Relationship between the Medial Longitudinal Arch Movement and the Pattern of Rearfoot Motion during the Stance Phase of Walking

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Abstract. The purpose of this study was firstly to investigate the pattern of the rearfoot (RF) motion, and secondly to determine any in vivo relationship between the medial longitudinal arch (MLA) movement as a measure of the windlass mechanism and the RF motion during the normal stance phase of walking. Seventeen healthy subjects between the ages of 22 and 33 years old were studied. The timing and magnitude of the RF motion and the first metatarsophalangeal (FMTP) joint extension were assessed using a six-camera Vicon motion analysis system. In addition, the MLA angle was recorded. The results indicate that the timing and magnitude of the RF motion were significantly associated with dynamic windlass function. Subjects could be divided into two groups (EARLY and LATE EVERSION ONSET) based upon the time when the RF motion began the maximum eversion during the stance phase of walking. The LATE EVERSION ONSET group had a greater magnitude of the RF eversion and the maximum MLA angle. In addition, this group had delayed onset of the FMTP joint extension.

Key words: Windlass mechanism, Medial longitudinal arch, Rearfoot motion

INTRODUCTION

Recent reports have revealed a relationship between dynamic motion of the rearfoot (RF) and static measurements of the medial longitudinal arch (MLA)1–4). The static measurement of MLA to predict dynamic RF motion could have important implications since there is evidence that excessive RF motion is associated with many foot and lower leg injuries5–7). The static measurements of MLA, however, are limited to predicting RF motion during walking. A static foot type (classified into three categories according to an arch index) measurement is not a good predictor of either RF angle at foot strike or maximum RF eversion angle during walking1). The calcaneal deviation and the MLA angle, measured by standing in asymptomatic people, are unable to predict abnormal RF motion during the stance phase of walking4).

Despite the dynamic measurement of MLA providing useful information about how the RF motion moves during walking, there has been little interest in the dynamic function of MLA. One of the first dynamic measurements of MLA was reported by Kayano8). He concluded that the dynamic change of MLA occurred under a complex relationship of body weight, bone structure, ligaments, and muscular force. More recently, a three-dimensional (3D) kinematic analysis of MLA has provided information about behavior of the arch and its mechanics during walking and running8–11). In these reports, however, there is no observation of the RF motion.

It is widely assumed that pronation and supination of the foot are important for determining the extent to which the foot will behave as a flexible or rigid body. For example, excessive pronation (indicating RF eversion) of the foot is linked to the
inability to transform itself into a more rigid structure to enable efficient and stable propulsion during walking. One factor that is thought to contribute to this transformation is the generation of tension in the plantar fascia\(^{12-14}\). The windlass mechanism, first described by Hicks\(^{15}\), has explained the raising of the MLA via tightening of the plantar fascia without direct muscular contraction, and by implication is an important factor in MLA movement and RF motion\(^{16}\). Little research, however, has been undertaken to elucidate the role of the windless mechanism during dynamic in vivo movement such as walking. Questions remain as to the relationship between the MLA movement and extension of the first metatarsophalangeal (FMTP) joint in normal individuals. In addition, there is a lack of evidence for the relationship of the windless mechanism to the pattern of RF motion during normal walking.

The purpose of this study was, therefore, firstly to investigate the pattern of the RF motion, and secondly to determine any in vivo relationship between the MLA movement as a measure of the windless mechanism and the RF motion during normal stance phase walking. We hope that information about the dynamic function of the foot may help in the treatment and design of foot orthosis for individuals with foot related injuries.

**METHODS**

**Subjects**

Seventeen healthy subjects (10 men and 7 women), between the ages of 22 and 33 years old, participated in this study. Their mean height was 166.9 cm (SD, 9.2 cm), and their mean body weight was 58.1 kg (SD, 7.4 kg). All subjects were free of clinical disorders of their foot or lower extremities that would affect their walking.

**Instrumentation**

Kinematic analysis was conducted using a six-camera Vicon 370 motion analysis system (Oxford Metrics Ltd., Oxford, UK). Each camera contained infrared light-emitting diodes with a flash rate of 60 Hz. The dynamic method of calibration was used for this study, and calibration residuals of less than 1 mm were obtained prior to data collection procedure. Ground reaction force was measured using two Kistler force platforms (type 9281A, Kistler, Japan) and was sampled at 120 Hz to determine heel contact and toe-off.

