Dynamic Midfoot Kinematics in Subjects with Medial Tibial Stress Syndrome

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Background: Medial tibial stress syndrome (MTSS) is a common diagnosis. Several studies have demonstrated that excessive static navicular drop (ND) is related to the diagnosis. However, no studies have yet investigated ND and the velocity of ND during dynamic conditions. The aim of this study was to evaluate ND characteristics in patients with MTSS in dynamic and static conditions.

Methods: In a case-control study, 14 patients diagnosed as having MTSS were included from an orthopedic outpatient clinic. A control group consisting of 14 healthy participants was matched regarding age, sex, and typical sporting activity. Navicular drop was evaluated during treadmill walking by a two-dimensional video analysis. Static foot posture, static ND, dynamic ND (dND), and velocity of dND were compared.

Results: The two groups were comparable in relation to age, sex, height, weight, and foot size. No significant difference was found in static foot posture. Static ND showed a mean difference of 1.7 mm between the groups (P = .08). During treadmill walking, patients with MTSS had, on average, a 1.5-mm-larger dND (P = .004) and a 2.4-mm/sec-larger mean velocity of dND (P = .03).

Conclusions: Patients with MTSS display a larger ND and a higher ND velocity during treadmill walking. Increased ND velocity may be important to this condition. Future studies should include velocity of dND to investigate the mechanisms of dND in relation to overuse injuries. (J Am Podiatr Med Assoc 102(3): 205-212, 2012)
bone mineral density and a lower tibial cortical cross-sectional area of tibia compared with healthy individuals. Individuals with a lower bone mineral density of the tibia and a lower cross-sectional area of the tibia may not be able to adapt to the stress being transmitted through the tibia during running, which causes a pain and stress reaction of the tibia.

As MTSS is seen primarily in individuals participating in weightbearing activity, the kinematics of the lower extremity has been investigated in numerous studies. Much focus has been placed on the kinematic characteristics of the foot and ankle with respect to the amplitude of the movements. Patients with MTSS have larger movement of the midfoot and rearfoot. In relation to MTSS, the amplitude of the pronatory motion of the foot may, however, not be the only important factor. At a given range of pronation, a larger pronation velocity could result in greater stress on the muscles controlling the pronation movement or in a greater load through the tibia. If the velocity of navicular drop (ND) increases, this may indicate less decelerating efficiency of the muscles controlling foot movement and may increase the workload of the involved muscles and the mechanical forces transmitted through the tibia. As a starting point for investigating this hypothesis, the aim of this study was to evaluate ND characteristics in patients with MTSS in dynamic and static conditions. We hypothesized that dynamic measures would be more sensitive than static measures in relation to MTSS and that dynamic ND (dND) and dND velocity would be increased in patients with MTSS.

Methods

Participants

In a case-control study, 14 patients with MTSS were included from an orthopedic outpatient clinic. All of the patients were diagnosed as having MTSS within 4 weeks. The patients were diagnosed by an experienced physiotherapist and an experienced orthopedic surgeon (S.K.). The MTSS was defined as continuous or intermittent pain in the medial tibial region, exacerbated with repetitive weightbearing activity, and localized soreness along the distal two-thirds of the posteromedial tibial crest. All of the patients had experienced symptoms for at least 3 months. A control group consisted of 14 healthy participants matched regarding age, sex, typical sporting activity, and former activity level. Individuals for the control group were recruited through advertising and were composed of university staff and students. All of the participants gave their informed consent, and the study was approved by the ethics committee of Region North Jutland (Denmark).

Measurements and Instrumentation

Foot length, measured with a sliding caliper, was defined as the length between the most posterior part of the calcaneus and the tip of the longest toe. The ND test ad modum Brody was used to measure static ND. Mueller et al. reported intratester reliability of static ND of 0.78 to 0.83. Pain level during activity was measured with a standard visual analog scale. The six-component Foot Posture Index (FPI-6) was used to classify standing foot posture. The FPI-6 score is based on clinical observations consisting of five visual assessments of foot posture and a palpatory evaluation of the position of the talus. Cornwall et al. reported the intratester reliability of the FPI-6 to be greater than 0.90.

