Flexibility of the transverse arch of the forefoot

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ABSTRACT

Purpose. To measure the percentage of the transverse arch length (%TAL) in 2 positions using a 3-dimensional motion capture system to determine the flexibility of the transverse arch of the forefoot.

Methods. 19 men and 10 women with no lower extremity injury or deformity were included. The %TAL of the left foot was measured using a digital caliper in the standing position and the lower leg maximum anterior tilting (LMAT) position. The difference in the %TAL between the 2 positions (δ%TAL) was calculated. 10 markers were mounted on skin over each metatarsal head and base of the left foot. Motion was captured using a 3-dimensional motion capture system. Coordinates of each marker were manually digitised. The percentage of the transverse arch height (%TAH) and angle between the first and fifth metatarsals (M1M5) were calculated, and differences in each forefoot parameter in the 2 positions were defined as δ%TAL, δ%TAH, δM1M5, and the forefoot flexibility magnitude (FFM) was calculated. Subjects were divided into 3 groups based on their δ%TAL: <25th percentile (hypo-flexibility group, n=7), >26th percentile to <74th percentile (control group, n=15), and >75th percentile (hyper-flexibility group, n=7). The 3 groups were compared in terms of the δ%TAL, δ%TAH, δM1M5, and FFM.

Results. The δ%TAL correlated with δM1M5 (r=0.61, p<0.001) and FFM (r=0.60, p=0.001). For the δM1M5, the hyper-flexibility group differed significantly from other groups (p=0.01). For the FFM, the hyper-flexibility group differed significantly from the hypo-flexibility group (p=0.02).

Conclusion. Measurement of the %TAL in both the standing and LMAT positions provides a simple and quantitative method of assessing the flexibility of the transverse arch of the forefoot.

Key words: forefoot, human; metatarsal bones

INTRODUCTION

Forefoot deformity (valgus hallux, metatarsalgia) can lead to chronic impairment and increased risk...
of falls, especially in the elderly. Metatarsal stress fractures may lead to dysfunction of the transverse arch of the forefoot. Dropping and splaying of the forefoot during loading play a role in decreasing mechanical stress and increasing stability. To predict the risk of injury and assess the course of recovery, it is important to assess the function and structure of the transverse arch of the forefoot.

Foot postures can be classified by the foot posture index (FPI), which shows a mild correlation between the static foot posture and dynamic foot function. Nonetheless, both static foot posture and mobility should be assessed as part of a comprehensive evaluation of the foot. The FPI can be used to assess a pronated or supinated foot but not a splay foot. Static foot alignment on radiographs accounts for about 35% of the variance in dynamic foot function.

The 3-dimensional motion capture system is a quantitative and highly reliable method to analyse foot motion. The skin impedance with skin-mounted markers is low, and when all plantar aspects contact the floor, the skin impedance is minimum. Therefore, the system may be used to assess the function of the transverse arch of the forefoot.

The percentage of the transverse arch length (%TAL) is defined as the distance from the first to the fifth metatarsal head divided by the foot length. It is correlated with the angle between the first and fifth metatarsals (M1M5). The %TAL is measured in the standing position with a load on the rearfoot, although some patients with forefoot pain may have a higher load on the forefoot. During loading, the %TAL can be used to assess the structure of the transverse arch of the forefoot but not its flexibility.

This study measured the %TAL in a standing position and a lower leg maximum anterior tilting (LMAT) position using a 3-dimensional motion capture system to determine the flexibility of the transverse arch of the forefoot.

**MATERIALS AND METHODS**

19 men and 10 women with a mean age of 22 (standard deviation [SD], 4) years, a mean weight of 60 (SD, 8) kg, and a mean height of 166 (SD, 8) cm were included. They had no lower extremity injury or deformity (flat foot, splay foot, high arch, valgus hallux). The study was approved by the ethics committee of our hospital, and informed consent was obtained from each subject.

