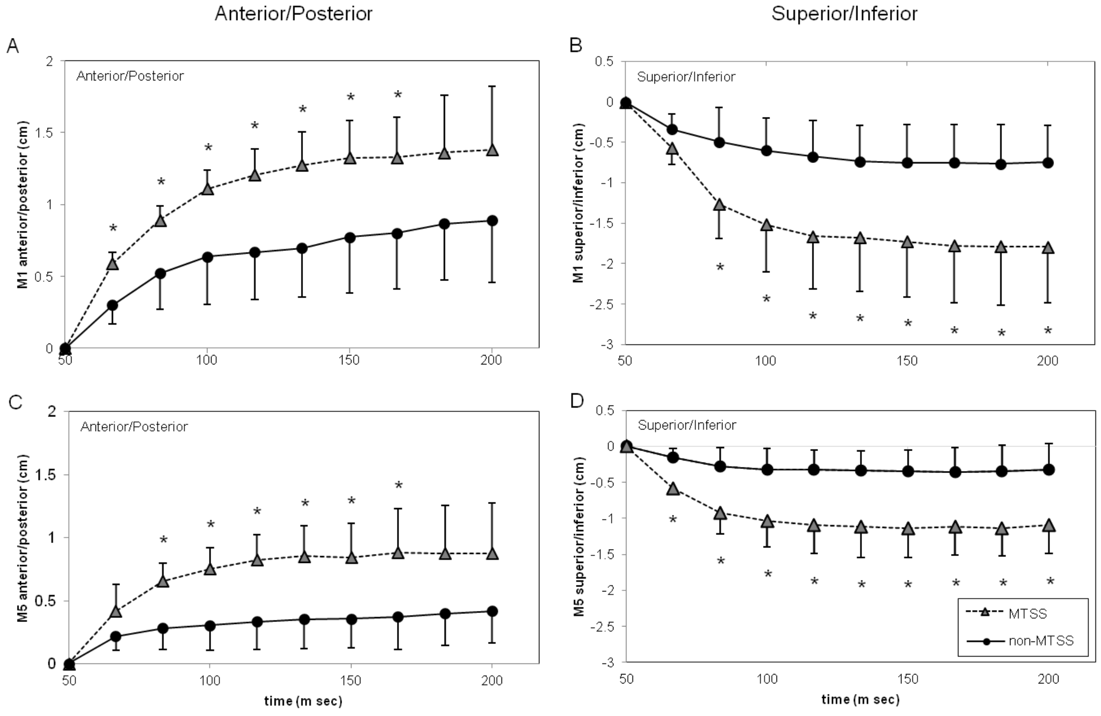

Figure 2-4. The medial and lateral longitudinal arches movements in the sagittal plane. The mean result of translational motion of medial(A, B) and lateral(C, D) longitudinal arches of the MTSS and non-MTSS group during running. Asterisk denotes statistically significant difference between groups at $P<0.05$.

d1 and d2 displacements

A significantly different d1 displacement was measured for the MTSS group as compared with the non-MTSS group [0.58 (0.24) cm vs. 0.41 (0.16) cm, respectively; $p < 0.05$] about 65 ms after foot strike (Figure 2-5A). Similarly, a significantly different d2 displacement was observed between the two groups after about 50 ms (Figure 2-5B; 0.47 (0.41) cm vs. 0.14 (0.03) cm, respectively; $p < 0.05$].

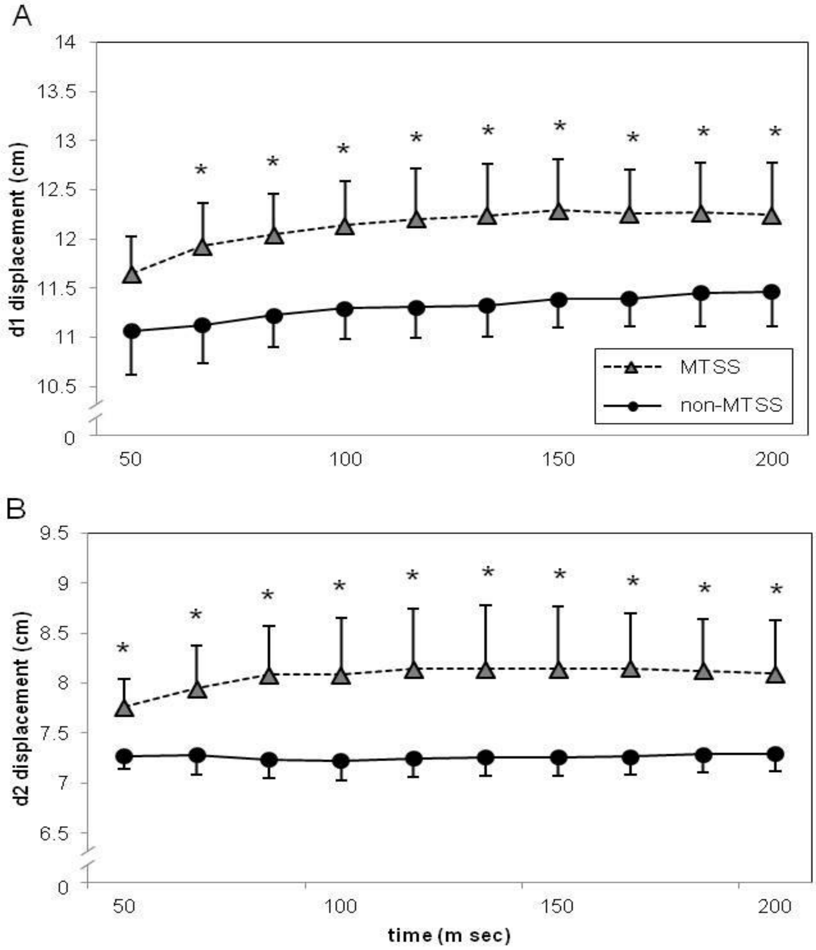

Figure 2-5. The medial and lateral longitudinal arches movements in the sagittal plane. The mean result of translational displacement of d1(A) and d2(B) of the MTSS and non-MTSS group during running. d1(MLA) shows the distance from calcaneus to first metatarsal and d2 shows the distance from calcaneus to fifth metatarsal. Asterisk denotes statistically significant difference between groups at $P<0.05$.

Discussion

This study investigated the structural deformation that occurs to the longitudinal arches during simulated running in subjects with MTSS using fluoroscopy and compared these findings with those of uninjured control subjects. The data confirmed the initial hypothesis that subjects with MTSS would show significantly different structural deformation of the foot from that of control subjects during running as compared with non-MTSS control subjects.

There is still much debate about the etiology of MTSS. MTSS has been broadly investigated, with studies showing that increased minor movements between the foot bones brought on by repetitive and, at times, malaligned weight bearing during landing in running could be the cause of the pathological changes in the connective tissues [Bates, 1985; Moen et al., 2012].

Increased angular changes of the arches in subjects with MTSS

In this Chapter, we showed that angular changes in the MLA and LLA were increased during running in subjects with MTSS as compared with control subjects. Moreover, we found that the angular change in the LLA was greater than that in the MLA after the foot strike. The amount of time to maximum angular change in the

MTSS group (at about 235-250 ms) was faster than that in the non-MTSS group (at about 265 ms). Excessive pronation, such as that observed with increased angular change of the MLA and LLA, exerts stress to the musculoskeletal structures of the foot and ankle, and transfers abnormal stresses on the lower leg [McKeag and Dolan, 1989; Yates and White, 2004]. Furthermore, because of the likely role of the MLA and LLA in resisting depression of the longitudinal arch during landing in running, this increased angular change in the MLA and LLA in MTSS athletes probably causes a decrease in the plantar flexor strength and an increase in the internal rotation torque of the lower extremity [Hintermann and Nigg, 1998]. This leads to inflammation and increased stress to the periosteum of the tibia through connective tissue in athletes with MTSS. While the maximal angular change of the MLA appeared during early stance phase, the maximal angular change of the LLA appeared during mid-support of movement of the foot. Thus, the LLA was in contact with the ground during the entire mid-support. For this reason, the LLA was directly under the influence of a load. Terawaki et al. [2009] showed that the center of pressure in the foot was located on the outside in subjects with MTSS more than that seen in the control subjects after the mid-stance during gait. Although the subjects in this Chapter were analyzed while running, one might hypothesize that the center of pressure was on the outer side of the foot after the mid-support. Thus, these results indicate that athletes with MTSS have an abnormal structural deformation of foot during stance phase of running.

Increased translational motion changes in subjects with MTSS

The MLA and LLA were anteroinferiorly displaced in subjects with MTSS as compared with non-MTSS subjects. Because the displacement of the metatarsals were increased, muscle strength of the plantar flexors (flexor digitorum longus, tibialis posterior, and soleus), which insert onto these bones, was reduced. Accordingly, because stress to the tibial periosteum was increased, traction forces through connective tissue also increased in MTSS athletes [Gath and Miller, 1989; Saxena et al., 1990; Beck and Osternig, 1994]. These plantar flexors then perform the functions of the primary foot supinators. In particular, the tibialis posterior generates the greatest supination torque. The extensive insertion of this muscle provides supination torque to the midfoot [Donald, 2004]. In this reasoning, it would seem that the plantar flexors could not provide proper arch support during landing in running because of reduced supinator strength. We therefore suggest that increased supination torque could improve the symptoms of MTSS; this could be achieved by strengthening the tibialis posterior with the use of balance training and elastic resistance band exercises.

One might hypothesize that the inferior displacement of the longitudinal arch components was likely caused by early muscle fatigue because of insufficient shock absorption on landing during the initial resistance to weight-bearing in sports involving running. Thus, these results indicate that translational motion of the metatarsals is controlled primarily by flexor digitorum longus, tibialis posterior and soleus. Therefore, effective prevention and rehabilitation for athletes with MTSS could be achieved by improving the function and strength of these muscles.

Mann and Inman [1964] showed that the intrinsic muscles in the foot exert considerable flexion force on the forefoot and play a critical role in muscle stabilization in the foot. Therefore, these muscles are likely to be the main contributors to the muscle support of the arch. Banks et al. [2001] also reported that ligaments in the foot provide enough passive support to maintain the integrity of the foot during quiet standing. Thus, the soft tissues of the foot determine foot shape and stabilization. However, in the case where there is a soft tissue problem, such as increased activation in the intrinsic muscles or increased ligamentous laxity in the foot, intrinsic muscles strength of the foot would be decreased. This may explain the long-range d1 and d2 displacement for subjects in the MTSS group.

Studies by Yates and White [2004] and Bartosik et al. [2010] found that individuals with MTSS had less ankle dorsiflexion. This would shorten the eccentric contraction time of the dorsi flexors from foot strike to mid-support during running. Plantar flexion torque transmits its forces to the ankle joint while the dorsi flexors engage in proper eccentric contraction on landing in running. Therefore, a shortened dorsiflexion time would lead to increased plantar flexion strength [Gehlsen and Seger, 1980] and range of motion in MTSS individuals [Hubbard et al., 2009] during the foot strike of running. This dysfunction would not provide proper arch support and the d1 and d2 would not be under the control of the dorsi flexors upon landing in running. To treat this dysfunction, we recommend that athletes with MTSS perform eccentric contraction exercises of the dorsi flexors to improve dorsi flexion torque. Furthermore, because decreased dorsiflexion suggests excessive tightness in the triceps surae muscle of calf, we also recommend that MTSS athletes perform triceps surae stretching to alleviate this tightness. It may also be beneficial for MTSS athletes to obtain neoprene insoles or custom-designed insoles for proper locomotion of the intrinsic muscles of the foot and to provide proper arch support during foot strike while running. These treatment options would collectively help to reduce internal rotation torque of the lower-extremity and provide proper arch support for athletes.