The preferred individual overground walking speed was used as the set speed for walking on the treadmill. To determine this parameter, participants walked along a 5-m runway with lightsensitive start and stop timers in both ends. Gait speed was averaged from three trials.

Three flat retroreflective markers (diameter, 12 mm) were placed on the most symptomatic foot of patients with MTSS. During marker attachment, participants were asked to stand in a relaxed position with straight knees and their weight distributed evenly on both feet. The feet were placed with the medial borders parallel and 15 cm apart. Marker 1 was placed at the center of the first metatarsal, and marker 2 was placed at the calcaneus. These markers were positioned 19 mm above the floor by using a laser alignment device (Stanley Works, New Britain, Connecticut). Marker 3 was placed on the navicular tuberosity (Fig. 1).

A video sequence analysis system was used to automatically identify the markers on the medial aspect of the foot during treadmill walking. The system consisted of a digital video camera (Basler Scout; Basler Inc, Exton, Pennsylvania); an 86-Hz, 12-mm lens; and a powerful light. The camera was placed perpendicular to the orientation of the treadmill, 2.975 mm from the center. Images were transferred to a computer via a FireWire interface (StreamPix; NorPix, Montreal, Quebec, Canada). Based on the recommendation from Matsas et al., the participants walked for a 6-min custom-
ization period on the treadmill at the established test walking speed. This was done before data collection. Recordings were taken for 20 consecutive strides, and kinematic variables were averaged. The center of the markers and their position, over time, were determined using a MatLab routine (MatLab 7.0.4; The MathWorks Inc, Natick, Massachusetts).

On the basis of two-dimensional (2-D) coordinates of the reflective markers on the medial aspect of the foot, the kinematic parameters were analyzed. The navicular height was calculated as the perpendicular distance between the center of marker 3 and the line between the center of markers 1 and 2 (x-axis). Dynamic ND was defined as the navicular height at heel strike minus the minimal height of the navicular during the stance phase. Velocity of dND was calculated as dND divided by the time from heel strike to the minimal height of the navicular during the stance phase. The ND phase is reported as the time from heel strike to the minimal navicular height during the stance phase. The ND phase and the stance phase are expressed as a percentage of the entire gait cycle. Heel strike and toe-off were manually determined from the video images of the first three steps. Subsequently, a MatLab routine applied a combination of distance and change over time criteria to automatically identify events for all of the steps in the video sequence.\(^{21}\)

In a previous study,\(^{21}\) this system proved reliable for measuring dND (intraclass correlation coefficient \([2,1]: 0.89 \text{ within day and } 0.94 \text{ between day, corresponding to coefficients of repeatability of } 1.4 \text{ and } 1.1 \text{ mm, respectively. The coefficient of repeatability is the value below which the difference between two single test results may be expected to lie in } 95\% \text{ of the patients.}

**Statistics**

Sample size calculations were conducted a priori based on dND. The minimum relevant difference was set at \(2.0 \text{ mm. The level of significance was set at } P < .05. \text{ With a statistical power of } 80\%, \text{ calculations revealed that a sample of 14 individuals in each group was required.}

Data from the FPI-6 were ordinal and were assessed with a Mann-Whitney test, and the exact 2-tailed \(P\) value is reported. All of the demographic data and the static and dynamic measures of ND were normally distributed, and an unpaired \(t\) test was applied. Pain during activity measured using a visual analog scale was nonnormally distributed, and the Spearman rank correlation was used to measure the strength of association between dynamic midfoot measures and pain level. The level of significance was set at \(P < .05. \text{ A software program (SPSS, version 15.0; SPSS Inc, Chicago, Illinois) was used for all of the statistical calculations.}

**Results**

The two groups were comparable regarding age, height, sex, weight, and foot size (Table 1). Both groups (ten females and four males in each group) consisted of 11 runners, one handball player, one soccer player, and one hiker.