The %TAL of the left foot was measured using a digital caliper (Fig. 1), with a measurement error of ±0.03 mm and a measurement unit of 0.1 mm. In the standing position (with feet apart in shoulder width), the load was on the heel. In the LMAT position (left foot forward and tilting anteriorly), the load was on the forefoot, and the plantar pressure on the forefoot was 70 to 80% of the body weight. Hyper-adduction/abduction of the hip and foot, and hyper-rotation of

![Figure 1](image-url) Measurements of the percentage of the transverse arch length in the (a) standing position and (b) lower leg maximum anterior tilting position.
the lower leg were restricted. Three measurements were made, and the median was used for analysis. The difference in the %TAL between the 2 positions (δ%TAL) was calculated.

10 spherical (4-mm diameter) markers were mounted on the skin of each metatarsal head and base of the left foot using double-sided adhesive tape (Fig. 2). Motion was captured using 4 video cameras sampling at 30 Hz. The ground reaction forces were recorded by a force plate sampling at 90 Hz. The plantar pressure distributions were recorded by Winpod sampling at 90 Hz. The centre of pressure data were filtered with a low path under 6Hz. The left foot in the standing position was first recorded, followed by foot motion when the whole plantar surface was in contact with the floor, and then the foot in the LMAT position. Hyper-adduction/abduction of the hip and foot, and hyper-rotation of the lower leg were restricted. Coordinates of each marker were manually digitised. Kinematic data were low-pass filtered using a fourth order Butterworth filter with cut-off frequencies of 6 Hz.

In the sagittal plane, a straight line passing through the markers of the head and base of each metatarsal was calculated from: 
\[ z = ay + b \ldots (1) \]
A line perpendicular to the metatarsal head marker with equation (1) was calculated from:
\[ z = -\frac{1}{a}y + c \ldots (2) \]
The thickness of the each metatarsal head was measured using a digital caliper, and a line which was in parallel and translated to half of the metatarsal head and the radius of markers was calculated from:
\[ z = ay + b - \left( 2 + \frac{MT}{2} \right) \ldots (3) \]
The centre of the metatarsal head was calculated...

**Figure 2** Markers are mounted on skin over each metatarsal head and base (MH and MB) of the left foot.

**Figure 3** (a) In the transverse plane, the percentage of the transverse arch height (%TAH) is defined as the distance from the centre of the second metatarsal head (MH2c) to the floor divided by the length of the centre of the first metatarsal head (MH1c) to the centre of the fifth metatarsal head (MH5c). (b) The angle between the first and fifth metatarsals is defined as the M1M5.
from equations (2) and (3). The percentage of the transverse arch height (%TAH) was defined as the distance from the centre of the second metatarsal head to the floor divided by the length of the centre of the first metatarsal head to the centre of the fifth metatarsal head. The M1M5 was also calculated (Fig. 3). The %TAH and M1M5 in the LMAT position were calculated when the centre of pressure was stable under the forefoot. The differences in each parameter (%TAH, M1M5) between the standing and LMAT positions were defined as δ%TAH and δM1M5, respectively. The Pythagorean theorem was used to calculate the forefoot flexibility magnitude (FFM). The δ%TAH represented the vertical side, and the δM1M5 represented the horizontal side of a right triangle. To calculate the FFM, the following formula was used: 

$$ FFM = \sqrt{(\delta%TAH)^2 + (\delta M1M5)^2} $$

The Pearson correlation coefficient was used to measure the correlation between δ%TAL and δ%TAH, δM1M5, and FFM, and the correlation between the %TAL in the standing position and δ%TAH, δM1M5, and FFM. A p value of <0.05 were considered statistically significant. The subjects were divided into 3 groups based on their δ%TAL: ≤25th percentile (hypo-flexibility group, n=7), >25th percentile to <74th percentile (control group, n=15), and ≥75th percentile (hyper-flexibility group, n=7). The δ%TAH and the δM1M5 in the 3 groups were assessed using one-way ANOVA, with post-hoc comparison using the Bonferroni adjustment. Differences in the FFM were assessed using the Kruskal-Wallis test, with post-hoc comparisons using the Bonferroni adjustment.