Perspectives

The research on motion characteristics of the longitudinal arches during sports activities provides important new insights into the etiology of medial tibial stress syndrome. Numerous studies have investigated the risk factors associated with the development of MTSS, assessing the function of the flexor digitorum longus, tibialis posterior and soleus muscles. In this Chapter, we show that movement of these muscles at their insertion on the plantar surface of the foot is higher in MTSS subjects. These results also implicate changes in LLA positioning as a risk factor for the development of MTSS. These results may help to establish preventive measures for and improve the management of MTSS in athletes.

Conclusions

This study investigated the kinematics of the longitudinal arches in subjects with MTSS during running. The data analysis confirmed the initial hypothesis, showing significant angular changes in the MLA and LLA of subjects with MTSS and an increased anteroinferiorly displaced translational motion of the first and fifth metatarsals during running. Excessive structural deformation to the medial and lateral longitudinal arches could be a risk factor for the development of MTSS.

CHAPTER 3

EFFECT OF PLANTAR FLEXORS IN RESPONSE TO DIFFERENT FOOT STRIKE PATTERNS DURING RUNNING IN MEDIAL TIBIAL STRESS SYNDROME

3-1. MUSCLE ACTIVATION OF PLANTAR FLEXORS IN RESPONSE TO DIFFERENT FOOT STRIKE PATTERNS DURING BAREFOOT AND SHOD RUNNING IN MEDIAL TIBIAL STRESS SYNDROME

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Introduction

Chapter 2 examined a method for using fluoroscopy to structural deformation of MTSS during running that compared with controls. The main findings in Chapter 2 were athletes with MTSS have an excessive structural deformation of foot during stance phase of running, with a large decreased in both the medial and lateral longitudinal arches. However, Chapter 2 has not been determined muscle abnormalities as inducing factors for traction-induced MTSS in response to excessive structural deformation of the foot. Thus, Chapter 3-1 will have to verify that MTSS has plantar flexor activations in response to excessive structural deformation of the foot. Additionally, it is possible that excessive structural deformation of the foot would relate to abnormal peroneal muscles as foot supinator (or evertor). Thus, this peroneal muscle also will have to verify in Chapter 3-1. And also, Chapter 3-1 will have to verify effect of different foot strike patterns and shoes for understanding whole running conditions.

MTSS is a common cause of exercise-induced leg overuse injury during running [Clanton and Solcher, 1994]. MTSS is defined as exercise-induced pain at the posteromedial border of the tibia not attributable to stress fracture or compartment syndrome and, on palpation, pain extending at least 5 cm at the posteromedial border of the tibia, with the symptoms having been present for at least 2 weeks [Yates and White, 2004]. Previous studies have reported incidences of this injury that varied from 4% to 35% in physically active populations [Clanton and Solcher, 1994; Bennett et al., 2001]. It appears especially in runners, for whom an overall injury rate of 2.8 per 1000 athletic exposures has been reported [Plisky et al., 2007].

There have been numerous debates regarding the mechanism behind MTSS development. A popular theory is that it is a traction-induced injury, suggesting that traction on the periosteum can result from a strong force exerted by the plantar flexors of the ankle joint [Devas, 1958; Reshef and Guelich, 2012]. Stickley et al. [2009] noted that theories involving the soleus, tibialis posterior, and flexor digitorum longus of the superficial and deep posterior compartments are not supported by anatomical evidence. The presence of tibial attachments of the DCF that have thickened to become a soleal aponeurosis suggest that it is capable of inducing traction-induced injury. Despite these various theories, the etiology of MTSS is still being debated. We therefore deemed it necessary to consider that muscle activation caused by excessive movement of the foot can lead to the development of MTSS during running. We especially considered the effect of wearing shoes and the different foot strike patterns. Several risk factors for MTSS addressed in previous studies were the choice of footwear [Tweed et al., 2008], muscle tightness, weakness of the tibialis posterior [Franklyn et al., 2008], lean calf girth [Burne et al., 2004], reduced isotonic endurance of the plantar flexors [Madeley et al., 2007], high body mass index [Plisky et al., 2007], increased ankle plantar flexion [Hubbard et al., 2009], increased foot pronation during quiet standing [Yates and White, 2004], and excessive navicular drop [Moen et al., 2010].

Footwear has developed from the early prototypes. Cushioning and stabilization is now incorporated in modern footwear. It is marketed for comfort, protecting the wearer from injuries, and correcting movement patterns [Altman and Davis, 2012]. It plays an important role during movement. Even with these advancements, however, most athletes and exercise participants have suffered their injuries in the shod condition. What, then, can we do better to prevent exercise-induced leg injuries and pain?

Habitual barefoot runners tend to use the FFS pattern, whereas shod runners use the RFS pattern [Lieberman et al., 2010]. The FFS and RFS running patterns associated with injury are not well understood. Barefoot running with the FFS is associated with relatively smaller collision forces than shod running with the RFS. It comprises a more plantar-flexed ankle joint at landing and more ankle compliance during landing, which cushions the effective body mass upon collision with the ground [Lieberman et al., 2010]. A previous study reported that the RFS is linked to moderate running-related injuries 2.5 times more often than the FFS [Daoud et al., 2012]. That study, however, was not conducted regarding the onset of MTSS. To our knowledge, there have been no articles in the literature in which either foot strike patterns or the effect of shoes was analyzed in relation to the development of MTSS. A few studies have started to study the increased number of injuries due to barefoot running, which is exhibiting an increasing trend [Giuliani et al., 2011; Salzler et al., 2012; Olin and Gutierrez, 2013]. Furthermore, a previous study revealed that athletes and runners using the RFS at landing during sports activities comprised 74.9% of all analyzed runners [Hasegawa et al., 2007]. Thus, a better understanding of plantar flexor activation changes at landing under barefoot or shod running conditions and different strike patterns during running can be used to develop training strategies for preventing MTSS and caring for it if it develops.

The purpose of this study was to determine changes in plantar flexor activation during barefoot or shod running in athletes with MTSS who have motion characteristics derived from mechanical factors. We also compared the FFS and RFS patterns to establish more clearly the mechanism of onset of MTSS. We hypothesized that, when running, plantar flexor activity would be higher in subjects with MTSS than in the controls (without MTSS). We also expected that the higher plantar flexor activity depended on whether the running was done using the FFS pattern or RFS pattern.

Methods

Participants

A total of 15 collegiate soccer players volunteered to participate in the study. They were divided into two groups: with MTSS and without MTSS. The MTSS group consisted of 7 male soccer players with MTSS [age 19.8 ± 1.5 years; height 1.73 ± 0.10 m; body mass 63.8 ± 11.1 kg; BMI 21.1 ± 1.4 kg/m^2]. Subjects in the MTSS group had been diagnosed with MTSS by an experienced orthopedic surgeon. The inclusion criteria [Yates and White, 2004] were as follows: (1) pain that was induced by exercise; (2) pain on at least 5 cm of the posteromedial border of the tibia; (3) these symptoms had been present for at least 2 weeks. However, the MTSS group included participants who currently have no any pain and symptoms. The control group consisted of 8 male soccer players without pain in the posteromedial aspect of the tibia (age 19.6 ± 1.9 years; height 1.69 ± 0.04 m; body mass 62.3 ± 4.4 kg, BMI 21.6 ± 1.2 kg/m^2). Participants in the control group were matched one-on-one to participants in the MTSS group on the basis of age, sex, height, total body mass, and BMI. All subjects, who were university soccer players recruited through advertising, gave their informed consent. The Ethics Committee of the Graduate School of Comprehensive Human Sciences, University of Tsukuba, Japan, approved this study.

Data collection

A three-dimensional motion analysis system (Vicon MX; Oxford Metrics, Oxford, UK) with 12 cameras (MX T020) was used to capture and analyze motion of the FFS and RFS patterns with a sampling frequency of 250 Hz. The trials were conducted in both barefoot and shod running conditions. The marker trajectories data were captured using the Vicon Nexus software package (Oxford Metrics).

Subjects performed the running task for least 3 trials of the FFS and RFS at 3.3 m/s on a runway (5.0 × 2.5 m) in barefoot and shod conditions (Figure 3-1). Retroreflective markers were attached according to the Plug-in Gait marker set. Prior to testing, verbal or visual instruction of the FFS and RFS techniques as the point of initial contact of the foot with the supporting surface by defined by Cavanagh and Lafortune [1980] was given (Figure 3-2). The participants were required to practice the technique before the data were captured for analysis. Standardized indoor futsal footwear (Wave Grevista Pro 3; Mizuno, Osaka, Japan) was provided to each subject (Figure 3-3). This footwear was selected to provide conditions similar to those of outdoor soccer spike shoes.

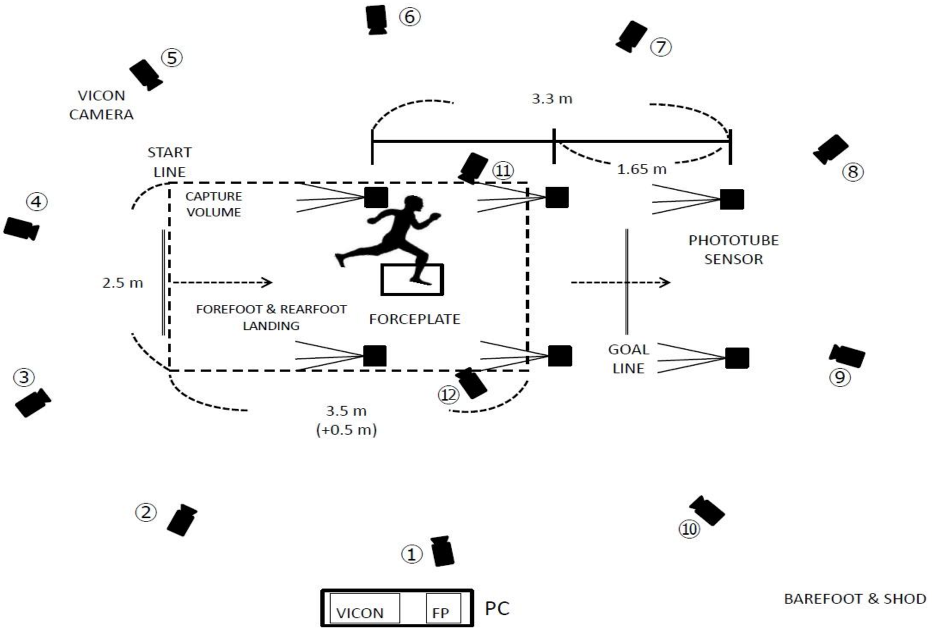


Figure 3-1. The set-up simulated running.

