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Foot pronation during walking is associated to the mechanical resistance of the midfoot joint complex

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ABSTRACT

Background: The demonstration of the relationship between midfoot passive mechanical resistance and foot pronation during gait may guide the development of assessment and intervention methods to modify foot motion during gait and to alter midfoot passive mechanical resistance.
Research question: Is foot pronation during the stance phase of gait related to the midfoot passive mechanical resistance to inversion?
Methods: The resistance torque and stiffness provided by midfoot soft tissues of 33 participants (21 females and 12 males) with average of 26.21 years were measured. In addition, the participants' forefoot and rearfoot kinematic data during the stance phase of gait were collected with the Qualisys System (Oqus 7+). Correlation Coefficients were calculated to test the association between kinematic variables representing pronation (forefoot-rearfoot inversion, forefoot-rearfoot dorsiflexion and rearfoot-shank eversion) and maximum resistance torque and maximum stiffness of the midfoot with $\alpha = 0.05$.
Results: Reduced maximum midfoot resistance torque was moderately associated with increased forefoot-rearfoot inversion peak ($p = 0.029$; $r = 0.38$), with forefoot-rearfoot dorsiflexion peak ($p = 0.048$; $r = -0.35$) and with rearfoot-shank eversion peak ($p = 0.008$; $r = -0.45$). Maximum midfoot stiffness was not associated to foot pronation.
Significance: The smaller the midfoot resistance torque, the greater the forefoot-rearfoot inversion and dorsiflexion peaks and the rearfoot-shank eversion peak during gait. The findings suggest the existence of a relationship between foot pronation and midfoot passive mechanical resistance. Thus, changes in midfoot passive mechanical resistance may affect foot pronation during gait.

1. Introduction

Foot pronation is characterized by simultaneous calcaneus eversion, talus adduction and plantarflexion, and forefoot inversion and dorsiflexion during closed kinematic tasks [1–3]. Passive mechanical resistance of the midfoot soft tissues may influence foot pronation during gait [4,5]. Midfoot soft tissues include ligaments, plantar aponeurosis, intrinsic muscles and intrinsic and extrinsic tendons [4,6,7]. During the early stance phase of gait, calcaneus eversion stretches midfoot soft tissues, while the metatarsal heads are in contact with the ground [4,5]. The mechanical resistance provided by these tissues may influence the magnitude of foot pronation. Thus, reduced mechanical resistance provided by the midfoot soft tissues may allow increased magnitudes of foot pronation. Similarly, increased foot pronation may also influence the mechanical resistance of the midfoot soft tissues in the long-term, due to tissue adaptation [8,9]. More specifically, increased foot pronation due to other factors may progressively reduce the resistance offered by the midfoot tissues as a result of repetitive stretching.

This study investigated the relationship between calcaneus (rearfoot) eversion and forefoot inversion and dorsiflexion, during the stance phase of gait, and the passive torque of resistance and passive stiffness provided by the tissues of the midfoot joint complex. We hypothesized

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that rearfoot eversion, forefoot inversion and dorsiflexion would be associated with reduced midfoot torque of resistance and stiffness. The findings of this study may guide the development of assessment and intervention methods to modify foot segments motion during gait and to alter midfoot mechanical resistance.

2. Methods

2.1. Participants

Thirty-three adults (21 females and 12 males) with average age, mass and height of 26.2 years (SD 5.3), 63.2 kg (SD 9.8) and 169 cm (SD 8.3), respectively, participated in this study. The inclusion criteria were age between 19 and 44 years old (to avoid aging influence), no neurological or orthopedic diseases, no history of lower limbs or back surgery and no use of foot orthoses during the last year. The exclusion criteria were the report of any discomfort or pain during data collection. Each participant signed a consent form approved by the university's Ethical Research Committee (CAAE: 78785717.7.0000.5149)

2.2. Procedures

The passive mechanical resistance to forefoot inversion provided by the tissues of the midfoot joint complex was measured using the Torsimeter instrument (Fig. 1) (patent deposit BR1020180152688). The Torsimeter had a potentiometer and a torque meter that measured the forefoot angle in the frontal plane and the midfoot resistance torque to inversion, respectively. To measure the midfoot resistance to inversion, the participant sat on a chair, with the left shank, rearfoot and forefoot attached to the Torsimeter and the potentiometer axis aligned to the foot second ray. Due to the laboratory set-up, only the left foot was evaluated. The hip was in neutral position in the transverse and frontal planes, the thigh was parallel to the ground and the shank had 45° degrees of inclination relatively to the ground (Fig. 1). The examiner asked the participant to maintain the leg and foot completely relaxed during data collection. The forefoot was passively positioned in 20° of eversion and then passively inverted by the examiner up to 50° of inversion. This measurement was performed at an angular velocity of approximately 2°/s. This was accomplished by accepting only trials in which the average velocity was between 1.8°/s and 2.2°/s. The real time velocity was constantly displayed on the computer screen, which allowed the examiner to maintain the predetermined angular velocity. Three trials were performed for viscoelastic accommodation of the soft tissues and, then, three valid trials were performed. The torque time-series were also displayed in real time and the trial was interrupted and discarded if any irregularity on the torque/angle time-series was visually perceived. This measure were recorded at 100 Hz, using the software LabVIEW® 2012.

