Relationship between total weight-bearing response of the navicular and talus bones and weight-bearing response of hindfoot valgus in normal foot arch

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Received: May 11, 2020 / Accepted: August 17, 2020

Abstract  Assessment of the total weight-bearing response of the navicular and talus bones is essential for evaluating the load absorption function. Although the weight-bearing response of the hindfoot valgus is likely related to the total weight-bearing response of the navicular and talus bones, this relationship is not well-understood. We evaluated the relationship between the total weight-bearing response of the navicular and talus bones and the weight-bearing response of the hindfoot valgus in the normal foot arch. Twenty-three males with normal foot arches were analyzed. We scanned the right foot of each participant under both non-loading and full weight-bearing conditions, using positional magnetic resonance imaging (pMRI). We measured the vertical and medial positions of the navicular and talus bones. The total positional changes of the navicular and talus bones (ΔTPCN and ΔTPCT, respectively) were calculated from the vertical and medial displacement values, using the Pythagorean theorem. To evaluate the weight-bearing response of the hindfoot valgus, the hindfoot alignment view (HAV) was measured. The difference in HAV (ΔHAV) between non-loading and full weight-bearing conditions was considered the weight-bearing response of the hindfoot valgus. Correlations between ΔTPCN, ΔTPCT, and ΔHAV were assessed using the Pearson correlation coefficient, and ΔTPCN and ΔTPCT were found to be moderately correlated with ΔHAV. Our study indicated that the total weight-bearing response of the navicular and talus bones correlated with the weight-bearing response of the hindfoot valgus in healthy adult males with normal foot arch.

Keywords: positional MRI, navicular, talus, hindfoot valgus, weight-bearing

Introduction

The human foot contains three arch structures: a medial longitudinal arch (MLA), a lateral longitudinal arch, and a transverse arch. The arch structure of the foot absorbs loads by functionally deforming in response to weight-bearing1). However, abnormal weight-bearing responses of foot arch bones can occur in the dysfunctional foot2). Therefore, an understanding of the normal weight-bearing responses of foot arch bones is essential for the clinical treatment of dysfunctional feet3).

The MLA plays an important role in absorbing the load4,5). The vertical weight-bearing responses of the navicular and talus bones serve as indicators of the load absorption function6-8). Furthermore, the medial weight-bearing responses of the navicular and talus bones should also be measured to examine the load absorption function in detail9,10). Thus, the assessment of the total weight-bearing response of the navicular and talus bones, which is the combination of the vertical and medial weight-bearing responses of the navicular and talus bones, is necessary to evaluate the load absorption function for the clinical field.

The weight-bearing response of the hindfoot valgus occurs when a load is applied from a non-loading condition11). A previous study suggested that the hindfoot and talonavicular joints are linked anatomically and functionally12). Additionally, Lundberg et al. evaluated the movement of the navicular and talus bones when the foot was moved from a neutral position to a pronated position, including the movement of the hindfoot valgus13,14). Their results showed that the movement of the hindfoot valgus affected the movement of the navicular and talus bones13,14). Therefore, the weight-bearing response of the hindfoot valgus is likely related to the total weight-bear-
ing response of the navicular and talus bones; however, this relationship has not been investigated in the normal foot arch because the direct measurement of weight-bearing responses in foot arch bones is difficult. Revealing the relationship between the total weight-bearing response of the navicular and talus bones and the weight-bearing response of the hindfoot valgus will increase our understanding of the load absorption mechanism.

Recently, positional magnetic resonance imaging (pMRI) has been developed. Using this device, we can perform scanning under physiologic loading, which allows us the direct measurements of the total weight-bearing response of the navicular and talus bones and the weight-bearing response of the hindfoot valgus, simultaneously. The purpose of our study is to clarify the relationship between the total weight-bearing response of the navicular and talus bones and the weight-bearing response of the hindfoot valgus, in the normal foot arch.

Materials and Methods

The Ethics Committee of the University of Tsukuba Physical Education Research Institutional Review Board approved this study [Task No.PE28-102]. We obtained written informed consent from all subjects before participating in this study.