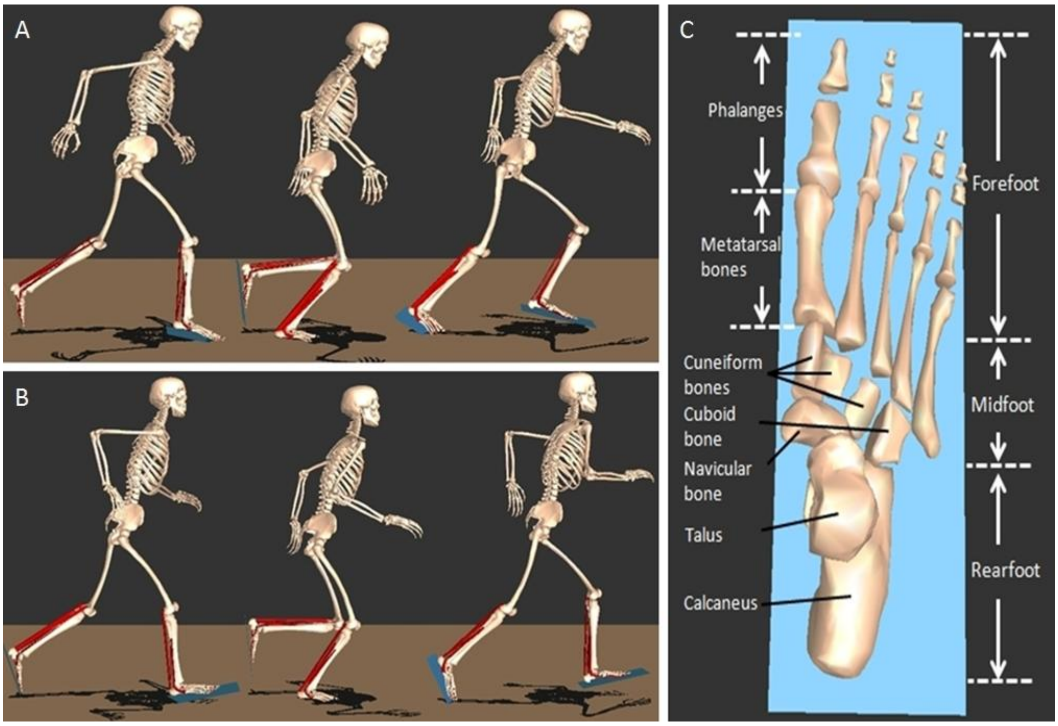


Figure 3-2. The musculoskeletal model snapshots from simulations of running support phase with different foot strike pattern as defined by Cavanagh and Lafortune. (A) FFS pattern. (B) RFS pattern. (C) Superior view of the bone structure and divisions of the foot.

Data analysis

Each trial was used to determine activation in the muscles using SIMM (MusculoGraphics, Santa Rosa, CA, USA). SIMM was used in conjunction with subjects’ kinematic data to estimate the changes in the normalized plantar flexors—such as the gastrocnemius medialis (GM), gastrocnemius lateralis (GL), soleus (Sol), tibialis posterior (TP), flexor digitorum (FD), flexor hallucis (FH), peroneus brevis (PB), and peroneus longus (PL)—activations in the ankle joint during running (Figure 3-4). An inverse kinematics is used to calculate joint angles by experimentally measured marker positions. And then, calculated joint angles are used to solve for the net reaction forces and net moments at each joint by inverse dynamics with angular velocities, angular accelerations, and ground reaction forces. Finally, for estimate muscle activations are used to static optimization tool by maximum isometric force and joint moments [Anderson and Pandy, 2001a; Pandy, 2003].

Muscle activation indicates similar with %MVC (Maximum Voluntary Contraction) of EMG and invigoration rates of motor unit in muscular physiology. However, eight plantar flexion muscles activations were investigated to determine how to change the activation ratio of the plantar flexor over a range of 0 to 1 (0 indicating fully deactivated; 1 indicating fully activated) during running simulation because this concept applied by robotics. To estimate muscle activations is computed by optimization as minimized the sum of the square of excluding maximum isometric forces from muscle force (objective function) within constraint as sum of the muscle torque and each muscle force is coincide with joint moment.

Figure 3-3. The indoor futsal shoes used in this study.

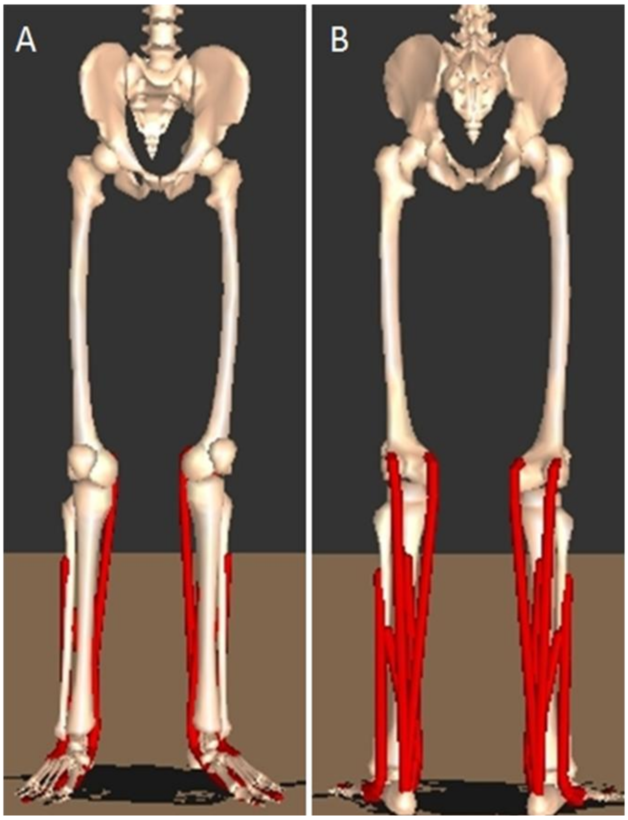


Figure 3-4. The musculoskeletal modeled plantar flexor activation was defined by ratios of 0 to 1. (A) Static anterior view of the plantar flexors (GM, GL, Sol, TP, FD, FH, PB, PL) model. (B) Static anterior view of the plantar flexor model of the lower extremity with the hip and knee joints fully extended.

Results are expressed as means ± SD. To compare the plantar flexor activation of each group, foot strike patterns were examined by two-way factorial analysis of variance (ANOVA) - the two factors were the groups and the foot strike patterns followed by the independent Student's t-test. The analysis was conducted using IBM SPSS Statistics 21 (IBM, Somers, NY, USA). Values of $p < 0.05$ were considered significant.

Results

Comparison of subjects' characteristics between groups

Table 3-1 shows the mean (SD) age, height, total body mass, and BMI for each group. There were no significant differences in age (p=0.80), height (p=0.43), total body mass (p=0.72), or BMI (p=0.51) in the two groups.

Two-way factorial ANOVA for each group and condition

The means of plantar flexor activation for the entire stance phase during running with and without shoes and for different strike patterns are shown in Table 2. There was a tendency for the estimated plantar flexor activation to be higher in the MTSS group than in the controls (non-MTSS group) (Figure 3-5a and 5b).

The main effects were significantly higher Sol (F [1, 26] = 4.261, $p < 0.05$) and

PB (F [1, 26] = 4.357, $p < 0.05$) muscle activation in the barefoot condition in both the MTSS and non-MTSS groups. However, there were no significant main effects for plantar flexor activations in barefoot condition with the RFS pattern and in shod condition with both patterns between groups.

Additionally, significant main effects of foot strike pattern were observed for GM (F [1, 26] = 22.614, $p < 0.001$; in barefoot condition), (F [1, 26] = 5.228, $p < 0.05$; in shod condition), GL (F [1, 26] = 6.758, $p < 0.05$; in shod condition), Sol (F [1, 26] = 28.677, $p < 0.001$; in barefoot condition), (F [1, 26] = 11.252, $p < 0.005$; in shod condition), TP (F [1, 26] = 7.602, $p < 0.05$; in shod condition), FD (F [1, 26] = 7.408, $p < 0.05$; in shod condition) muscle activations. There was a tendency towards higher GL ($p = 0.061$; in barefoot condition) and PB ($p = 0.051$; in shod condition) muscle activation in both the MTSS and non-MTSS groups. There were no significant interactive effects between groups regarding the foot strike pattern (Table 3-2).

Comparison of normalized plantar flexors activation

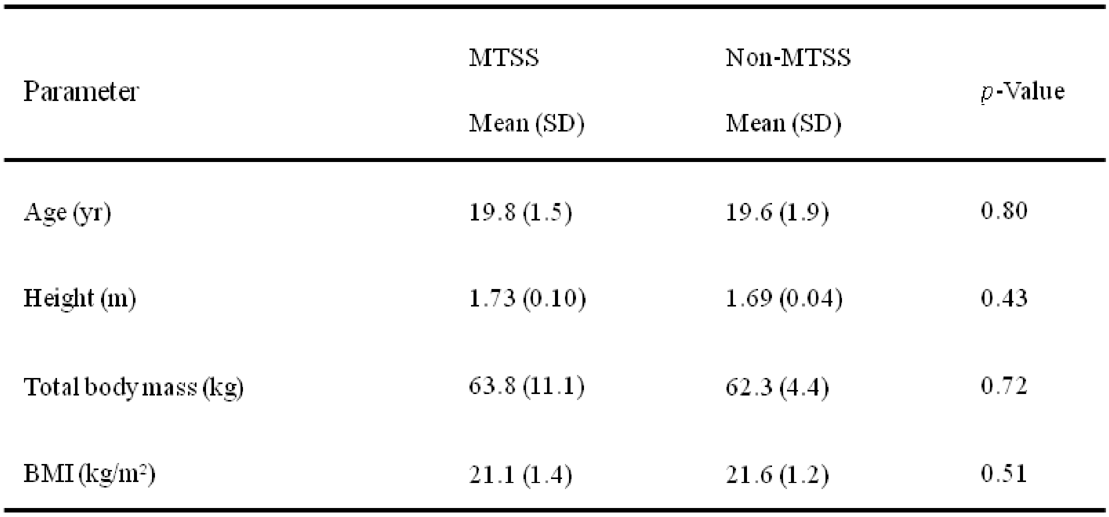
In comparison of groups, Sol (at first 20-55% of stance) and PB (at first 40-55% of stance) muscle activations were significantly higher in the MTSS group than in the non-MTSS group during barefoot running with the FFS pattern ($p < 0.05$).

In comparison of different foot strike pattern with barefoot condition, GM (at first 10-55% of stance) and Sol (at first 5-55% of stance) muscle activations with the FFS pattern were significantly higher than with the RFS pattern in the MTSS group during first half of stance ($p < 0.05$).

In comparison of different foot strike pattern with shod condition, GM (at first 15-55% of stance), GL (at first 15-50% of stance), Sol (at first 5-50% of stance), TP (at first 10-40% of stance), and FD (at first 15-40% of stance) muscle activations with the FFS pattern were also significantly higher than that with the RFS pattern in the MTSS group during first half of stance ($p < 0.05$). However, GM (at first 90-95% of stance), Sol (at first 70-80% of stance), and FD (at first 55-60% of stance) muscle activations were significantly higher with the RFS pattern than with the FFS pattern in the MTSS group at after half of stance ($p < 0.05$).

