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**Muscle activation of plantar flexors in response to different strike patterns during barefoot and shod running in medial tibial stress syndrome**

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**Abstract** Medial tibial stress syndrome (MTSS) is one of the most common causes of exercise-induced lower leg pain in running athletes. The purpose of this study was to compare plantar flexor activation changes in response to different strike patterns during barefoot and shod running in subjects with and without MTSS. The changes were assessed by observing motion characteristics derived from mechanical factors. The 15 collegiate soccer players who volunteered to participate were divided into two groups (7 MTSS, 8 non-MTSS). 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 the running with and without shoes, and different strike patterns as the forefoot strike pattern (FFS) and rearfoot strike pattern (RFS) were collected. Plantar flexor activation was investigated by software for interactive musculoskeletal modeling (SIMM) based on how the activation ratio changed from 0 to 1 at landing. Compared to controls, the MTSS group had higher tendency muscle activity of the plantar flexors that involved the peroneal muscle during first half of stance (\(p <0.05\)). For the stance phase of running, the MTSS group had greater muscle activity during plantar flexion in running with the FFS pattern than running with the RFS pattern (\(p <0.05\)). These results suggest that subjects with MTSS have higher activity of the plantar flexors during running, especially with the FFS pattern, which suggests greater stress on soft tissues of the tibial portion and a tendency to develop MTSS.

**Keywords**: medial tibial stress syndrome, plantar flexors, muscle activation, SIMM, running

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**Introduction**

Medial tibial stress syndrome (MTSS) is a common cause of exercise-induced leg overuse injury during running\(^1\). 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\(^2\). Previous studies have reported incidences of this injury that varied from 4% to 35% in physically active populations\(^3,13\). It appears especially in runners, for whom an overall injury rate of 2.8 per 1000 athletic exposures has been reported\(^6\).

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\(^10\). Stickley et al.\(^7\) 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 deep crural fascia (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 foot strike patterns. Several risk factors for MTSS addressed in previous studies were the choice of footwear\(^8\), muscle tightness, weakness of the tibialis posterior\(^9\), lean calf girth\(^9\), reduced isotonic en-
Habitual barefoot runners tend to use the forefoot strike (FFS) pattern, whereas shod runners use the rearfoot strike (RFS) pattern. Footwear is designed for comfort, protect the wearer from injury, and correct movement patterns. It also plays an important role during movement. The FFS and RFS running patterns associated with injury are not well understood. Barefoot running with FFS is associated with relatively smaller collision forces than shod running with 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. A previous study reported that RFS is linked to moderate running-related injuries 2.5 times more often than FFS. That study, however, was not conducted regarding the onset of MTSS. To our knowledge, there have been no articles in the literature in which foot strike patterns were analyzed in relation to the development of MTSS. A few studies have started to examine the increased number of injuries due to barefoot running, which is exhibiting an increasing trend. Furthermore, a previous study revealed that athletes and runners using RFS at landing during sports activities comprised 74.9% of all analyzed runners. Thus, a better understanding of plantar flexor activation due to different strike patterns during barefoot and shod 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 seven male soccer players with MTSS (age 19.8 ± 1.5 years; height 1.73 ± 0.10 m; body mass 63.8 ± 11.1 kg; body mass index [BMI] 21.1 ± 1.4 kg/m²). An experienced orthopedic surgeon diagnosed their MTSS. The inclusion criteria were as follows: (1) pain induced by exercise; (2) pain on at least 5 cm of the posteromedial border of the tibia; (3) symptoms present for at least 2 weeks. The control group consisted of eight 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/m²). Participants in the control group were matched one-on-one to participants in the MTSS group on the basis of age, gender, 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 three trials of FFS and RFS at 3.3 m/s on a runway (5.0 × 2.5 m) in barefoot and shod conditions. Reflective markers were attached according to the Plug-in Gait marker set. The participants were given verbal or visual instructions about the FFS and RFS techniques prior to trials and were required to practice the technique before the data were captured for analysis. The FFS and RFS patterns were classified according to Cavanagh and LaFortune as the point of initial contact of the foot with the supporting surface (Fig. 1). Standardized indoor Futsal footwear (Wave Grevista Pro 3; Mizuno, Osaka, Japan) was provided to each subject. This footwear was selected to provide conditions similar to those requiring outdoor soccer cleats.

Data analysis. The running gait is divided according to two phases of movement: stance and swing. The stance phase is subdivided into three sub-phases: initial contact (foot strike), mid-support phase, and propulsion (toe-off phase). This study focused on the stance phases (normalized from 0% to 100% - i.e., from the moment the foot comes into contact with the ground (foot strike; 0% of stance phase) - to end of toe-off (100% of stance phase)). Each trial was used to determine activation in the muscles using software for interactive musculoskeletal modeling (SIMM) (MusculoGraphics, Santa Rosa, CA, USA) based on reporting by Delp and Loan. To estimate plantar flexor activation, this study used SIMM, which can calculate the mechanical stress (or load) on the body caused by human movement from musculoskeletal mechanical characteristics of the body. SIMM is highly flexible as it is able to take into consideration the addition of muscles, origin and insertion of muscles, characteristics of musculotendon activities, and degrees of freedom of the joints. In contrast, it is difficult to investigate individual muscle activity or deep muscle activity with electromyography (EMG) unless needle EMG is used. SIMM, how-
ever, can estimate deep muscle activity easily and quantitatively assess individual forces. Thus, SIMM was used to make a comparison between participants and muscles. SIMM was used in conjunction with the subjects’ kinematic data to estimate 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 (Fig. 2). Eight plantar flexion muscle 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) - a range based on the concept applied for robotics - during running simulation. 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 the constraint condition. The maximum isometric forces were set at default values specified in the SIMM literature for adult men.