**Procedures**

Eight reflective markers (8 mm in diameter) were attached to the skin overlying the following landmarks on the left leg and foot of each subject: medial calcaneus, navicular tuberosity, head of the first metatarsal, distal phalanx of the hallux, proximal and distal aspects of the posterior calcaneus, and proximal and distal aspects of the posterior lower leg (Fig. 1).

The subject was first asked to stand on both legs in their relaxed standing position while static data of the eight reflective markers were recorded. This position was used as the reference point for all angular measurements, because previous studies indicated this to be the position about subjects’ function during walking\(^{2,17}\).

After completion of the static measurement, each

![Fig. 1. Diagram of the reflective markers positions calculated for RF angle (inversion/eversion) (A), FMTP joint extension and MLA angle (B).](image-url)
subject was asked to walk barefoot along a 6 m walkway at their natural speed and stride length. Each condition of experiments (standing and walking) consisted of at least five trials of data capture. Data from heel contact to toe off was selected and normalized to 100% of the stance phase of walking.

Data and statistical analysis

The RF angle was defined as the angle formed by the bisection line on the lower leg and calcaneus drawn from the four reflective markers previously described. The mean RF motion pattern of each subject was calculated by normalizing the data with respect to their stance phase duration (SPD) and then averaging across trials. The FMTP joint extension was defined as the angle formed by the navicular tuberosity, medial aspect of the head of the first metatarsal and distal phalanx of the hallux. The MLA angle was defined as the angle formed by the medial calcaneus, navicular tuberosity and medial aspect of the first metatarsal (Fig. 1). The following variables were calculated from analyzing the RF motion pattern data and the MLA movement for each trial:

1) SPD;
2) Maximum RF eversion (MRFE);
3) Time to maximum RF eversion (TMRFE);
4) Time to the FMTP joint extension (TFME);
5) MLA height: Length ratio (H: L ratio);
6) MLA angle;
7) Maximum MLA angle (MMLA).

Several investigations indicated that there was large between-subjects variability of the RF motion pattern during normal walking\(^{17-20}\). In this study, therefore, a cluster analysis was used to identify possible subpopulations with respect to the time of MRFE. This was done to classify into two subgroups to estimate the relationship between the time of the RF motion and all other variables with respect to the windlass mechanism and the MLA movement.

An independent t-test was used and the statistical significance level were set at \(p<0.05\) using computer application software, SPSS 11.0J (SPSS, Japan).

RESULTS

The mean TMRFE for all 17 subjects was 55.6% (SD, 15.5%) of stance phase and the mean MRFE for all subjects was 5.6° (SD, 2.7°) respectively. The result of the cluster analysis revealed that there were two subgroups based on the TMRFE. Table 1 indicates the characteristics of the two subgroups. In one group, TMRFE occurred at a mean of 41.8% (SD, 3.1%) of stance phase. This group was called the ‘EARLY EVERSION ONSET’ group (n=9). In the other group, TMRFE occurred at a mean of 71.1% (SD, 4.6%) of the stance phase. This group was called the ‘LATE EVERSION ONSET’ group (n=8). The result of the independent t-test indicated that these values were significantly different \((p<0.001)\) from each other (Fig. 2).

### Table 1. Mean and standard deviation of the characteristics of the two subgroups for the RF motion, the MLA angle and the Windlass mechanism found in this study

<table>
<thead>
<tr>
<th>Variable</th>
<th>EARLY EVERSION ONSET GROUP</th>
<th>LATE EVERSION ONSET GROUP</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Men</strong></td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td><strong>Women</strong></td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Ages (years)</td>
<td>25.3 (2.2)</td>
<td>28.1 (4.4)</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>164.7 (9.6)</td>
<td>169.4 (8.6)</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>56.8 (7.4)</td>
<td>59.5 (7.7)</td>
</tr>
<tr>
<td>TMRFE (% stance)</td>
<td>41.8 (3.1)</td>
<td>71.1 *** (4.6)</td>
</tr>
<tr>
<td>SPD (msec)</td>
<td>581.4 (86.9)</td>
<td>595.9 (84.2)</td>
</tr>
<tr>
<td>MLA Angle (deg)(^a)</td>
<td>148.2 (3.8)</td>
<td>146.0 (2.8)</td>
</tr>
<tr>
<td>MLA H:L ratio</td>
<td>0.249 (0.02)</td>
<td>0.262 (0.02)</td>
</tr>
<tr>
<td>MRFE (degree)</td>
<td>3.74 (1.1)</td>
<td>7.69 ** (2.4)</td>
</tr>
<tr>
<td>MMLA (degree)</td>
<td>4.7 (2.4)</td>
<td>7.24 * (2.0)</td>
</tr>
<tr>
<td>TFME (% stance)</td>
<td>41.2 (5.5)</td>
<td>64.3 *** (5.7)</td>
</tr>
</tbody>
</table>

\(^a\) measured at standing position.