The MTSS group and the non-MTSS group had broadly similar features in all conditions of running, although a more activated plantar flexor was observed in the MTSS group than in the non-MTSS group.

Table 3-1. Subjects' characteristics



Parameter	MTSS Mean (SD)	Non-MTSS Mean (SD)	*p*-Value
Age (yr)	19.8 (1.5)	19.6 (1.9)	0.80
Height (m)	1.73 (0.10)	1.69 (0.04)	0.43
Total body mass (kg)	63.8 (11.1)	62.3 (4.4)	0.72
BMI (kg/m^2)	21.1 (1.4)	21.6 (1.2)	0.51

BMI – body mass index; SD – standard deviation; yr = year; MTSS – medial tibial stress syndrome.

Table 3-2. Muscle activation at the whole support phase at various conditions

Muscle	Barefoot running				Shod running			
	non-MTSS with FFS	non-MTSS with RFS	MTSS with FFS	MTSS with RFS	non-MTSS with FFS	non-MTSS with RFS	MTSS with FFS	MTSS with RFS
Gastrocnemius medialis^{B,S}	0.40 ± 0.15	0.34 ± 0.14	0.43 ± 0.20	0.32 ± 0.15	0.26 ± 0.16	0.11 ± 0.07	0.31 ± 0.17	0.26 ± 0.17
Gastrocnemius lateralis^{S}	0.41 ± 0.10	0.39 ± 0.09	0.44 ± 0.15	0.38 ± 0.10	0.41 ± 0.10	0.35 ± 0.10	0.37 ± 0.13	0.35 ± 0.11
Soleus^{B,S,G}	0.33 ± 0.29	0.29 ± 0.27	0.40 ± 0.36	0.28 ± 0.28	0.34 ± 0.30	0.28 ± 0.26	0.33 ± 0.33	0.26 ± 0.25
Tibialis posterior^{S}	0.23 ± 0.11	0.24 ± 0.12	0.20 ± 0.09	0.21 ± 0.11	0.33 ± 0.19	0.27 ± 0.17	0.29 ± 0.20	0.24 ± 0.17
Flexor digitorum^{S}	0.34 ± 0.05	0.34 ± 0.06	0.32 ± 0.05	0.33 ± 0.06	0.37 ± 0.08	0.33 ± 0.08	0.34 ± 0.09	0.33 ± 0.08
Flexor hallucis	0.34 ± 0.05	0.32 ± 0.05	0.32 ± 0.06	0.32 ± 0.06	0.36 ± 0.08	0.33 ± 0.07	0.33 ± 0.09	0.33 ± 0.08
Peroneus brevis^{G}	0.40 ± 0.05	0.38 ± 0.04	0.43 ± 0.08	0.43 ± 0.06	0.41 ± 0.05	0.37 ± 0.05	0.37 ± 0.08	0.35 ± 0.07
Peroneus longus	0.47 ± 0.10	0.45 ± 0.09	0.46 ± 0.13	0.45 ± 0.10	0.36 ± 0.04	0.33 ± 0.04	0.34 ± 0.07	0.32 ± 0.05

Results are the means ± SD.

A (B; in barefoot condition) and (S; in shod condition) indicates a main effect of the foot strike pattern and a (G) a main effect of groups in barefoot condition ($p<0.05$).

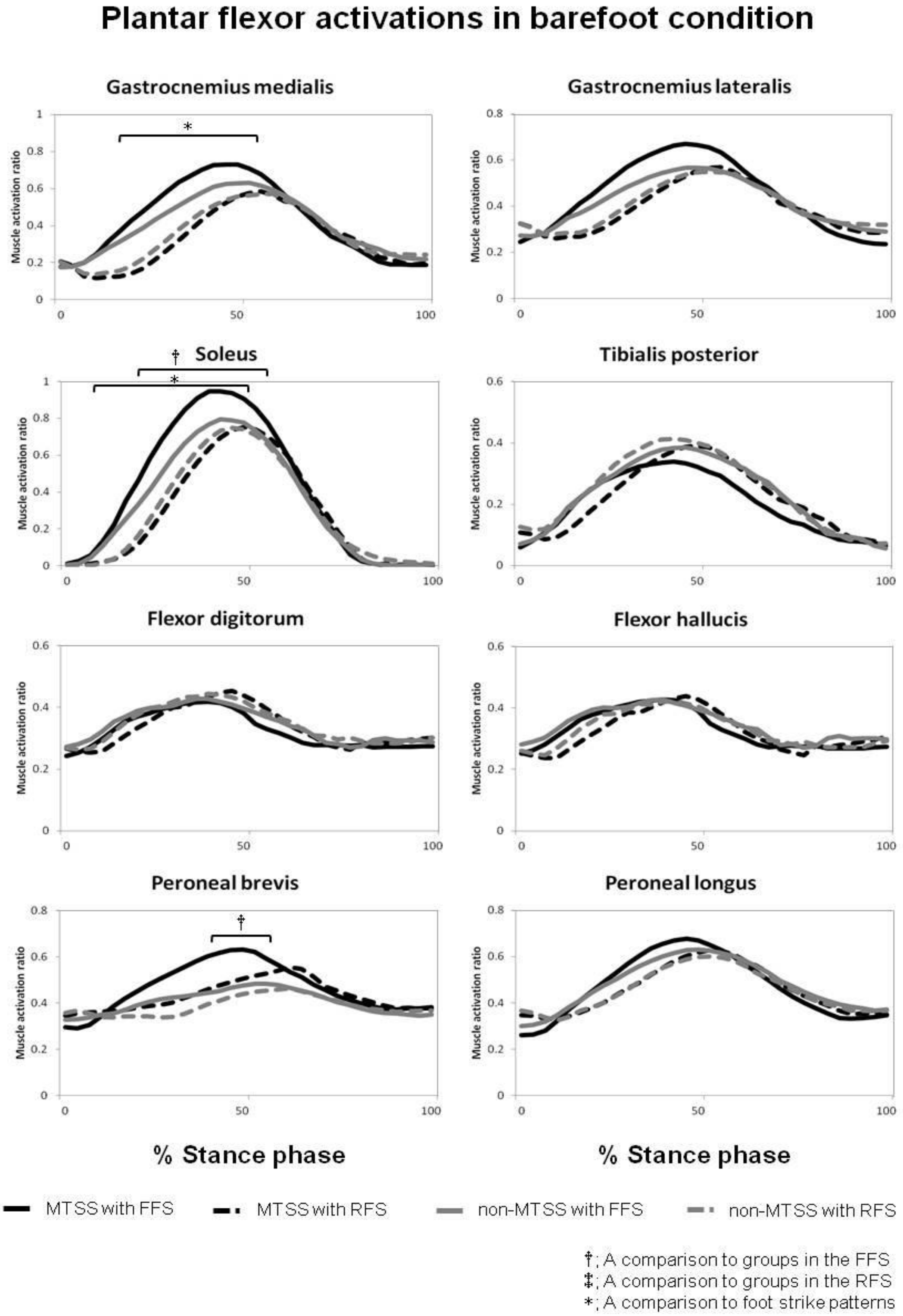


Figure 3-5a. Means of muscle activation production for the non-MTSS and MTSS groups for each frame in barefoot condition. The x-axis of group mean muscle activation indicates normalized stance phase of running gait cycle. Additionally, 0% of the x-axis indicates beginning of foot strike and 100% indicates end of toe off. Each plantar flexor muscle indicates activation in response to foot strike patterns during the stance phase of barefoot running.

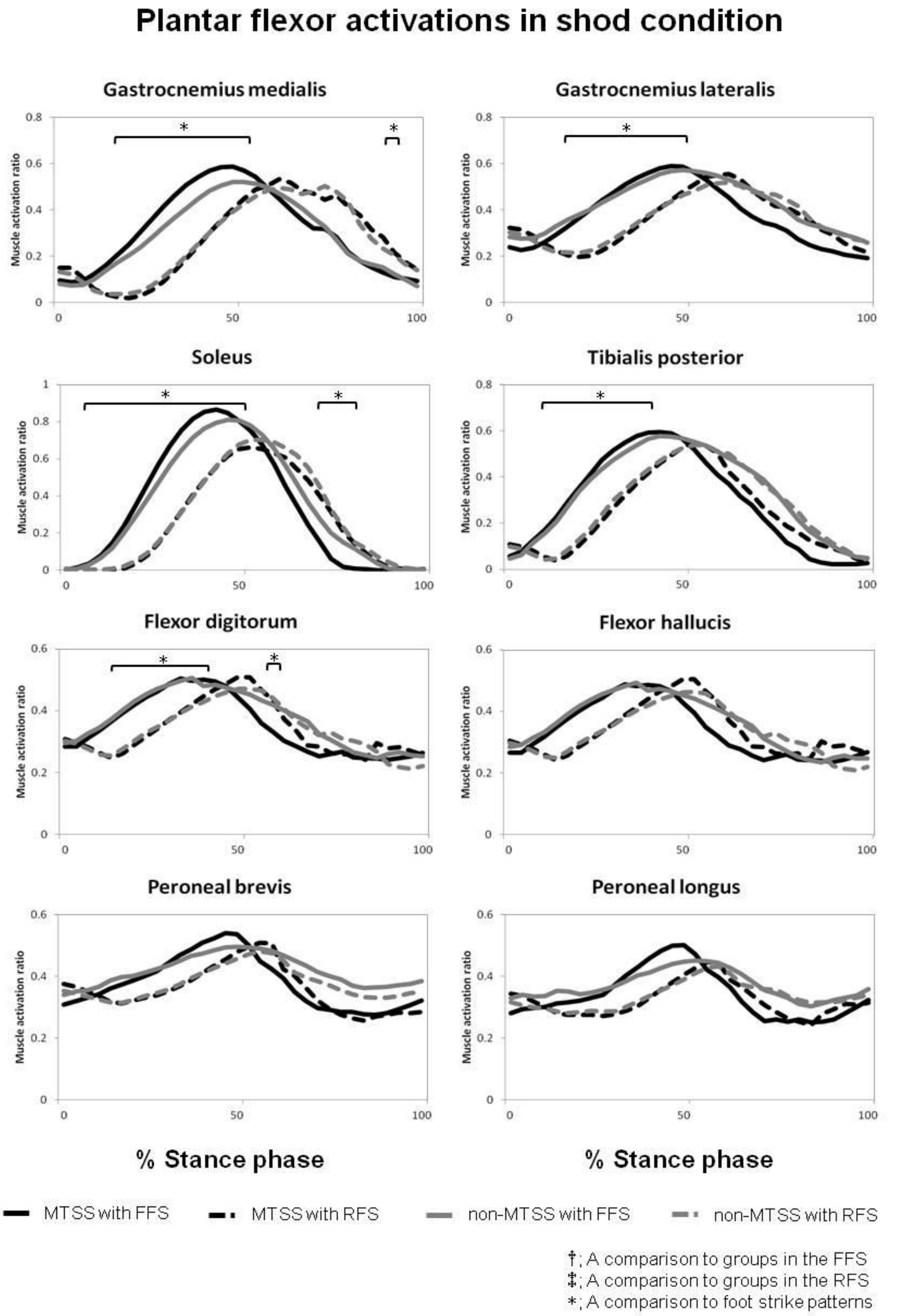


Figure 3-5b. Means of muscle activation production for the non-MTSS and MTSS groups for each frame in shod condition. The x-axis of group mean muscle activation indicates normalized stance phase of running gait cycle. Additionally, 0% of the x-axis indicates beginning of foot strike and 100% indicates end of toe off. Each plantar flexor muscle indicates activation in response to foot strike patterns during the stance phase of shod running.