The groups did not differ regarding preferred overground walking speed. No significant difference between groups could be detected in the FPI-6 score \((P > .05)\) (Table 2). Neither did the subitems in the FPI-6 reveal any statistical differences (Table 3). Static ND showed a 1.7-mm-higher value in the group with MTSS, but the difference was not significant \((P = .08)\). During treadmill walking, patients with MTSS had, on average, a 1.5-mm-larger dND \((P = .004)\) and a 2.4-mm/sec-larger dND velocity \((P = .03)\) compared with the control group (Fig. 2). Patients with MTSS had, on average, a 3% longer ND phase \((P = .045)\) and a 4.2% longer stance phase \((P = .01)\) compared with controls (Fig. 3). With the numbers available, there were no significant correlations between dND and pain during activity \((r = 0.02, P = .96)\) or between dND velocity and pain during activity \((r = 0.20, P = .50)\).

**Discussion**

The purpose of this study was to evaluate ND characteristics in patients with MTSS in dynamic...
and static conditions compared with a matched control group. The main findings in the study were that 1) no difference was observed in FPI-6 scores between patients and controls, 2) no statistically significant difference was observed between groups in static ND, and 3) patients with MTSS demonstrated larger dND and velocity of dND.

No significant differences were found in FPI-6 scores between patients with MTSS and controls. This result is in line with that of Bartosik et al., who also compared patients with MTSS and controls and found no difference in static foot posture. These findings are, however, in contrast with those of Yates and White, who used the FPI-8 to classify static foot posture and reported that patients with a pronated foot type had a significantly higher risk of MTSS.

Table 1. Characteristics of the Study Groups

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>MTSS Group (n = 14)</th>
<th>Control Group (n = 14)</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>27.8 ± 8.8</td>
<td>27.3 ± 6.2</td>
<td>.86</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>172.7 ± 10.4</td>
<td>172.9 ± 10.1</td>
<td>.84</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>77.8 ± 16.2</td>
<td>75.9 ± 16.3</td>
<td>.76</td>
</tr>
<tr>
<td>BMI</td>
<td>25.8 ± 5.1</td>
<td>25.4 ± 5.3</td>
<td>.84</td>
</tr>
<tr>
<td>VAS rest (cm)</td>
<td>0 (0–1)</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>VAS activity (cm)</td>
<td>6.5 (5–7)</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Foot length (mm)</td>
<td>251 ± 18.6</td>
<td>249 ± 18.1</td>
<td>.73</td>
</tr>
</tbody>
</table>

Abbreviations: BMI, body mass index (calculated as weight in kilograms divided by height in meters squared); CI, confidence interval; MTSS, medial tibial stress syndrome; NA, not applicable; VAS, visual analog scale.

*Both VAS rest and VAS activity are pain scores on a scale from 0 to 10 presented as median (interquartile range).

Table 2. Static and Dynamic Foot Characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>MTSS Group (n = 14)</th>
<th>Control Group (n = 14)</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preferred walking speed (km/h)</td>
<td>4.6 ± 0.7</td>
<td>4.7 ± 0.4</td>
<td>.56</td>
</tr>
<tr>
<td>FPI-6 score</td>
<td>3.5 (2–4)</td>
<td>3 (2–4)</td>
<td>1.00</td>
</tr>
<tr>
<td>Static ND (mm)</td>
<td>7.1 ± 2.8</td>
<td>5.4 ± 2.4</td>
<td>.08</td>
</tr>
<tr>
<td>Dynamic ND (mm)</td>
<td>6.5 ± 1.3</td>
<td>5.0 ± 1.2</td>
<td>.004</td>
</tr>
<tr>
<td>Velocity of dynamic ND (mm/sec)</td>
<td>14.2 ± 3.1</td>
<td>11.8 ± 2.5</td>
<td>.03</td>
</tr>
</tbody>
</table>

Abbreviations: CI, confidence interval; FPI-6, six-component Foot Posture Index; MTSS, medial tibial stress syndrome; NA, not applicable; ND, navicular drop.