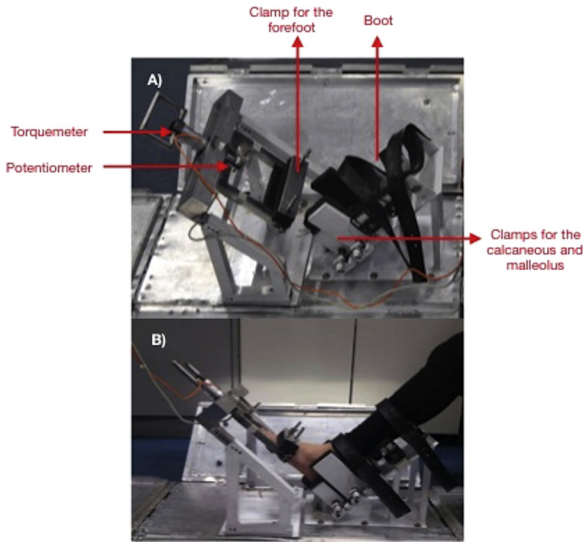

Fig. 1. Torsimeter. (A) Parts of the equipment. (B) Positioning of the participant.

For the gait analysis, data were recorded at 100 Hz using a 11-camera motion capture system (Oqus 7+, Qualisys, Sweden), and 1 force platform (Custom BP model, AMTI, Massachusetts, USA), at a frequency of 1000 Hz, which was downsampled to 100 Hz. Passive anatomical and tracking markers were placed at the participant left shank and foot – we used a multisegmented foot model [10,11]. A static data collection was performed with the participant in orthostatic position, which was later used to define the segments' coordinate systems. Then, each participant walked at self-selected speed for at least 5 trials with proper foot contact with the force plate.

2.3. Data reduction

The torque-angle data obtained with the Torsimeter were filtered with a Chebyshev 3rd order, low-pass filter with a 4 Hz cutoff frequency. Next, an analysis to identify large irregularities in each torque-angle time-series, which might indicate the presence of voluntary resistance to motion, was carried out, and time-series with large irregularities were excluded. From 99 time-series, three from each participant, 16 were excluded. The following variables were extracted from the torque-angle time-series: maximum midfoot resistance torque; and maximum midfoot stiffness (rate of the resistance torque change). For detailed information about the irregularity analysis, the calculation of maximum midfoot stiffness, and reliability of the torque and stiffness measures, see the Supplementary material. All the procedures were performed in the Matlab® Software (R2017a). The average values were considered for statistical analyses.

The forefoot and rearfoot angles during the stance phase of gait were computed in the Visual 3D software (C-Motion Inc, Rockville, USA). The linear displacements of the tracking markers and the force data were filtered with a Butterworth 4th order low-pass filter with 6 Hz and 25 Hz cutoff frequencies, respectively. Heel contact and toe-off were determined automatically using the vertical ground reaction force and a threshold of 20 N. The following joint rotation data were computed: (1) forefoot-rearfoot dorsiflexion-plantarflexion; (2) forefoot-rearfoot inversion-eversion; and (3) rearfoot-shank inversion-eversion. Positive values represent forefoot eversion and dorsiflexion and rearfoot eversion. Kinematic data were calculated based on the following Cardan sequence: flexion/extension, inversion/eversion and adduction/abduction. Data were normalized to 101 points, one for each percentage of the stance phase of gait. Average values of at least five trials were considered for analysis. The following variables, representing different components of foot pronation, were extracted: (1) forefoot-rearfoot inversion peak, (2) forefoot-rearfoot dorsiflexion peak and (3) rearfoot-shank eversion peak.

2.4. Data analysis

Data were tested for normal distribution using the Shapiro-Wilk test. Only the maximum midfoot resistance torque was not normally distributed. Therefore, Spearman Correlation Coefficients tested the association between maximum midfoot resistance torque and foot kinematics and Pearson Correlation Coefficients tested the association of foot kinematics and maximum midfoot stiffness, considering $\alpha = 0.05$. All the analyses were carried out with SPSS 24 (SPSS Inc, Chicago, USA).