Thirty-five healthy male participants took part in this study. Participants who were injury-free within the last year and had no history of lower limb surgery were recruited from the University of Tsukuba students through e-mail and information sharing. Participants with an arch ratio of less than 0.275 were excluded, to evaluate only feet with normal arches. The arch ratio was calculated as follows:

\[
\text{Arch ratio} = \frac{\text{the height of the foot dorsum from the floor (at 50% of the foot length) (DOORS)}}{\text{truncated foot length (TFL)}},
\]

where truncated foot length (TFL) represents the distance between the most posterior portion of the calcaneus and the medial joint space of the first metatarsal phalangeal joint. As a result, twelve people were excluded due to low arch ratios. Finally, twenty-three male volunteers took part in this study. All participants had no subjective symptoms that would interfere with daily life at the time of measurement.

Sample size estimation. The sample size was calculated based on a previous study. Considering a power of 0.80 and an \( \alpha \) level of 0.05, a sample size of twenty participants was found to be necessary based on the data of the previous study. To accommodate for events of study exclusion, we finally decided to recruit thirty-five participants.

MRI procedure. This study was performed using a positional MRI system (0.25 T G-scan, Esaote SpA, Genoa, Italy). The right foot of each participant was scanned in two different conditions: non-loading (NL) and full weight-bearing (FW) conditions. The applied MRI protocol included a scout [slice thickness: 10 mm, field of view: \( 280 \times 280 \text{ mm} \), scan time 39 s] and three-dimensional [echo time: 4 ms, repetition time: 8 ms, fractional anisotropy: 75, field of view: \( 350 \times 350 \times 280 \); matrix: \( 208 \times 208 \times 122 \), scan time 8 m 6 s] sequences. When scanning under NL conditions, subjects were positioned in the supine position, with their knee extended, and the talocrural joint was positioned at a 90° angle to the long axis of the tibia [Fig. 1(a)]. Under FW conditions, subjects were positioned in a two-legged stance and were instructed to stand with equally distributed pressure on the heel and the anterior plantar sole [Fig. 1(b)]. The foot was oriented vertically to the scanner bed with the participant’s feet the same width as a relaxed standing position apart.

Image analysis. A radiologist with 18 years of experience in musculoskeletal imaging performed image analysis. We used commercially available software, ITK SNAP (www.itksnap.org), for image analysis. The navicular bone height (NH), talus bone height (TH), medial navicular bone position (MNP), medial talus bone position (MTP), and hindfoot alignment view (HAV) were analyzed. We analyzed the NH, TH, MNP, and MTP as described in previous studies.

To measure the NH and TH, we used coronal images of the foot. To determine the measuring point, we chose the coronal image in which the lowest point of the navicular bone is pictured [Fig. 2(a)] and the coronal image in which the lowest point of the talus bone is pictured [Fig. 2(b)]. Using these images, the NH and TH were measured as the distance from the floor to the lowest point of the navicular bone and the talus bone, respectively [Fig. 2(a) and (b)].

To measure the MNP and MTP, we used axial images of the foot. First, to determine a baseline for the measurements of MNP and MTP, we chose an axial image in which the head of the fifth metatarsal is pictured [Fig. 3(a)] and an axial image in which the most caudal point of the calcaneus is pictured [Fig. 3(b)]. Using these two pictures, we determined the baseline for the measurements of MNP and MTP [Fig. 3(c)]. Finally, the MNP and MTP were measured as the distances between the baseline and the most medial points of the navicular bone and the talus bone, respectively [Fig. 3(d) and (e)].

To measure HAV, we used coronal images of the foot. First, to determine the distal tibial shaft axis, we chose the coronal image, in which the most central image through the distal tibial shaft is pictured. This image was identified as the one in which the tibial shaft diameter was maximal, with a sharply defined tibial cortex [Fig. 4(a)]. (With three-dimensional sequence MRI, cortex bone is imaged in black.) Using this image, we drew the
Fig. 1  (a) Images of a participant in non-loading (NL) condition, on the pMRI scanner. (b) Images of a participant in full weight-bearing (FW) condition, on the pMRI scanner.

Fig. 2  Measuring the navicular bone height (NH) and the talus bone height (TH). (a) The NH was measured as the distance from the floor to the lowest point of the navicular bone. (b) The TH was measured as the distance from the floor to the lowest point of the talus bone.
distal tibial shaft axis along the midpoints of two pairs of points on the distal tibial cortex\textsuperscript{21} [Fig. 4(a)]. Secondly, we chose the coronal image, in which the lowest point of the calcaneus is pictured [Fig. 4(b)]. Using this image, we marked the lowest point of the calcaneus bone\textsuperscript{21} [Fig. 4(b)]. Finally, we measured the distance between the distal tibial shaft axis and the lowest point of the calcaneus as the HAV\textsuperscript{21} [Fig. 4(c)]. Positive values indicate hindfoot valgus, whereas negative values indicate hindfoot varus.