*Preferred walking speed refers to overground walking.

The FPI-6 scores are presented as median (interquartile range).

Table 3. Subitems of the Six-Component Foot Posture Index

<table>
<thead>
<tr>
<th>Subitem</th>
<th>MTSS Group (n = 14)</th>
<th>Control Group (n = 14)</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Talar head palpation</td>
<td>1 (1–1)</td>
<td>1 (1–1)</td>
<td>.38</td>
</tr>
<tr>
<td>Curves above and below the malleoli</td>
<td>0 (0–1)</td>
<td>0 (0–0)</td>
<td>.77</td>
</tr>
<tr>
<td>Calcaneal inversion/eversion</td>
<td>0 (0–0)</td>
<td>0 (0–0)</td>
<td>.35</td>
</tr>
<tr>
<td>Talonavicular congruence</td>
<td>0 (0–0)</td>
<td>0 (0–0)</td>
<td>.25</td>
</tr>
<tr>
<td>Medial arch height</td>
<td>1 (0–1)</td>
<td>0.5 (0–1)</td>
<td>.38</td>
</tr>
<tr>
<td>Forefoot abduction/adduction</td>
<td>1 (1–1)</td>
<td>1 (1–1)</td>
<td>.54</td>
</tr>
</tbody>
</table>

Note: Foot Posture Index scores range from −2 to +2; scores are presented as median (interquartile range).
8. The FPI-8 includes two items that are not part of the new validated FPI-6 model. The items that were removed from the original FPI-8 were lateral border congruency and Helbing’s sign. Both items showed poor validity. It has also been noted that this study could be subject to selection bias.

In a prospective study of high school cross-country runners, Plisky et al observed no relationship between static ND and the development of MTSS. The results of the present study are in line with those findings as no significant difference was observed in static ND measurements between patients and controls.

The finding of increased dND and dND velocity may be explained by both of the MTSS theories, which were mentioned at the beginning of this article. In relation to the tibial traction theory, muscles such as the soleus and tibialis posterior have been described as the primary inverters of the subtalar joint. Bouche and Johnson conducted an in vitro study of the strain in the tibial fascia adjacent to its distal medial tibial crest insertion during contraction of the tibialis posterior, flexor digitorum longus, and soleus tendons. They found a consistent linear relationship between tension in the tendon and strain measured at the tibial fascia. However, this study was a cadaver study, and caution should be applied when relating these findings to living human patients. The results of the present study can be related to a more functional context. As patients with MTSS have increased dND and dND velocity, it could be theorized that their symptoms were related to the forces exerted by the primary inverters of the foot. The soleus and tibialis anterior muscles contract eccentrically to counteract the pronation forces, and this causes increased traction forces in the medial aspect of the tibial fascia. Although the tibial traction theory presents one possible mechanism that may underlie MTSS, the findings from the present study could also be explained by the tibial bending theory. There is a coupled kinematic relationship between the midfoot and the rearfoot and between the rearfoot and the tibia. Increased inversion of the foot may, therefore, affect the tibia. Franklyn et al showed that uninjured individuals participating in sports have tibial bones that are better adapted to axial loading, torsion, and pure bending than are the tibiae of patients with MTSS. The present results show a significantly higher velocity of dND in patients with MTSS, which may reflect increased inversion and increased load on the tibia. Patients with MTSS have a higher velocity
of dND, although their stance phase and ND phase are significantly longer. This indicates altered timing of maximal pronation, as speculated by Bartosik et al.\textsuperscript{22}

Factors such as foot length\textsuperscript{27} and static foot posture\textsuperscript{28} have been shown to influence dND. The two groups in the present study did not differ in static foot posture or in foot length. Although static measures of foot length and posture revealed no significant differences, dynamic measures were significantly different between groups. This corresponds well to the findings of Bandholm et al.,\textsuperscript{11} who demonstrated that patients with MTSS display a larger medial longitudinal arch deformation during gait. Thus, it has now been demonstrated by two different methods that the sagittal plane movement of the midfoot is increased in patients with MTSS.