3. Results

Means and standard deviations for midfoot maximum resistance torque and maximum stiffness were 4.58 Nm (SD 1.67) and 0.22 Nm/°

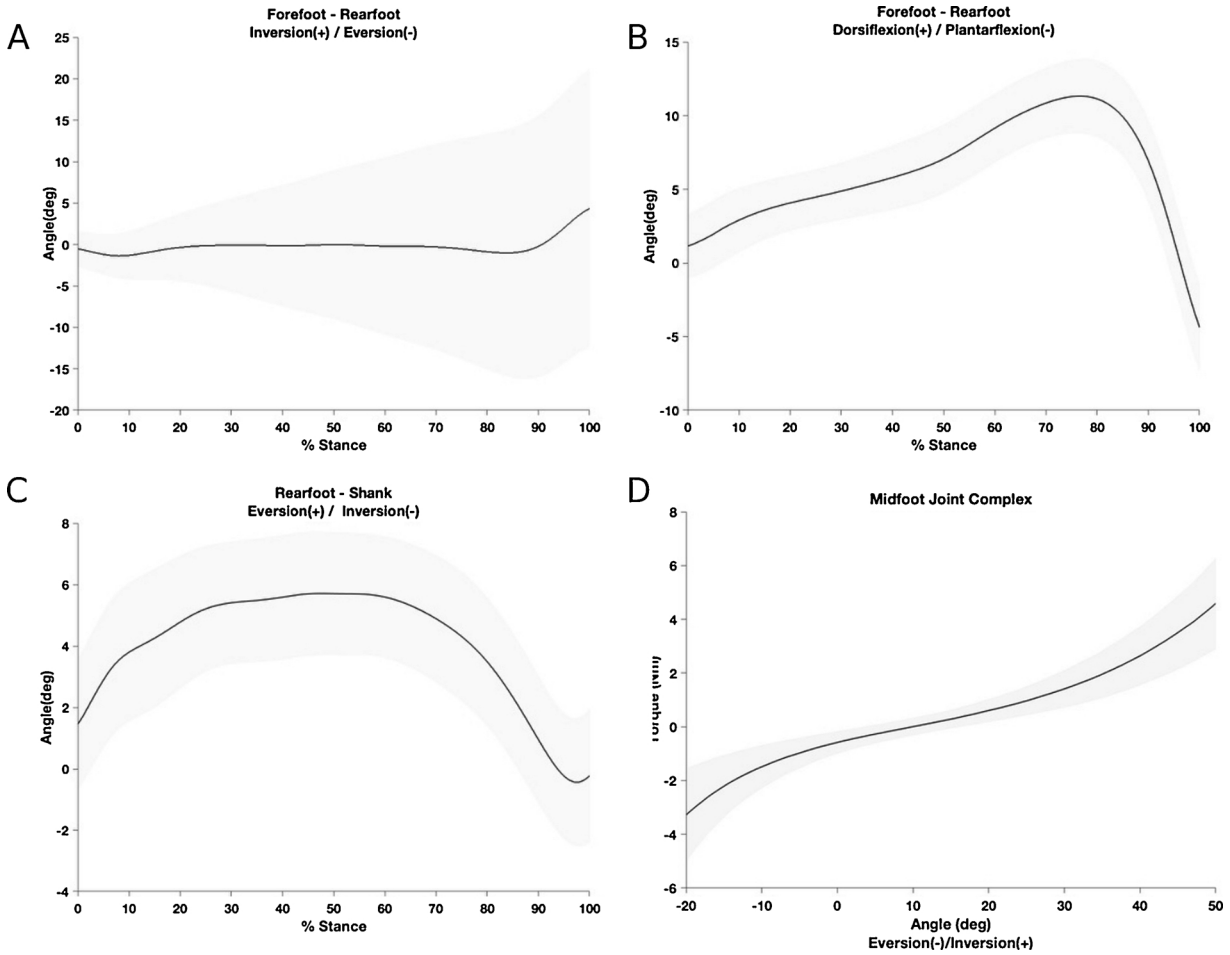

Fig. 2. Foot segments mean and standard deviation angles during the stance phase of gait: A) Forefoot-rearfoot eversion/inversion; B) Forefoot-rearfoot dorsiflexion/plantarflexion; C) and rearfoot-shank eversion/inversion. D) Mean and standard deviation midfoot torque-angle time-series.