To guarantee the quality of the data, we performed an additional analysis. To assess intraobserver reproducibility, the reader performed a re-analysis on a separate day at least one week apart. Then, we calculated the intraclass correlation coefficient (ICC) as ICC (1, 1).

Calculations of navicular and talus bone position changes.

Changes in the NH, TH, MNP, MTP, and HAV (ΔNH, ΔTH, ΔMNP, ΔMTP, and ΔHAV, respectively) were calculated between NL condition and FW condition (Δ = FW − NL).

Furthermore, to evaluate the combinations between the vertical and the medial weight-bearing responses of the navicular and talus bones, the total positional changes of the navicular and talus bones [ΔTPCN, and ΔTPCT, respectively, Fig. 5(a) and (b)] were calculated from the vertical and medial displacements between the NL and FW conditions.
\[ TP_{CN} = \sqrt{\Delta NH^2 + \Delta MNP^2} \]
\[ TP_{CT} = \sqrt{\Delta TH^2 + \Delta MTP^2} \]

Additionally, the total positional angle change of the navicular and talus bones [TPACN and TPACT, respectively, Fig. 5(a), and (b)] were estimated by using the following equation:

\[ TP_{ACN} = \tan^{-1} \frac{\Delta NH}{\Delta MNP} \]
\[ TP_{ACT} = \tan^{-1} \frac{\Delta TH}{\Delta MTP} \]

**Statistical analyses.** A paired Student’s t-test was performed to compare the values between the NL and FW conditions. Correlations between \( \Delta TP_{CN} \), \( \Delta TP_{CT} \), TPACN, TPACT, and \( \Delta HAV \) were assessed using the...
Pearson correlation coefficient across all subjects. Besides, correlations between body weight, body mass index (BMI), arch ratio, ΔTPCN, ΔTPCT, TPACN, TPACT, and ΔHAV were also assessed using the Pearson correlation coefficient across all subjects. For all analyses, a two-tailed P-value of < 0.05 was determined to be significant. Magnitudes of correlations were interpreted qualitatively, using the Evans guidelines: r = 0.00–0.19: very weak; 0.20–0.39: weak; 0.40–0.59: moderate; 0.60–0.79: strong; and 0.80–1.0: very strong. Statistical analyses were conducted using SPSS software, version 25.0, for Windows (IBM SPSS Japan Inc., Japan).

**Results**

Table 1 shows the characteristics of the participants, and Table 2 shows the results of reproducibility analyses. Intraobserver reliability was substantial for all measured items, with ICC values all over 0.80

Table 3 shows the measured NH, TH, MNP, MTP, and HAV values for the NL and FW conditions. The NH and TH values in the FW condition were significantly smaller than those in the NL condition. The MNP, MTP, and HAV values in the FW condition were significantly larger than those in the NL condition.

Table 4 shows the calculated results for ΔNH, ΔTH, ΔMNP, ΔMTP, ΔHAV, ΔTPCN, ΔTPCT, TPACN, and TPACT.

Table 5 shows the correlations between ΔTPCN, ΔTPCT, TPACN, TPACT, and ΔHAV. ΔTPCN and ΔTPCT were moderately correlated with ΔHAV (r = 0.58, P < 0.01 and r = 0.56, P < 0.01, respectively). TPACN and TPACT were not significantly correlated with ΔHAV (r = −0.03, P = 0.90 and r = 0.16, P = 0.47, respectively).

Table 6 shows the correlations between body weight, BMI, arch ratio, ΔTPCN, ΔTPCT, TPACN, TPACT, and ΔHAV. No significant correlations were observed.