**RESULTS**

The δ%TAH and δM1M5 were normally distributed (Table 1). The δ%TAL correlated with δ%TAH, δM1M5, and FFM, and the correlation between the %TAL in the standing position and δ%TAH, δM1M5, and FFM. A p value of <0.05 were considered statistically significant. The subjects were divided into 3 groups based on their δ%TAL: ≤25th percentile (hypo-flexibility group, n=7), >25th percentile to <74th percentile (control group, n=15), and ≥75th percentile (hyper-flexibility group, n=7). The δ%TAH and the δM1M5 in the 3 groups were assessed using one-way ANOVA, with post-hoc comparison using the Bonferroni adjustment. Differences in the FFM were assessed using the Kruskal-Wallis test, with post-hoc comparisons using the Bonferroni adjustment.

**Table 1**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean±SD</th>
<th>Median (25–75%tile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>δ%TAL (%)</td>
<td>1.02±0.45</td>
<td>1.00 (0.75–1.18)</td>
</tr>
<tr>
<td>δ%TAH (%)</td>
<td>1.29±1.45</td>
<td>1.28 (0.48–1.12)</td>
</tr>
<tr>
<td>δM1M5 (degrees)</td>
<td>1.98±1.72</td>
<td>2.00 (1.00–3.01)</td>
</tr>
<tr>
<td>FMM</td>
<td>2.98±1.41</td>
<td>3.00 (1.66–4.00)</td>
</tr>
</tbody>
</table>

* δ%TAL denotes the difference in the percentage of the transverse arch length between the standing position and the lower leg maximum anterior tilting position, δ%TAH the difference in the percentage of the transverse arch height between the 2 positions, δM1M5 the difference in the angle between the first and fifth metatarsals between the 2 positions, and FMM forefoot flexibility magnitude

**Table 2**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>r</th>
<th>r²</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>%TAL and δ%TAH</td>
<td>-0.19</td>
<td>0.04</td>
<td>0.33</td>
</tr>
<tr>
<td>%TAL and δM1M5</td>
<td>-0.03</td>
<td>0.00</td>
<td>0.89</td>
</tr>
<tr>
<td>%TAL and FMM</td>
<td>0.03</td>
<td>0.00</td>
<td>0.87</td>
</tr>
<tr>
<td>δ%TAL and δ%TAH</td>
<td>0.23</td>
<td>0.07</td>
<td>0.24</td>
</tr>
<tr>
<td>δ%TAL and δM1M5</td>
<td>0.61</td>
<td>0.22</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>δ%TAL and FMM</td>
<td>0.60</td>
<td>0.36</td>
<td>0.001</td>
</tr>
<tr>
<td>δ%TAH and δM1M5</td>
<td>0.34</td>
<td>0.11</td>
<td>0.07</td>
</tr>
</tbody>
</table>

* δ%TAL denotes the percentage of the transverse arch length, δ%TAH the difference in the %TAL between the standing position and the lower leg maximum anterior tilting position, δ%TAH the difference in the percentage of the transverse arch height between the 2 positions, δM1M5 the difference in the angle between the first and fifth metatarsals between the 2 positions, and FMM forefoot flexibility magnitude

**Table 3**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Hypo-flexibility (n=7)</th>
<th>Control (n=15)</th>
<th>Hyper-flexibility (n=7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean±SD age (years)</td>
<td>22±4</td>
<td>23±4</td>
<td>21±1</td>
</tr>
<tr>
<td>No. of male/female</td>
<td>4/3</td>
<td>12/3</td>
<td>3/4</td>
</tr>
<tr>
<td>Mean±SD δ%TAL (%)</td>
<td>0.97±0.62%</td>
<td>1.05±1.70%</td>
<td>2.14±1.25%</td>
</tr>
<tr>
<td>Mean±SD δM1M5 (degrees)</td>
<td>1.19±1.94</td>
<td>1.60±1.68</td>
<td>3.50±1.00</td>
</tr>
<tr>
<td>Median (25–75%tile) FFM</td>
<td>1.68 (1.32–2.15)</td>
<td>2.98 (1.63–3.98)</td>
<td>4.39 (3.71–5.19)</td>
</tr>
</tbody>
</table>

* δ%TAL denotes the difference in the percentage of the transverse arch length between the standing position and the lower leg maximum anterior tilting position, δ%TAH the difference in the percentage of the transverse arch height between the 2 positions, δM1M5 the difference in the angle between the first and fifth metatarsals between the 2 positions, and FMM forefoot flexibility magnitude
height, weight, and δ%TAH (Table 3). For the δM1M5, the hyper-flexibility group differed significantly from other groups (p=0.01). For the FFM, the hyper-flexibility group differed significantly from the hypo-flexibility group (p=0.02).