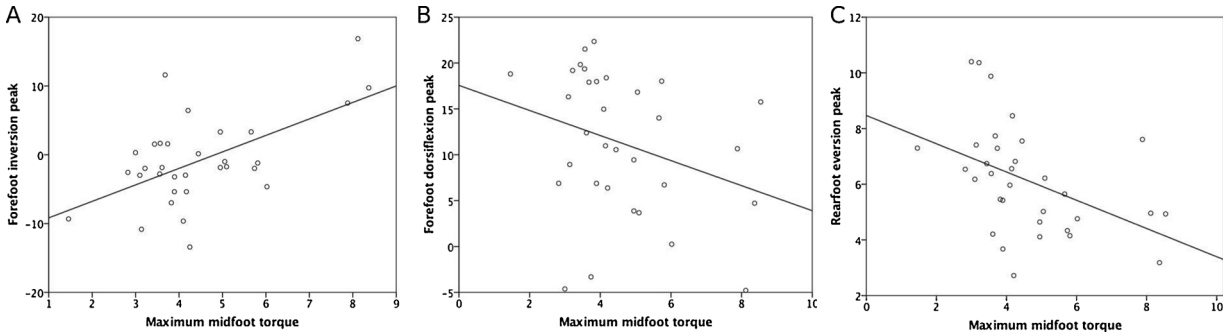

Fig. 3. Scatter plots of the pair of variables that demonstrated significant correlations. A) Forefoot inversion peak/Maximum midfoot torque; B) Forefoot dorsiflexion peak/Maximum midfoot torque; C) Rearfoot eversion peak/Maximum midfoot torque.

(SD 0.07), respectively. The participants demonstrated mean forefoot-rearfoot inversion and dorsiflexion peaks of −2.0° (SD 1.9) and 11.5° (SD 2.5), respectively, and mean rearfoot eversion peak of 6.1° (SD 1.9) during the stance phase of gait. Fig. 2 shows the mean forefoot and rearfoot angles during the stance phase of gait and the mean midfoot torque-angle time-series. Reduced maximum midfoot resistance torque was associated with increased forefoot-rearfoot inversion peak ($r = 0.38$; $p = 0.029$) and with increased forefoot-rearfoot dorsiflexion peak ($r = -0.35$; $p = 0.048$). In addition, reduced maximum midfoot resistance torque was associated with increased rearfoot eversion peak ($r = -0.45$; $p = 0.008$). Fig. 3 shows the scatter plots for each pair of variables that demonstrated significant correlations. Maximum midfoot stiffness was not associated to forefoot-rearfoot inversion ($r = 0.34$; $p = 0.052$) and dorsiflexion peaks ($r = -0.33$; $p = 0.059$) and to rearfoot eversion peak ($r = -0.29$; $p = 0.093$).

4. Discussion

Increased forefoot-rearfoot inversion and dorsiflexion and rearfoot eversion angles were associated to reduced midfoot passive resistance torque. These findings are in accordance with the assumption that the passive mechanical resistance offered by the midfoot soft tissues may help controlling foot pronation during gait [12]. Conversely, the results could also indicate that repetitive foot pronation could decrease the passive mechanical resistance of midfoot tissues in the long-term, due to tissue adaptation. Future studies are necessary to resolve this dispute

and to investigate if increased mechanical resistance of the midfoot is related to increased foot and ankle internal moments during gait [1,13,14].

The equipment (i.e. Torsimeter) used to measure midfoot passive mechanical resistance is portable and low-weight (10.5 kg) and may be easily adaptable for clinical settings. The information provided by this equipment may help guiding assessment and/or intervention approaches to individuals with increased foot pronation. Despite the lack of association between midfoot stiffness and foot pronation, which may have been influenced by the reduced statistical power, it can be argued that individuals with excessive foot pronation during gait may have reduced midfoot passive mechanical resistance.

Conflict of interest

None.

CRediT authorship contribution statement

Raphael B.O. Gomes: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing - original draft. **Thales R. Souza:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Supervision, Validation, Visualization, Writing - review & editing. **Bruno D.C. Paes:** Data curation, Methodology, Validation, Visualization, Writing - review & editing. **Fabrício A. Magalhães:** Conceptualization, Data curation, Funding acquisition, Methodology, Resources, Software, Validation, Visualization, Writing - review & editing. **Bruna A. Gontijo:** Data curation, Methodology, Validation, Visualization, Writing - review & editing. **Sérgio T. Fonseca:** Conceptualization, Funding acquisition, Investigation, Methodology, Resources, Writing - review & editing. **Juliana M. Ocarino:** Funding acquisition, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing - review & editing. **Renan A. Resende:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing.

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Raphael B.O. Gomes: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing - original draft. **Thales R. Souza:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Supervision, Validation, Visualization, Writing - review & editing. **Bruno D.C. Paes:** Data curation, Methodology, Validation, Visualization, Writing - review & editing. **Fabrício A. Magalhaes:** Conceptualization, Data curation, Funding acquisition, Methodology, Resources, Software, Validation, Visualization, Writing - review & editing. **Bruna A. Gontijo:** Data curation, Methodology, Validation, Visualization, Writing - review & editing. **Sérgio T. Fonseca:** Conceptualization, Funding acquisition, Investigation, Methodology, Resources, Writing - review & editing. **Juliana M. Ocarino:** Funding acquisition, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing - review & editing. **Renan A. Resende:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.gaitpost.2019.01.027.

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