**Discussion**

To the best of our knowledge, our study is the first study to directly investigate the relationship between the total weight-bearing response of the navicular and talus bones (ΔTPCN, ΔTPCT, TPACN, and TPACT) and the weight-bearing response of the hindfoot valgus (ΔHAV). The most important finding of our study is that ΔTPCN and ΔTPCT correlate with ΔHAV. Our results showed that ΔTPCN and ΔTPCT were correlated with ΔHAV. A previous study reported that when a load was applied from a NL condition, the rotation of the talonavicular joint around the subtalar joint axis occurred simultaneously with the weight-bearing response of the hindfoot valgus, which may explain why ΔTPCN and ΔTPCT correlate with ΔHAV. However, considering the moderate correlation, the potential importance of other unmeasured factors should be kept in mind. Previous studies suggested that the weight-bearing response of the 2nd–5th metatarsal bones, such as the abduction and anterior translation of the 2nd–5th metatarsal bones, could affect the weight-bearing response of the navicular and talus bones and the weight-bearing response of the hindfoot valgus. Therefore, we believe that the weight-bearing response of the 2nd–5th metatarsal bones may also affect ΔTPCN and ΔTPCT. A method for measuring the weight-bearing response of the 2nd–5th metatarsal bones based on MRI images should be established in future studies.

Our results indicated that TPACN and TPACT did not correlate with ΔHAV. A previous study reported that when the load was applied, the navicular and talus bones slid down the subtalar articular surfaces as a rigid unit. Additionally, the subtalar joint axis orientation, especially in the medial-lateral direction, is widely known to have...
Table 1. Subject characteristics (n = 23).

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>24.30 ± 2.54</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>172.75 ± 5.85</td>
</tr>
<tr>
<td>Body weight (kg)</td>
<td>69.00 ± 5.94</td>
</tr>
<tr>
<td>BMI</td>
<td>23.11 ± 1.54</td>
</tr>
<tr>
<td>Foot length (mm)</td>
<td>259.23 ± 12.32</td>
</tr>
<tr>
<td>Foot width (mm)</td>
<td>98.96 ± 6.27</td>
</tr>
<tr>
<td>Arch ratio</td>
<td>0.31 ± 0.02</td>
</tr>
</tbody>
</table>

Body mass index = BMI

Table 2. Reproducibility data for measurements of the navicular bone height, talus bone height, medial navicular bone position, medial talus bone position, and hindfoot alignment view, in non-loading (NL) and full weight-bearing (FW) conditions. Intraclass correlation coefficient values are provided, with 95% confidence intervals (CI) in parentheses.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Non-loading (NL)</th>
<th>Full weight-bearing (FW)</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Navicular bone height (NH) (mm)</td>
<td>43.90 ± 6.73</td>
<td>31.05 ± 5.12</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Talus bone height (TH) (mm)</td>
<td>53.23 ± 5.08</td>
<td>43.10 ± 3.71</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Medial navicular bone position (MNP) (mm)</td>
<td>50.44 ± 3.60</td>
<td>56.29 ± 3.85</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Medial talus bone position (MTP) (mm)</td>
<td>39.13 ± 4.92</td>
<td>47.79 ± 4.95</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Hindfoot alignment view (HAV) (mm)</td>
<td>−1.81 ± 7.09</td>
<td>7.73 ± 6.63</td>
<td>&lt; 0.01</td>
</tr>
</tbody>
</table>

Data are expressed as mean ± SD.

Table 3. The position of the foot arch bones in non-loading (NL) and full weight-bearing (FW) conditions (n = 23).

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Non-loading (NL)</th>
<th>Full weight-bearing (FW)</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Navicular bone height (NH) (mm)</td>
<td>43.90 ± 6.73</td>
<td>31.05 ± 5.12</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Talus bone height (TH) (mm)</td>
<td>53.23 ± 5.08</td>
<td>43.10 ± 3.71</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Medial navicular bone position (MNP) (mm)</td>
<td>50.44 ± 3.60</td>
<td>56.29 ± 3.85</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Medial talus bone position (MTP) (mm)</td>
<td>39.13 ± 4.92</td>
<td>47.79 ± 4.95</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Hindfoot alignment view (HAV) (mm)</td>
<td>−1.81 ± 7.09</td>
<td>7.73 ± 6.63</td>
<td>&lt; 0.01</td>
</tr>
</tbody>
</table>

Table 4. Calculation results for ΔNH, ΔTH, ΔMNP, ΔMTP, ΔHAV, ΔTPCN, ΔTPCT, TPACN, and TPACT (n = 23).