**DISCUSSION**

Techniques to quantitatively measure the transverse arch of the forefoot include plantar pressure measurement,11–13 ultrasonography,14,15 and radiography.16,17 In plantar pressure measurement, dropping of the transverse arch of the foot is indicated by the concentration of plantar pressure on the second or third metatarsal heads. During a normal gait, the peak plantar pressure is under the second, third, and fourth metatarsal heads, and the maximum plantar pressure distribution on the forefoot varies with each step and each subject.5 Therefore, plantar pressure measurement is insufficient to assess the structure of the transverse arch of the forefoot.

Radiographs can be used to determine the M1M516 and the %TAH17; both of which reflect the structure of the transverse arch in the horizontal and transverse plane, respectively. The arch of the foot is flattened and lengthened during loading, whereas the transverse arch of the forefoot is flattened and splayed out on both sides of the second metatarsal, and the forefoot is widened by 12.5 mm when bearing weight.18 In our study, δ%TAL did not correlate with δ%TAH. The midfoot mobility magnitude has been calculated by the use of the Pythagorean theorem.19 We calculated the FFM, as it reflects changes in both the height and length of the forefoot, but it is difficult to use in the clinical setting. The %TAL is a known quantitative method and can be easily used in the clinical setting, but is associated with certain problems. First, many subjects have dropping of the transverse arch of the forefoot during loading when walking and running, although the transverse arch is maintained in the standing position. Second, the %TAL is measured in the standing position with the load on the rear foot, but some patients with forefoot pain may have a higher load on the forefoot. Therefore, the %TAL in the standing position cannot accurately assess the flexibility of the transverse arch during forefoot loading. In our study, the %TAL in the standing position did not correlate with the 3 forefoot flexibility parameters (δ%TAH, δM1M5, and FMM) measured using the 3-dimensional motion capture system. However, δ%TAL correlated with δM1M5 and FFM, indicating that δ%TAL can be used to assess the flexibility of the transverse arch of the forefoot in the clinical setting.

The flat foot deformity indicates hyper-flexibility forefeet (≥75th percentile δ%TAL). The risk of injury varies in persons with different foot types (high- vs. low-arch feet, rigid vs. flexible feet).20 Persons with diabetes mellitus have reduced segmental foot mobility, because of changes in joint stiffness and increased plantar fascia stiffness,21 which is associated with segmental foot mobility.22 Reduced segmental foot mobility is associated with a combination of increased forefoot loading and reduced frontal and transverse plane forefoot mobility, which results in increased torsional moment of the midfoot.23 In clinical practice, both hypo- and hyper-flexibility of the forefeet result in pain but are caused by different mechanisms and necessitate different types of physiotherapy. Subjects diagnosed with hyper-flexibility forefeet should undergo therapy to increase rigidity of the foot by intrinsic plantar muscles training and insertion of metatarsal pads, whereas subjects diagnosed with hypo-flexibility forefeet should undergo therapy to relax the intrinsic plantar muscles by closed kinetic trainings with forefoot loading, so as to activate the intrinsic plantar muscles with correct timing and extent during motion.

One limitation of this study was that there were individual differences among normal feet. The δ%TAL could not distinguish differences between control and hyper-flexibility or hypo-flexibility. In addition, only young healthy subjects with no foot deformity were included. Therefore, δ%TAL cannot distinguish normal from abnormal feet. In the clinical setting, it is better to compare δ%TAL before and after therapy, and between symptomatic and asymptomatic feet. Nonetheless, δ%TAL can assess the flexibility of the transverse arch of the forefoot during loading. For assessing forefoot motion during loading, δ%TAL should be used together with foot pressure distribution and radiography. Measurement of the %TAL in both the standing and LMAT positions provides a simple and quantitative method of assessing the flexibility of the transverse arch of the forefoot.

**DISCLOSURE**

No conflicts of interest were declared by the authors.
REFERENCES