Discussion

This Chapter investigated, using SIMM, the muscle activations that occur in the plantar flexors during running in subjects with MTSS. We then compared these findings with those of uninjured control subjects. The data partially confirmed our hypothesis that subjects with MTSS have higher plantar flexor activity than that in control subjects. We also expected higher plantar flexor activity with the FFS pattern than with the RFS pattern.

Our results showed that a few of the plantar flexors indicated significantly different strike patterns in barefoot and shod conditions between groups. These parameters could represent additional risk factors for MTSS to develop during running. The results in this Chapter indicated that more research is needed regarding these parameters.

Higher plantar flexor activity in subjects with MTSS

We showed that there were higher Sol and PB muscle activation of the plantar flexor muscles during first half of stance of running in subjects with MTSS than in the controls. This result implicated that the higher activity of these muscles creates a great load on soft tissue of the lower extremity during running or sports activities. This load may cause faster and more severe plantar flexor contraction repetitively in subjects with MTSS at the initial stance phase of running. Previous studies reported that the higher muscle activity while running indicates a greater load on those muscles, which could cause injury [McClay, 2000; Shih et al., 2013]. It may lead to increased stress and overload the tibial attachments of the DCF in subjects with MTSS. A previous study established increased ankle plantar flexion range of motion as a risk factor for developing MTSS [Hubbard et al., 2009], which also could be related to higher plantar flexor activity.

Another result implied that cause of the increased muscle activation of the plantar flexors in those with MTSS was excessive foot pronation [Yates and White, 2004; Moen et al., 2010; Noh et al., 2015]. The foot supinator with plantar flexion muscles may be activated to compensate for excessive foot pronation during stance of running [Beck, 1998]. The sequence of these actions could add a load to the medial musculoskeletal structures of the foot and ankle, transferring abnormal loads further up the kinetic chain [McClay and Manal, 1998]. We therefore suggest that, as reported in the literature, adjusting the frequency, duration, and intensity of the athlete’s training could alleviate the symptoms of MTSS without interrupting sports activities completely. Stretching calf muscles and eccentric calf exercises are also recommended to prevent muscle fatigue during sports activities [Beck, 1998; Kortebein et al., 2000; Couture and Karlson, 2002]. These treatment options would help reduce abnormal plantar flexor activity during running or sports activities in subjects with MTSS and may provide an appropriate load to the DCF, which might avoid the development of MTSS.

In this Chapter, we also showed that there was higher PB muscle activitiy during running in subjects with MTSS than in matched controls. The peroneal muscle is the principal simultaneous evertors of the foot and plantar flexors [Ambagtsheer, 1978]. Subjects with MTSS have a large decrease in their longitudinal arches during the stance phase of running [Noh et al., 2015], which might be caused when peroneal muscle is strongly activated during this phase. It might be one of the characteristics of the MTSS group during running. This characteristic also leads to a decreased longitudinal arch during running, which is yet another risk factor for MTSS. Moreover, peroneal muscle is linked to the medial longitudinal arch because of insertion in the plantar aspect of the base of the first metatarsal bone. High peroneal muscle activity was indicated regardless of any of the conditions. The decreased arches could therefore be a risk factor because of abnormally high peroneal muscle activity during running. This implies that treatment of peroneal muscle is a key point in subjects with MTSS.

The results of this Chapter showed that all conditions of running in the non-MTSS group were broadly similar to those for the MTSS group, although a few of the plantar flexors were more activated in the MTSS group than in the non-MTSS group.

Higher plantar flexors activity in barefoot running with the FFS

Shih et al. [2013] reported barefoot running with the FFS pattern in which the foot was at initial contact with a plantar flexed posture and immediately followed by a dorsiflexion movement, which is controlled by the eccentric contraction of calf muscles. It provides greater absorption of the impact by the plantar flexors [de Wit et al., 2000; Lieberman et al., 2010]. As noted in the literature, this relates well to our results showing that running with the FFS pattern generally had higher plantar flexor activity than running with the RFS pattern during the stance phase in MTSS. It could therefore be another risk factor. Other studies reported that a high incidence of running-related overuse injuries were associated with shod running with the RFS pattern more than with barefoot running with the FFS pattern [Lieberman et al., 2010; Daoud et al., 2012]. Despite these reports, it is impossible to completely prevent running-related overuse injuries with barefoot running and the FFS pattern. We could, however, reduce the number of those injuries [Giuliani et al., 2011; Salzler et al., 2012; Olin and Gutierrez, 2013]. Also, this running pattern is a risk for MTSS development due to plantar flexors. Thus, we suggest that the FFS pattern should not be allowed in athletes who have any risk factors for MTSS, especially in the barefoot condition. Further investigation of the effect of shoes and foot-strike patterns during running on MTSS is needed.

Further research is needed to investigate the development of MTSS involving the effect of peroneal muscle and the tibial muscle activation ratio to the longitudinal arches, as well as the kinetics of MTSS patients, such as joint moments, muscle forces, and muscle length during running (involving peroneal muscle and analysis of running phases). Our results provide information that can help establish preventive programs and improve the management of athletes with MTSS.

Conclusions

This Chapter investigated plantar flexor muscle activation in subjects with MTSS during barefoot and shod running with two foot strike patterns. Data analysis partially confirmed our hypothesis that the activity of plantar flexor muscles (involving peroneal muscle) was significantly higher in subjects with MTSS. Also, muscle activity during plantar flexion was significantly higher during running with the FFS pattern, which could indicate stress on soft tissue of the tibia and a tendency to develop MTSS.

3-2. MUSCLE FORCES OF PLANTAR FLEXORS IN RESPONSE TO DIFFERENT STRIKE PATTERNS DURING RUNNING IN MEDIAL TIBIAL STRESS SYNDROME

Introduction

We examined plantar flexor activations of MTSS during running compared with controls using SIMM in Chapter 3-1. The main findings in Chapter 3-1 were athletes with MTSS have a higher activity of some plantar flexors during running, especially barefoot running with the FFS pattern. In addition, those with MTSS have a higher muscle activation of the peroneal muscle during running. This could be linked to results of Chapter 2 that found excessive structural deformation of the foot during running in MTSS because these muscles contribute to foot pronation during running.

However, even though the results of Chapter 3-1 were found to be related to those in Chapter 2, they were insufficient to verify the traction-induced theory of MTSS. Thus, to verify the traction-induced theory, it is necessary to establish that the theory is directly linked to plantar flexor forces and is thought to provide traction force to connective tissues. Chapter 3-2 will verify that MTSS has plantar flexor forces in response to higher plantar flexor activation during running. This chapter will also verify the effect of different foot strike patterns for understanding whole running conditions.

van Gent et al. [2007] conducted a systematic review of running injuries, and the incidence of lower extremity injuries which involved MTSS varied from 19.4% to 79% of runners, despite technological developments in running footwear. MTSS is a common injury among lower extremity running related injuries [Clanton and Solcher, 1994], the incidence rate of this injury is reported from 5% to 15% to the lower extremity describing the development of MTSS in patients [Bates, 1985]. Numerous studies defined MTSS as pain in the posteromedial border of the tibia on palpation of at least 5 cm. Furthermore, patients with MTSS had suffered symptoms for at least 2 weeks [Yates and White, 2004].

Much literature has addressed that plantar flexion muscles including the soleus, tibialis posterior, and flexor digitorum longus muscles were involved in the development of MTSS as mechanical factors [Jones and James. 1987; Saxena et al., 1990; Beck and Osternig, 1994; Bouché and Johnson. 2007]. These plantar flexors, especially the soleus, are connected with the DCF attached to the tibia bone, and it is possible to induce traction-induced injury by the DCF [Stickley et al., 2009].

Meanwhile, a well-known theory by Devas [1958] had addressed traction to the periosteum by any strong force exerted by calf muscles. This theory was approved as the most apparent etiology of MTSS. However, not enough anatomical evidence exists to show the development of MTSS, and its causes are still under debate. Hence, more research is needed with musculoskeletal models to determine its mechanisms. In addition, MTSS could be a huge annoyance to athletes, especially soccer players [Clanton and Solcher, 1994; Ugalde and Batt, 2001] because of soccer games and training involving extensive amounts of running but there is no literature regarding the incidence of MTSS in soccer players, although various studies attempted to find the incidence of injuries. Moreover, as which foot strike pattern (e.g., the FFS and RFS) is used during running in soccer games and training is not well understood, which foot strike pattern is associated with injury, and the effect of foot strike patterns on the development of MTSS is also unclear. Therefore, we especially considered the effect of the different foot strike patterns on the development of MTSS.

Running is an integral part of most of sports such as soccer, and is associated with an increased risk of running injury to the lower extremity [Rooney and Derrick, 2013]. Recently, numerous studies focused on the influence of different foot strike patterns on lower extremity injury during running as one risk factor [Lieberman et al., 2010; Giuliani et al., 2011; Daoud et al., 2012; Salzler et al., 2012; Olin and Gutierrez, 2013].

Foot strike pattern was defined by Cavanagh and Lafortune [1980] as the part of first landing point with the landed surface of the foot as the FFS or RFS. Numerous studies on the FFS pattern have found a relatively smaller risk of running injury than associated with the RFS pattern [Lieberman et al., 2010; Daoud et al., 2012]. Lieberman et al. [2010] found that running with the FFS pattern causes comparatively smaller collision forces than the RFS pattern. The shock can be absorbed by the more flexed plantar posture of the ankle joint and more compliance during impact, which decreases the effective body mass that collides with the ground. However, it is possible that there is increased load to the calf muscles during impact. Previous research also reported that the collision forces are not as important as the acting force in running overuse injuries because the greater magnitudes of internal loads can damage the soft tissues, typically in the lower extremity, more than external loads [Scott and Winter, 1990]. Additionally, some studies have recently started to investigate the onset of running injuries in response to the FFS pattern [Giuliani et al., 2011; Salzler et al., 2012; Olin and Gutierrez, 2013]. Hence, the literature regarding foot strike pattern still debates which foot strike pattern is better for reduction of running injuries. In addition, the foot strike pattern associated with the development of MTSS is unclear so determining the effect of the foot strike pattern on the onset of MTSS during running is required. Notably, plantar flexion muscles play a critical role and may compensate activation against excessive foot pronation on striking when running [Beck, 1998]. As in previous studies, abnormally activated plantar flexors were consistently propounded as a risk of the development of MTSS. Therefore, the acting plantar flexors muscle forces and mechanical characteristics driven by SIMM in athletes with MTSS must be clarified.