Several studies\textsuperscript{29,30} have demonstrated that static measurements are not predictive of dynamic foot movement, and from a theoretical point of view, the dynamics of the pronatory movements are important factors when considering the forces transmitted through the musculoskeletal system. The present study underlines the importance of measuring dynamic foot motion and suggests that dND velocity may be a relevant measure. The two- and three-dimensional video analyses are generally accepted methods for kinematic movement analysis and may be implemented in dynamic analysis of functional foot alignment in foot and ankle research. Dynamic measures require more time and equipment than do simple static assessments, but they are probably necessary for diagnosing less obvious conditions.

Because of the retrospective design of this study, no cause-and-effect relationship can be interpreted from the results. The use of a treadmill in the collection of kinematic data may be seen as another limitation of the study, but mechanically there are no theoretical differences between overground walking and treadmill walking.\textsuperscript{20,31} Matsas et al.\textsuperscript{20} showed that knee joint kinematics obtained from treadmill walking after 6 min of customization are not significantly different from those obtained from overground walking. Jordan et al.\textsuperscript{19} examined how different velocities affected different gait variables during treadmill walking. In five of eight variables, they found U-shaped curves as a function of walking speed, where the minimum fell between 100% and 110% of the preferred walking speed. This finding indicates that the preferred walking speed is the speed where the locomotor system is most stable. Based on the results of the studies by Jordan et al.\textsuperscript{19} and Matsas et al.\textsuperscript{20} the validity of the measures was optimized by the choice of a self-selected velocity and a 6-min customization period to the treadmill. The initial goal was to examine ND during barefoot running, but during pilot testing, patients with MTSS complained of excessive pain during barefoot running.

A video sequence analysis system was used to track navicular height during the stance phase of walking. This allowed measuring movements of only the midfoot in the sagittal plane. Although the single plane measurement can distinguish patients with MTSS from controls, significant movement of the navicular also exists in the transverse plane. Cornwall and McPoil\textsuperscript{32} used an electromagnetic tracking system to measure movement of the navicular in the sagittal and transverse planes and found significant movement characteristics in the mediolateral movement of the midfoot. Nevertheless, a significant difference between groups was noted for sagittal plane movement.

The present study was powered to test only the primary hypothesis of differences in dND between groups. A study with a larger sample size is needed to draw a conclusion about group differences in static ND and correlations among dND, dND velocity, and pain level. The difference in dND between the two groups was below the minimal clinically relevant difference we used in an a priori sample size calculation but still larger than the coefficient of repeatability. This finding indicates that the difference in dND was not a result of measurement error but a true difference. A recent study\textsuperscript{27} showed that the mean dND in 280 patients was 5.3 mm. The difference of 1.5 mm found in the present study translates into approximately 30% of a normal dND. The groups with MTSS had a 30% larger ND than the healthy group. A prospective cohort study conducted by Willems et al.\textsuperscript{12} investigated whether foot kinematics was associated with risk of exercise-related lower-leg pain. They found that patients who later developed exercise-related lower-leg pain had at baseline a 25% larger maximal everted position of the calcaneus and a 16% larger maximal eversion velocity during walking. These findings indicate that even small differences in foot kinematics may increase the risk of overuse injury. Further investigation of dynamic navicular displacement involving transverse plane movements may now be warranted.

**Conclusions**

This study supports the hypothesis that dND and velocity of dND are increased in patients with
MTSS. Dynamic measures may be more sensitive than static measures in diagnosing foot dysfunction associated with MTSS, and this study demonstrates that increased velocity of dND may be important to this pathogenesis.

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Conflict of Interest: None reported.

References

29. Hunt AE, Faeby AJ, Smith RM: Static measures of calcaneal deviation and arch angle as predictors of