\(*p<0.05. \ **p<0.01. \ ***p<0.001.\)
Despite no significant difference being found between the two groups with respect to the static variables of the MLA measured as the MLA angle and the MLA H: L ratio, there was a statistically significant difference between the two groups for MRFE (p<0.01), TFME (p<0.001) and MMLA (p<0.05). In addition, there was no difference in SPD between the two groups. Figure 3 shows the mean TFME for the two subgroups. The mean TFME in the LATE EVersion ONSET group was delayed by more than 23% of stance phase compared to that of the EARLY EVersion ONSET group. Figure 3 shows the mean MLA angle for the two subgroups. The mean MLA angle for the LATE EVersion ONSET group was greater than that of the EARLY EVersion ONSET group throughout the stance phase of walking.

DISCUSSION

In the present study, we found that the time and the magnitude of RF motion were significantly associated with the onset of the windlass mechanism and the MLA movement. One of the greater interests is the fact that two subgroups were found for the time of MRFE. It is assumed that there is large between-subjects variability for the timing of MRFE, which was shown in the mean values presented by Hunt et al.\(^4\) (25% stance), Reischl et al.\(^21\) (44.2% stance), Moseley et al.\(^18\) (57% stance) and Pierrynowski et al.\(^19\) (73.3% stance). These differences of MRFE time in previous studies could indicate that the result of the present study suggests the presence of two subpopulations.

The EARLY EVersion ONSET group may have more inversion of RF and supination of the foot during both the shock absorption and the propulsion phase of walking. Freychat et al.\(^22\) described that the more the foot was “closed,” the more the forefoot was medially rotated, while RF was laterally rotated. He concluded that “closed foot” behavior was associated with a rigid and inverted foot. Bojsen-Møller\(^23\) observed that, in the inverted foot, the extension of the toes occurred mainly about the second to the fifth metatarsophalangeal joint. He also described that the short lever arm between the rear extremity of the calcaneus and the oblique axis of the toe extension was called “low gear”. Because of this short lever arm, the muscular action during flexion-extension of the foot could be faster and transfer between the shock absorption and propulsion phase could occur
more quickly\textsuperscript{22}). Thus, the fact that the EARLY EVERSION ONSET group exhibited a shorter TFME may indicate the effective establishment of the windlass mechanism. In addition, the MLA is effectively shortened by the winding of the windlass mechanism, because the proximal end of the metatarsal moves dorsally and proximally during the propulsion phase\textsuperscript{24}). Therefore, the fact that this group exhibited a lesser magnitude of the MLA angle (indicating increased height of the MLA) may explain the effective function of the MLA in raising the foot.

On the other hand, the LATE EVERSION ONSET group may have a greater magnitude of their plantar fascial tension produced by the extension of the FMTP joint. The increase in the plantar fascial tension would facilitate “high-gear” push off, while the extension of the toes occurs about the first to the second metatarsophalangeal joint\textsuperscript{23}). The long lever arm between the rear extremity of the calcaneus and the transverse axis of the toe extension may increase the stance time\textsuperscript{22}). Freychat\textsuperscript{22}) described that the more the foot was “open”, the more the forefoot was laterally rotated, while the RF was medially rotated. He concluded that “open foot” behavior was associated with a flexible and everted foot. In the present study, the LATE EVERSION ONSET group had a greater magnitude of RF eversion and MMLA during the stance phase of walking. In addition, this group had delayed onset of the FMTP extension. These facts may correlate with ineffective establishment of the windlass mechanism. The excessive RF eversion may improve the flexibility of the MLA and shock absorption mechanism\textsuperscript{23}). Aquino\textsuperscript{14}) and several investigators\textsuperscript{25–27}) have theorized that the position of the subtalar joint axis can influence the pronatory moment about that joint. A more medially deviated subtalar joint axis position causes the ground reaction forces against the lateral metatarsal heads to increase the pronation moment acting upon the subtalar joint\textsuperscript{14}). The increase of the pronation moment would indicate that the ineffective windlass mechanism does not contribute to the extension of the FMTP in a timely manner. Further studies are required to elucidate whether the observed LATE EVERSION ONSET is representative of normal or abnormal motion patterns.

REFERENCES