The purpose of this study was to use a SIMM-driven musculoskeletal model of the lower extremity to estimate plantar flexor forces during running in subjects with MTSS and compare those forces with non-MTSS control subjects who have motion characteristics derived from mechanical factors. We also compared the FFS and RFS patterns in the MTSS group to more clearly establish the mechanism of the development of MTSS. It was hypothesized that when running the plantar flexor forces would be greater in subjects with MTSS than in non-MTSS. We also expected that the greater plantar flexor forces depended on whether the running was done the FFS pattern or the RFS pattern.

Methods

Chapter 3-2 provides calculated muscle forces from data collected from the same participants and same methods as Chapter 3-1.

Data Analysis

The SIMM (Musculographics, Santa Rosa, CA, USA) driven musculoskeletal model was used for whole data as muscle forces of the plantar flexor. Each trial was used to determine forces in the muscles of the plantar flexor as follows: the GM, GL, Sol, TP, FD, FH, PB, and PL. Inverse kinematics is used to calculate joint angles by experimentally measured marker positions. Next, calculated joint angles are used to solve the net reaction forces and net moments at each joint by inverse dynamics with

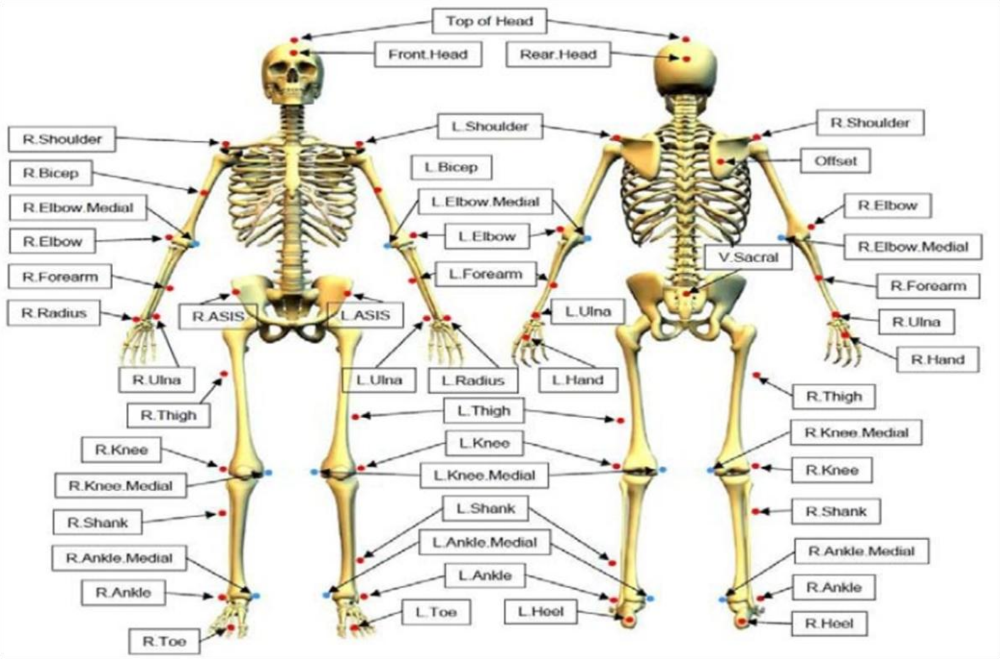


Figure 3-7. Plug-in Gait marker set placements for SIMM.

angular velocities, angular accelerations, and ground reaction forces. Finally, estimation of muscle forces is used for the static optimization tool. In the optimization approach, the dynamic equations are solved first to calculate the muscle forces, the net forces and moments at the joints from experimental kinematics measurement (inverse dynamics) [Anderson and Pandy, 2001a; Pandy, 2003]. The static optimization tool is estimated muscle force by minimizing the sum of the square of muscle excitations while accounting for muscle activation, length, and shortening velocity [Zajac, 1989].

Chapter 3-2 showed normalized muscle forces of the plantar flexor, which possibly affects the onset of the mechanical factor on the development of MTSS. In order to normalize muscle forces, data measured during running were divided by multiplying the height and body mass for each muscle to facilitate comparison for muscle forces between individuals and groups.

Statistical analysis

Results are expressed as means ± SD. To compare the plantar flexor force of each group, foot strike patterns were examined by two-way factorial analysis of variance (ANOVA) - the two factors were the groups and the foot strike patterns followed by the independent Student’s t-test. Analysis was conducted using IBM SPSS

Statistics 21 (IBM, Somers, NY, USA). Values of $p < 0.05$ were considered significant.

Results

Comparison of subjects' characteristics between groups

One-to-one matched subjects' characteristics results of the mean (SD) age, height, body mass, and body mass index between groups showed that there were no significant differences in age (*p*=0.80), height (*p*=0.43), total body mass (*p*=0.72), or BMI (*p*=0.51) in the two groups.

Two-way factorial ANOVA for each group and condition

The means of plantar flexor muscle forces for the entire stance phase during running with shoes for different strike patterns are shown in Figure 3-8a and 3-8b.

The main effects were significantly greater Sol ($F [1, 26] = 4.596$, $p < 0.05$) and PB ($F [1, 26] = 5.580$, $p < 0.05$) muscle forces in the barefoot condition in both the MTSS and non-MTSS groups. There were no significant effects for mean of normalized plantar flexor muscle forces between groups in the shod condition. In the RFS pattern, the MTSS group indicated relatively less plantar flexor forces, or was similar in both groups.

Additionally, significant effects of foot strike pattern were observed for GM (F [1, 26] = 17.020, $p < 0.001$; in barefoot condition), (F [1, 26] = 4.397, $p < 0.05$; in the shod condition), Sol (F [1, 26] = 8.978, $p < 0.01$; in the barefoot condition), (F [1, 26] = 12.135, $p < 0.005$; in the shod condition), and TP (F [1, 26] = 5.012, $p < 0.05$; in the shod condition) muscle forces in the MTSS group. There was a tendency towards greater GL ($p = 0.095$; in the barefoot condition, $p = 0.068$; in the shod condition) muscle forces in both the MTSS and non-MTSS groups. There were no significant interactive effects between groups regarding the foot strike pattern.

Comparison of normalized plantar flexors force

In a comparison of groups, Sol (at first 5-40% of stance) and PB (at first 40-50% of stance) muscle forces were significantly greater in the MTSS group than in the non-MTSS group during barefoot running with the FFS pattern ($p < 0.05$).

Additionally, in a comparison of different foot strike pattern in the barefoot condition, GM (at first 10-50% of stance), GL (at first 15-55% of stance), and Sol (at first 5-45% of stance) muscle forces with the FFS pattern were significantly greater than with the RFS pattern in the MTSS group during the first half of stance ($p < 0.05$).

In a comparison of different foot strike pattern with shod condition, the GM (at first 15-50% of stance), GL (at first 15-50% of stance), Sol (at first 5-50% of stance), and TP (at first 10-45% of stance) muscle forces had significantly greater in the FFS pattern than the RFS pattern in the MTSS group ($p < 0.05$). Next, GM (at first 90-100% of stance) and Sol (at first 70-80% of stance) muscle forces where significantly greater in the RFS pattern than in the FFS pattern in the MTSS group ($p < 0.05$).

The MTSS group and the non-MTSS group had broadly similar features in all conditions of running, although more generated plantar flexor forces were observed in the MTSS group than in the non-MTSS group.

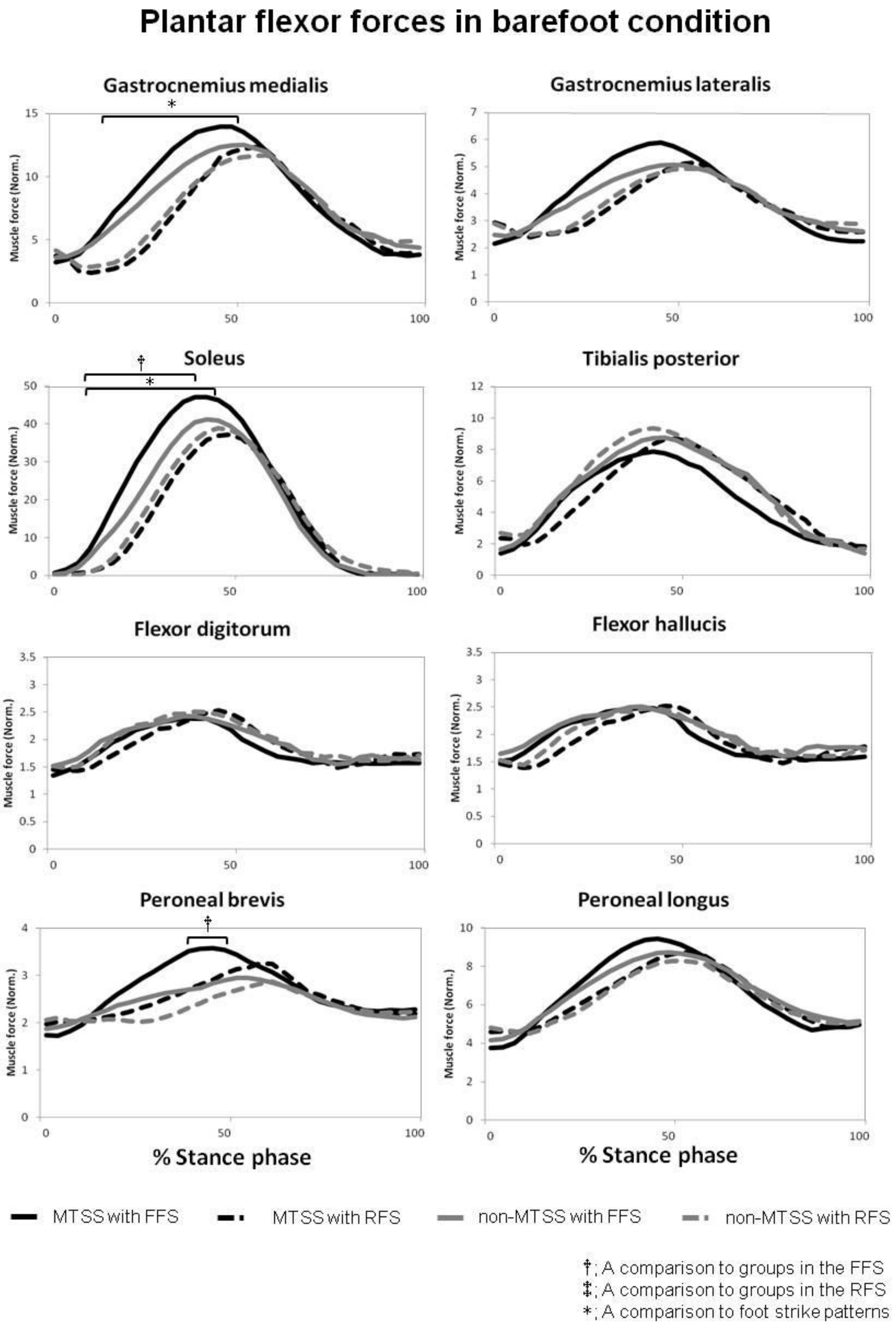


Figure 3-8a. Means of muscle force production for the non-MTSS and MTSS groups. Each plantar flexor muscle indicates force during the support phase for foot strike patterns in barefoot running.