Statistical analysis. 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.

Fig. 1 Musculoskeletal model snapshots from generated simulations of the running stance phase with different foot strike patterns as defined by Cavanagh and Lafortune. (A) FFS pattern. (B) RFS pattern. (C) Superior view of the bone structure and divisions of the foot.

Fig. 2 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

Comparison of subjects’ characteristics between groups.

Table 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) (Figs. 3 and 4).

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 shod condition 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 were no significant interactive effects between groups regarding the foot strike pattern (Table 2).

### Table 1. Subjects’ characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>MTSS Mean (SD)</th>
<th>Non-MTSS Mean (SD)</th>
<th>$p$-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yr)</td>
<td>19.8 (1.5)</td>
<td>19.6 (1.9)</td>
<td>0.80</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.73 (0.10)</td>
<td>1.69 (0.04)</td>
<td>0.43</td>
</tr>
<tr>
<td>Total body mass (kg)</td>
<td>63.8 (11.1)</td>
<td>62.3 (4.4)</td>
<td>0.72</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>21.1 (1.4)</td>
<td>21.6 (1.2)</td>
<td>0.51</td>
</tr>
</tbody>
</table>

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

### Table 2. Muscle activation at the whole stance phase at various conditions

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Barefoot running</th>
<th>Shod running</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>non-MTSS with FFS</td>
<td>non-MTSS with RFS</td>
</tr>
<tr>
<td>Gastrocnemius medialis</td>
<td>0.40 ± 0.15</td>
<td>0.34 ± 0.14</td>
</tr>
<tr>
<td>Gastrocnemius lateralis</td>
<td>0.41 ± 0.10</td>
<td>0.39 ± 0.09</td>
</tr>
<tr>
<td>Soleus</td>
<td>0.33 ± 0.29</td>
<td>0.29 ± 0.27</td>
</tr>
<tr>
<td>Tibialis posterior</td>
<td>0.23 ± 0.11</td>
<td>0.24 ± 0.12</td>
</tr>
<tr>
<td>Flexor digitorum</td>
<td>0.34 ± 0.05</td>
<td>0.34 ± 0.06</td>
</tr>
<tr>
<td>Flexor hallucis</td>
<td>0.34 ± 0.05</td>
<td>0.32 ± 0.05</td>
</tr>
<tr>
<td>Peroneus brevis</td>
<td>0.40 ± 0.05</td>
<td>0.38 ± 0.04</td>
</tr>
<tr>
<td>Peroneus longus</td>
<td>0.47 ± 0.10</td>
<td>0.45 ± 0.09</td>
</tr>
</tbody>
</table>

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 ($p < 0.05$).
Plantar flexor activations in barefoot condition

Fig. 3 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.
Plantar flexor activations in shod condition

Fig. 4 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.
Comparison of normalized plantar flexors activation.

Sol muscle activation was significantly higher in the MTSS group than in the non-MTSS group during barefoot running with the FFS pattern ($p < 0.01$). GM and Sol muscle activation with the FFS pattern (barefoot condition) was significantly higher than with the RFS pattern in MTSS group ($p < 0.005$). Sol and TP muscle activation with the FFS pattern (shod condition) were also significantly higher than that with the RFS pattern in the MTSS group ($p < 0.05$). Similarly, GM (barefoot condition), GL, Sol, and FD (shod condition) muscle activation were significantly higher with the FFS pattern than with the RFS pattern in the non-MTSS group ($p < 0.05$).

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.

Discussion

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

Our results showed that a few of the plantar flexors indicated tendencies toward 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 study indicated that more research is needed regarding these parameters.

High plantar flexor activity in subjects with MTSS. We showed that there are higher tendencies toward activation of the plantar flexor muscles during first half of stance of running in subjects with MTSS than in the controls, although statistically significant differences were seen for Sol and PB muscles activation. We speculated 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 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. 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, which also could be related to higher plantar flexor activity.

Another speculation on the cause of the higher tendency of muscle activation of the plantar flexors in those with MTSS was excessive foot pronation. The foot supinator with plantar flexion muscles may be activated to compensate for excessive foot pronation during the running landing. 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. 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. 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 study, we showed that there were tendencies toward higher PB muscle activities during running in subjects with MTSS than in matched controls. The peroneal muscle is the principal simultaneous evertors of the foot and plantar flexors. Subjects with MTSS have a large decrease in their longitudinal arches during the stance phase of running, which might be caused when peroneal muscle is strongly activated during this phase. We speculated that it is 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. 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.

High plantar flexor activity with the FFS pattern. Shih et al. 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. 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. 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. 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. Also, this running pattern is a risk for MTSS development due to plantar flexors. Thus, we suggest that the FFS pat-
tern 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.

The results of this study showed that all conditions of running in the non-MTSS group were broadly similar to those for the MTSS group, although the plantar flexors were more activated in the MTSS group than in the non-MTSS group. We speculated that overactivated peroneal muscle might be involved in the decrease in the longitudinal arch. The foot supinator 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.

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.

Limitations. There are limitations to this study that must be considered when interpreting the results. First, 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. Second, 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 the 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 them. Third, 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 muscle activation recorded after SIMM simulation and during experimental EMG had similar features. Thus, simulated muscle activation by SIMM is valid and reliable. Finally, the joint torque is generated from multiple muscles involved with biarticular muscles. The estimated muscle activation was computed by optimization, however, this musculoskeletal model doesn’t take into consideration the functions of the biarticular muscles concerned with body control.

Conclusions

This study investigated plantar flexor muscle activation in subjects with MTSS during barefoot and shod running with two foot-strike patterns. Data analysis 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.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this article.

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