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔNH (mm)</td>
<td>−12.85 ± 4.06</td>
</tr>
<tr>
<td>ΔTH (mm)</td>
<td>−10.14 ± 2.76</td>
</tr>
<tr>
<td>ΔMNP (mm)</td>
<td>5.85 ± 2.44</td>
</tr>
<tr>
<td>ΔMTP (mm)</td>
<td>8.66 ± 3.51</td>
</tr>
<tr>
<td>ΔHAV (mm)</td>
<td>9.55 ± 5.70</td>
</tr>
<tr>
<td>ΔTPCN (mm)</td>
<td>14.31 ± 4.12</td>
</tr>
<tr>
<td>ΔTPCT (mm)</td>
<td>13.54 ± 3.80</td>
</tr>
<tr>
<td>TPACN (°)</td>
<td>25.64 ± 11.62</td>
</tr>
<tr>
<td>TPACT (°)</td>
<td>39.90 ± 10.73</td>
</tr>
</tbody>
</table>

ΔNH, change in the navicular bone height between non-loading and full weight-bearing conditions
ΔTH = change in the talus bone height between non-loading and full weight-bearing condition
ΔMNP = change in the medial navicular bone position between non-loading and full weight-bearing conditions
ΔMTP = change in the medial talus bone position between non-loading and full weight-bearing conditions
ΔHAV = change in the hindfoot alignment view between non-loading and full weight-bearing conditions
ΔTPCN = total positional change of the navicular bone
ΔTPCT = total positional change of the talus bone
TPACN = total positional angle change of the navicular bone
TPACT = total positional angle change of the talus bone
relationship between the total weight-bearing response of the navicular and talus bones and the weight-bearing response of the hindfoot valgus in healthy adult males with a normal foot arch in a sufficiently-sized sample. Our study revealed that ΔTPCN and ΔTPCT correlated with the weight-bearing response of the hindfoot valgus in healthy adult males with normal foot arch. Therefore, it may be possible to manage the deteriorated displacement of the navicular and talus bones in the dysfunctional foot by controlling the weight-bearing response of the hindfoot valgus, using insoles. Thus, our findings provide useful knowledge for the clinical field. However, it should be noted that the present study examined the relationship between the total weight-bearing response of the navicular and talus bones and the weight-bearing response of the hindfoot valgus exclusively in healthy adult males with a normal foot arch. Age, gender, and foot function could affect the weight-bearing response of the foot arch bones. Therefore, the effect of these factors on this relationship should be examined in future studies.

Individual differences in the subtalar joint axis orientation among individuals, especially in the medial-lateral direction, may affect TPACN and TPACT, which may be why TPACN and TPACT did not correlate with ΔHAV. Furthermore, a previous study reported that the medial deviation of the subtalar joint axis orientation is likely related to the functional decline of the foot. Therefore, clarifying the relationship between TPACN, TPACT, and the subtalar joint axis could provide useful knowledge for the clinical treatment of dysfunctional feet. However, a method for measuring the subtalar joint axis based on MRI images is yet to be established.

Previous studies have reported that body weight, BMI, and foot morphology affect the weight-bearing response of foot arch bones. Nevertheless, our results indicated that body weight, BMI, and arch ratio exhibited no association with the weight-bearing response of foot arch bones. Our results could be caused by the characteristics of the participants who were only healthy adult males with a normal foot arch. We believe this is why body weight, BMI, and arch ratio were not associated with the weight-bearing response of the foot arch bones.

Previous clinical studies have reported that the displacement of the navicular and talus bones deteriorates in the dysfunctional foot. In our study, we examined the relationship between the total weight-bearing response of the navicular and talus bones and the weight-bearing response of the hindfoot valgus exclusively in healthy adult males with a normal foot arch. Age, gender, and foot function could affect the weight-bearing response of the foot arch bones. Therefore, the effect of these factors on this relationship should be examined in future studies.