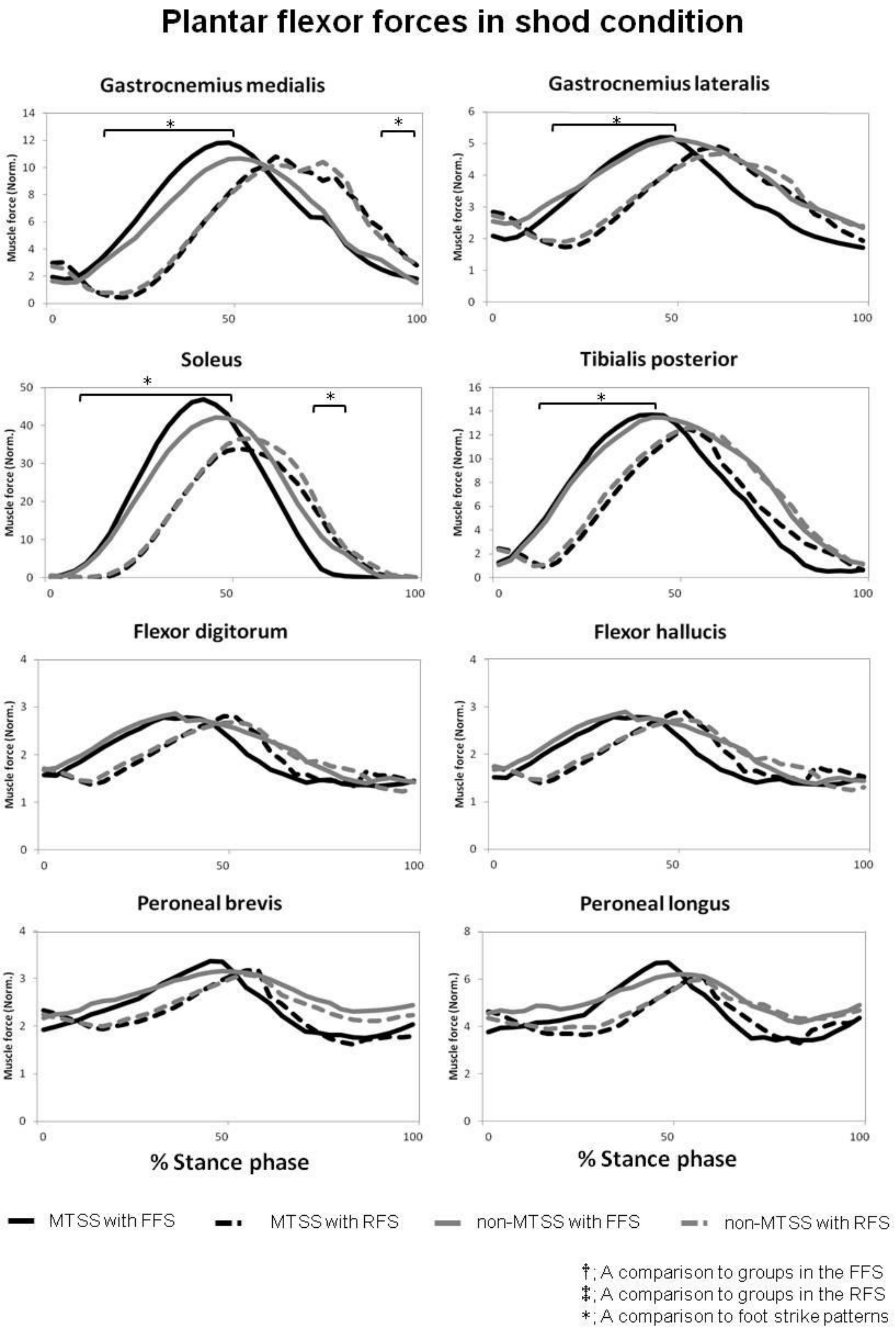


Figure 3-8b. Means of muscle force production for the non-MTSS and MTSS groups. Each plantar flexor muscle indicates force during the support phase for foot strike patterns in shod running.

Discussion

Using SIMM, this chapter investigated the muscle forces that occur in the plantar flexors during running in subjects with MTSS. We then compared these findings with those of uninjured control subjects. The data partially confirmed our hypothesis that subjects with MTSS have greater plantar flexor force than that in control subjects. We also expected greater plantar flexor force with the FFS pattern than with the RFS pattern.

Our results showed that a few of the plantar flexors, such as Sol and PB, relatively increased muscle forces could indicate the generation of traction force of certain connective tissues repetitively during the first half of stance in MTSS. Additionally, the FFS pattern has indicated greater GM, GL, and, Sol (barefoot) and GM, GL, Sol, and TP (shod) muscle forces during the first half of stance. The results in this chapter indicated that more research is needed regarding these parameters.

Moreover, results of Chapter 3-1 (muscle activation) and 3-2 (muscle force) showed similar features and patterns. Estimated plantar flexor activation and force were calculated as 2 times of maximum isometric muscle force (F^{MAX}) of the static model. Muscle force was normalized by multiplying the height and body mass for each muscle. Thus, we might find similar features and patterns between muscle activation and force occurred in response to this interpretation. However, these results are consistent with literature that suggests similar timing and magnitudes of muscle activation and force by EMG [Neptune and Sasaki, 2005; Rooney and Derrick, 2013; Haight et al., 2014].

Comparison of normalized plantar flexors forces between groups

We showed that barefoot running with the FFS pattern had greater Sol and PB muscle forces in the MTSS group than in controls during first half of stance. Stickley et al. [2009] have also reported that the Sol muscle is attached to the tibia connecting with the DCF. Hence, relatively increased Sol muscle forces during the first half of stance may imply that great mechanical stress could be repetitively generated through the DCF causing inflammation at the posteromedial site of the periosteum of the tibia, caused by sudden increased training volume or prolonged running. In shod running the FFS pattern had tendencies toward greater GM and Sol ($p < 0.1$) muscle forces in the MTSS group than in controls during the first half of stance, although there was no statistically significant difference for plantar flexor muscle forces between groups. However, such results may imply important points. Previous study reported that repetitive loading could create microscopic damage in tissue [Adams, 2004]. Some literature reported that MTSS was caused by comparatively greater plantar flexor forces (or tension) [Detmer, 1986; Bouche and Johnson, 2007], and even though there was a relatively small difference between groups, repetitive stress could generate traction force on the periosteum of the tibia in subjects with MTSS. However, further research is needed to investigate the physiological mechanism of this repetitive stress.

We also assessed the time to reach the peak value of muscle forces. Relatively increased GL (FFS in the barefoot condition) and Sol (FFS in the shod condition) muscle forces in the MTSS group showed a tendency for an earlier peak value than the non-MTSS group. Abnormal traction force may have occurred strongly and rapidly and damaged the soft tissue repetitively during the first half of stance. However, this needs further verification. The combined action of triceps surae muscles produces 80% of plantar flexion force associated with inversion/supination. This plantar flexion force is produced in response to the great triceps surae muscle-cross sectional area and relatively longer moment arm length [Murray et al., 1976], which could apply a great traction force on the periosteum of the tibia.

There were no statistically significant differences for plantar flexor muscle forces between groups in the shod condition, although there were greater tendencies toward force of the GM and Sol muscle forces during running in subjects with MTSS than in the controls. In addition, PB and PL muscle forces in the MTSS group indicated a relatively low level of muscle force compared to controls. We may consider plantar flexor forces in the MTSS group were relatively stabilized in response to footwear in the plantar flexor activations results of Chapter 3-1. Footwear technology has been developed to prevent lower leg muscle overuse and should provide stability and motion control for the runner [Drez, 1980; Cheung et al., 2006]. Thus, plantar flexor muscle forces in the MTSS group were able to maintain a more stable condition in the shod condition and footwear may help to decrease the onset of MTSS.

Comparison of plantar flexor forces in response to foot strike patterns in MTSS

Our results showed that the greater GM, GL, and, Sol (barefoot) and GM, GL, Sol, and TP (shod) muscle forces were determined in the FFS pattern during the first half of stance. This result is in consensus with a previous study that demonstrated similar results of plantar flexor forces being greater in the FFS pattern compared to the RFS pattern during the first half of stance [Rooney and Derrick, 2013]. Furthermore, the FFS pattern has a comparatively smaller impact peak of vertical ground reaction force than the RFS pattern during running [Lieberman et al., 2010]. In a more plantar flexed posture of the ankle joint when the foot strikes in running, the plantar flexor contracts eccentrically [Michael and Holder, 1985] for generation of smaller collision force.

Based on these findings, the FFS pattern can generate great traction force than the RFS pattern at initial contact by increased plantar flexor force. This result contrasted with previous studies which reported a reduction in running injury from using the FFS pattern [Lieberman et al., 2010; Daoud et al., 2012]. Ultimately, these findings suggest that great plantar flexor force in the FFS pattern leads to connective tissues (as the DCF) of the lower extremity as traction force, and the development of MTSS may indicate that increased plantar flexor forces act in the initial contact of running. Rooney and Derrick [2013] concluded that it is necessary to improve understanding of the potential for injury in response to different foot strike patterns. Thus, it implies that these results could be a key role for athletes to find and choose their proper foot strike pattern, considering their physical characteristics such as body alignment in order to prevent or reduce running injuries.

However, our results also indicate that the RFS pattern delayed show after the FFS pattern, fundamentally, similar with both foot strike patterns. Several studies reported that relatively higher training loads could lead to the onset of overuse injuries [Jones et al., 1993]. The results of this chapter showed that a sharp increase of muscle force acted as great load on the tibia with repetition, and the amount of time spent training or running, as well as this great load, might be combined with other risk factors.

Especially, the FFS pattern generates a greater load on plantar flexors than the RFS pattern, therefore, great stress could be applied to the tibia by both small amounts of time spent moving, and repetitive training or running.

Further research is needed in order to establish the cause of the development of MTSS in athletes, which may involve their foot strike pattern in running or training and the stress (or load) carrying path in response to different foot strike patterns. Our results provide valuable information that may be used in training feedback for foot strike pattern for preventive management of athletes with MTSS.

Conclusions

This study demonstrated plantar flexor forces compared to subjects with MTSS and uninjured controls in response to different foot strike patterns during barefoot and shod running. Partial hypotheses can be derived from this chapter are there were greater Sol and PB muscle forces in subjects with MTSS during the first half of stance in the barefoot condition, however, there were no statistically significant differences for other plantar flexor forces between groups and in the shod condition. On the other hand, GM, GL, and, Sol (barefoot) and GM, GL, Sol, and TP (shod) muscle forces were greater in the FFS pattern than in the RFS pattern during the first half of stance in the MTSS group. This could suggest that abnormal mechanical stress in response to increased muscle force is placed on the posteromedial site of the tibia by repetitive landing in athletes, especially in those who tend to use the FFS pattern during the first half of stance and suddenly increase training volume or running.