**Additional analyses.** Moreover, the understanding of the relationship between the total weight-bearing response of the MLA bones other than navicular and talus bones and the weight-bearing response of the hindfoot valgus will increase our understanding of the load absorption mecha-

### Table 5. Correlations between ΔHAV and ΔTPCN, ΔTPCT, TPACT, and TPACN.

<table>
<thead>
<tr>
<th></th>
<th>ΔHAV</th>
</tr>
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<tbody>
<tr>
<td>ΔTPCN</td>
<td>0.58**</td>
</tr>
<tr>
<td>ΔTPCT</td>
<td>0.56**</td>
</tr>
<tr>
<td>TPACN</td>
<td>−0.03</td>
</tr>
<tr>
<td>TPACT</td>
<td>0.16</td>
</tr>
</tbody>
</table>

ΔHAV = change in the hindfoot alignment view between the non-loading and full weight-bearing conditions
ΔTPCN = total positional change of the navicular bone
ΔTPCT = total positional change of the talus bone
TPACN = total positional angle change of the navicular bone
TPACT = total positional angle change of the talus bone
**P < 0.01

### Table 6. Correlations between body weight, body mass index (BMI), arch ratio, ΔTPCN, ΔTPCT, TPACN, TPACT, and ΔHAV.

<table>
<thead>
<tr>
<th></th>
<th>Weight</th>
<th>BMI</th>
<th>Arch ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>r</td>
<td>P-value</td>
<td>r</td>
</tr>
<tr>
<td>ΔTPCN</td>
<td>0.15</td>
<td>0.50</td>
<td>−0.07</td>
</tr>
<tr>
<td>ΔTPCT</td>
<td>0.17</td>
<td>0.44</td>
<td>−0.02</td>
</tr>
<tr>
<td>TPACN</td>
<td>−0.18</td>
<td>0.42</td>
<td>−0.29</td>
</tr>
<tr>
<td>TPACT</td>
<td>−0.23</td>
<td>0.30</td>
<td>−0.31</td>
</tr>
<tr>
<td>ΔHAV</td>
<td>−0.03</td>
<td>0.89</td>
<td>−0.27</td>
</tr>
</tbody>
</table>

ΔTPCN = total positional change of the navicular bone
ΔTPCT = total positional change of the talus bone
TPACN = total positional angle change of the navicular bone
TPACT = total positional angle change of the talus bone
ΔHAV = change in the hindfoot alignment view (HAV) between the non-loading and full weight-bearing conditions
nism. Therefore, we performed additional analyses to investigate the relationship between the total weight-bearing response of the medial cuneiform and base of the first metatarsal bones and the weight-bearing response of the hindfoot valgus. The methods and results of the additional analyses are shown in the Supplemental Data section.

Our results indicated that ΔTPCM and ΔTPC1 were significantly correlated with ΔHAV. Previous results suggested that the MLA flattens as a whole, which may explain why ΔTPCM and ΔTPC1 also correlate with ΔHAV11,34. Thus, our results suggested that the total weight-bearing response of the entirety of the MLA and the weight-bearing response of the hindfoot valgus could functionally link to absorb the load.

**Limitations.** Our study had some limitations. We analyzed the intraobserver reproducibility; however, we did not investigate interobserver or between-day reproducibility. Nonetheless, previous studies have demonstrated that the analysis methods used in our study are robust20-22). Therefore, we believe that our method is secure.

Because of MRI characteristics, we could not measure the plantar pressure during MRI scanning. Therefore, we could not quantitatively confirm whether the participants could stand with equally distributed pressure on the heel and the anterior plantar sole. However, we checked the loading conditions before we performed MRI scanning. There were no artifacts in MRI images caused by motion. Therefore, we believe that the participants followed our instructions.

In this study, we used HAV as an index of hindfoot valgus35,36. This method evaluates the mechanical axis of the hindfoot to the tibia. A previous study reported that our method is robust35,36. In addition, we instructed the participants to orient their foot vertically to the scanner bed with their feet the same width as a relaxed standing position apart during scanning on both NL and FW conditions. Therefore, we believe that our method is suitable for evaluating the weight-bearing response of the hindfoot valgus. Whereas, the medial tilt and internal rotation of the tibia may also affect our results. We should examine the effect of these factors on the weight-bearing response of the hindfoot valgus in future studies.

**Conclusion**

The present study indicated that the total weight-bearing response of the navicular and talus bones correlates with the weight-bearing response of the hindfoot valgus in healthy adult males with normal foot arch.

**Acknowledgments**

This work was partially supported by JSPS KAKENHI [Grant Number 19H05730].

**Conflict of Interests**

The authors declare no conflicts of interest associated with this work.

**Author Contributions**

Experiment conception and design: MM and HS. Experiment implementation: MM and YO. Data analysis: MM and YO. Paper composition: MM. Analyzing and writing advisory: MM, AY, and HS. All authors approved the final version of the manuscript.

**Supporting Information**

Supplemental Data

**References**