CHAPTER 4

COMPREHENSIVE DISCUSSION AND GENERAL CONCLUSION

The goal of this research project was to determine foot kinematics during running and to produce a musculoskeletal model of running in athletes with MTSS in order to verify the traction-induced theory of MTSS. To achieve this goal, we performed two experiments of running with fluoroscopy and with motion capture by Vicon cameras. Based on these data, we demonstrated the kinematics of the longitudinal arches in subjects with MTSS during running using fluoroscopy. We also demonstrated plantar flexor muscles activation in subjects with MTSS in response to different foot strike patterns during barefoot and shod running compared to uninjured controls. In addition, we focused on plantar flexor forces in subjects with MTSS compared to uninjured controls in response to different foot strike patterns during barefoot and shod running using a musculoskeletal model. Our results showed that athletes with MTSS have excessive structural deformation of the foot, higher muscle activations and greater muscle forces in some plantar flexors, especially during barefoot running. The FFS pattern showed higher values in some plantar flexor activations and also some greater plantar flexor forces than the RFS pattern. This suggests that excessive structural deformation to the medial and lateral longitudinal arches could be a risk factor for the development of MTSS. This may be linked to our result which showed significantly higher peroneal muscle activations during running because these muscles contribute to foot pronation during running. Over-activated peroneal muscles might be involved in the decrease in the longitudinal arch. Peroneal muscle was thus activated as compensatory activation for the plantar flexor or calf muscle. This implied that muscle abnormalities provided traction forces to the soft tissues of the tibia, along with prolonged muscle activation. Finally, our results of muscle force have indicated that great mechanical stress in response to greater muscle forces of some plantar flexors was applied repetitively on the posteromedial site of the tibia in athletes who tend to use the FFS during the first half of stance. Our study data are as follows:

1. Athletes with MTSS showed significant angular changes in the MLA and LLA.

2. An increased anteroinferiorly displaced translational motion of the first and fifth metatarsals during running in athletes with MTSS.

3. The activity of plantar flexor muscles was significantly higher in athletes with MTSS and barefoot running with the FFS pattern.

4. The activity of the peroneal muscle was also significantly higher in athletes with MTSS during barefoot running.

5. An increased muscle force of Sol and PB muscles could be applied repetitively on the posteromedial site of the tibia during barefoot running.

6. The MTSS group showed that plantar flexor forces were greater in the FFS pattern.

Limitations to the Study

Several limitations of this study should be noted. The purpose of this study was to investigate structural deformation of the foot and plantar flexor abnormalities in MTSS during running using fluoroscopy and SIMM, to establish the traction-induced theory. Thus, this study cannot be directly linked to prevention of MTSS. To prevent MTSS, further research is needed, such as logistic regression analysis and principal component analysis.

Chapter 2 and its experimental design have some methodological limitations that should be considered when interpreting the results. Firstly, only 10 subjects were included. This chapter had a relatively small sample size because of the risk of X-ray radiation exposure. Secondly, we investigated foot biomechanics during running in soccer players with MTSS, that consisted of three-dimensional movements but had only two-dimensional data interpretation. We endeavored to minimize potential misrepresentations by using an attached guideline with white tape for the landing point. Nonetheless, there is the possibility that error in the angular deformation calculations could have occurred due to pronation or out of plane movement of the foot. Thirdly, this study was performed using a relatively low sampling frequency of 60 Hz compared with other motion analysis techniques. Sampling frequency was restricted to evaluate bony movements during running. However, to minimize these technical limitations of fluoroscopy, we used a single investigator to perform the measurements. Finally, subjects performed the running test at a relatively low velocity of 150 bpm. However, the subjects were asked to perform a single foot landing that simulated real running conditions and allowed us to compartmentalize the run and gait.

Chapter 3-1 and 3-2 have the same limitations that must be considered when interpreting the results. Firstly, this study included habitual forefoot and rearfoot strikers. We taught FFS and RFS techniques prior to the trials, and the subjects were required to practice them. It is possible, however, that activation of the participants' plantar flexors were fundamentally different from those of habitual forefoot strikers and rearfoot strikers. Secondly, this study focused on soccer players. Soccer has characteristic movements—jumping, cutting, sprinting, kicking, running—on grass-wearing soccer cleats. Therefore, any study on the development of MTSS in soccer players should consider these movements. Additionally, muscle activation in soccer players might be different from that in athletes in other sports that involve running. Thus, these results cannot be used to determine the development of MTSS in all athletes and cannot be generalized to other sports. Most studies on MTSS were primarily performed in middle- and long-distance runners because it is commonly found in those athletes. Specialized analysis with feedback is important in soccer players, however, because MTSS is also commonly encountered in soccer players. Thirdly, muscle activation of this study was simulated using SIMM. We did not use experimental EMG data because not all of the plantar flexors could be evaluated with surface EMG. A previous study reported that the muscle activation recorded after SIMM simulation and during experimental EMG had similar features. Thus, simulated muscle activation by SIMM is valid and reliable. Fourthly, the muscle is a solid, not a rigid body. Therefore, muscle would change due to the position of the joint and contraction and also has several muscle origins and insertions. Additionally, there is a normal anatomic variation for each individual. Furthermore, a simulated musculoskeletal model by optimization is still technically incomplete at present. Currently, development of the algorithm is being done is a newer version. Despite this, simulated results of Chapter 3-1 and 3-2 could be changed by change of maximum isometric force. For this reason, the traction-induced theory of MTSS could not be verified in this study. Further research is needed to investigate the validity of this simulated model and should consider other methods to verify the traction-induced theory of MTSS. In addition, the traction-induced theory may not be an influential mechanism of MTSS. However, as mentioned in the discussion of Chapter 3-2, even though there was a relatively small difference between groups, repetitive stress by suddenly increased training volume or running, could generate traction force on the periosteum of the tibia in subjects with MTSS. Yet improvement of symptoms of MTSS, for example less tibia pain, is experienced after temporarily stopping training or running. Other risk factors may also be involved. Therefore, this study could not reliably determine the traction-induced theory of MTSS. Further research is needed to investigate by a MECHANICAL FINDER with muscle force to investigate stress on the periosteum. Finally, running trials in Chapter 3 were performed and data collected at 3.3 m/s as a relatively slow running speed for two steps. For this reason, it would seem that muscle activation and force data show similar features and patterns. Furthermore, this implied that Chapter 3-1 and 3-2 data could be changed in accordance with a change of running speed, especially increased speed.

Future Research Directions

To improve understanding and the development of MTSS, future study is required. We need to investigate the relationship between the LLA and the development of MTSS, and we should do in depth investigation as to how the peroneal muscles are related to muscle activation and force and development of MTSS during sports activities in athletes with MTSS. We must establish the development of MTSS in soccer players involving foot strike pattern by studying play in soccer games because subjects in this study were soccer players, and further research is needed to investigate the stress (or load) carrying path in response to different foot strike patterns. Finally, a musculoskeletal model of other running related injuries is needed and collection of all of the motion characteristics for running simulation using principal component analysis. This simulation can be identified to athletes who have a risk of running related injury, as motion characteristics. We also must clarify the traction-induced theory of MTSS clearly by mechanical finder with muscle force to find if it is able to investigate stress on the periosteum.

LIST OF ABBREVIATIONS

FFS	forefoot striking
RFS	rearfoot striking
PFPS	patellofemoral pain syndrome
ITBS	iliotibial band syndrome
MTSS	medial tibial stress syndrome
DCF	deep crural fascia
BMI	body mass index
ROM	range of motion
RICE	rest, icing, compression, and elevation
ESWT	extracorporal shock wave therapy
EMG	electromyography
MVC	maximum voluntary contraction
SIMM	software for interactive musculoskeletal modeling
ISB	international society of biomechanics
CE	contractile element
PEE	parallel elastic element
SEE	series elastic element

F_T	tendon force
F_{PE}	elastic component force
F_{CE}	contractile component force
l_T	tendon length
l_{CE}	contractile component length
l_{MTC}	musculotendon complex length
a	pennation angle
q	activation
MLA	medial longitudinal arch
LLA	lateral longitudinal arch
m	miter
kg	kilogram
Hz	hertz
mA	milliamp
ms	millisecond
cm	centimeter
bpm	beats per minute
ICC	interclass correlation coefficient

deg and °	degree
m/s	miter per second
kg/m^2	kilogram per square meter
GM	gastrocnemius medialis
GL	gastrocnemius lateralis
Sol	soleus
TP	tibialis posterior
FD	flexor digitorum
FH	flexor hallucis
PB	peroneus brevis
PL	peroneus longus
SD	standard deviation

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ABSTRACT

Incidence data of running related injuries of the lower extremity suggest 19.4% to 79.3% of runners (athletes involved in running in their sports) experience an overuse injury. Medial tibial stress syndrome (MTSS) is one of the most common causes of running related lower extremity injuries in athletes. However, there is no literature dynamically analyzing MTSS to clarify the traction-induced theory, and MTSS associated with shoes and foot strike pattern is not well understood. The purpose of this study was to compare angular change and translational motion from the medial and lateral longitudinal arches during running between MTSS and non-MTSS athletes. Additionally, this study compared plantar flexor activation and force in response to different strike patterns during barefoot and shod running in subjects with and without MTSS using software for interactive musculoskeletal modeling (SIMM). The changes were assessed by observing muscle abnormalities derived from mechanical factors.

We determined each hypothesis by first demonstrating bone structural deformation of running. Next, a musculoskeletal model was used to examine plantar flexor activation and force in subjects with MTSS and in uninjured controls. The collegiate soccer players who volunteered to participate were divided into two groups (MTSS, non-MTSS). All subjects performed a test movement that simulated running.

This study conducted two experiments, the first experiment by fluoroscopic imaging [operated at 60 Hz, 50 kV・200 mA (1 msec)] was used to investigate movement of foot bones during landing. Sagittal motion was defined as the angular change and translational motion of the foot arch.

The second experiment captured motion during running. Three-dimensional marker positions were recorded with a 12-camera motion capture system (Vicon) operating at 250 Hz while the subjects ran along a runway at 3.3 m/s. Each subject completed running with and without shoes, and different strike patterns as the forefoot strike pattern (FFS) and rearfoot strike pattern (RFS) were collected. Plantar flexors—such as the gastrocnemius medialis, gastrocnemius lateralis, soleus, tibialis posterior, flexor digitorum, flexor hallucis, peroneus brevis, and peroneus longus—activations and forces were investigated by SIMM.

The magnitude of angular change for the medial and lateral longitudinal arches was significantly greater in subjects with MTSS than for control subjects. Translational motion of the medial and lateral longitudinal arch of the MTSS group was also significantly greater than that of the non-MTSS group.

Compared to controls, the MTSS group had a higher muscle activity of some plantar flexors which involved the peroneal muscle. Normalized plantar flexor forces in barefoot running with the FFS pattern had greater Sol and PB muscle forces in the MTSS group than in controls during the first half of stance, although there were no statistically significant differences for other plantar flexor muscle forces between groups and shod running. In plantar flexor activations and forces due to foot strike pattern, the FFS pattern showed higher plantar flexor activations and forces than the RFS pattern.

As a whole, the results from this study suggest that an excessive structural deformation of the foot during the stance phase of running could be a risk factor for the development of MTSS in these subjects. In addition, results of musculoskeletal modeling suggest that subjects with MTSS have higher activities and greater muscle forces of the plantar flexor during running, especially barefoot running with the FFS pattern. It also suggests higher plantar flexor activation may provide traction force to connective tissues. Increased forces in some plantar flexors generated great traction force by repetitively landing on connective tissues in the deep crural fascia causing inflammation at the posteromedial site of the tibia and a tendency to develop MTSS.