Gait & Posture 72 (2019) 228–233

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Full length article

Effects of an ankle brace on the in vivo kinematics of patients with chronic ankle instability during walking on an inversion platform

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ARTICLE INFO

Keywords:
Ankle brace
Chronic ankle instability
Kinematics
Tibiotalar joint
Subtalar joint

ABSTRACT

Background: As in vivo tibiotalar and subtalar joint kinematics are not currently known following the application of an ankle brace, an investigation of these kinematics may provide insight into the mechanisms of ankle braces.
Research question: This study aimed to determine the effect of an ankle brace on in vivo kinematics of patients with chronic ankle instability.
Methods: Eleven patients with chronic ankle instability were recruited in this study. A dual fluoroscopic imaging system and a solid modeling software were utilized to calculate the joint positions of the participants as they walked barefooted on a level platform, walked barefooted on a 15° inversion platform, and walked with an ankle brace on a 15° inversion platform. The joint positions during the three walking conditions were compared.
Results: Tibiotalar joints were more inverted (pose 2, p = .004), and subtalar joints were more anteriorly translated (pose 2–6, p = .003), more plantarflexed (pose 2, p = .008; pose 3, p = .013; pose 5, p = .008; pose 6, p = .016) and more inverted (pose 1–5, p = .003; pose 6, p = .013) during barefooted walking on the inversion platform than during walking on the level platform. The inversion of subtalar joints was decreased after the brace application (pose 2–4, p = .003; pose 5, p = .004; pose 7, p = .016).
Significance: Brace application reduced the increased subtalar inversion induced by the inversion platform. Nevertheless, increased subtalar anterior translation and plantarflexion persisted after brace application. The ankle brace might be beneficial for clinical populations with increased subtalar inversion.

1. Introduction

More than one fifth of patients with lateral ankle sprain develop residual symptoms, such as pain, swelling, recurrent ankle sprains, giving way, and feeling of instability; these symptoms are collectively known as chronic ankle instability (CAI) [1]. Brace application can effectively prevent recurrent ankle sprains in patients with CAI [2], and exerts a pronounced effect on dynamic balance of patients with CAI without hindering objective sports performance [3,4].

The mechanism underlying the ability of ankle braces to prevent recurrent ankle sprains and promote balance remains unknown. Considerable efforts have been exerted to study the mechanisms of ankle bracing [5]. Ankle braces decrease muscle activity during dynamic activities [5–7] without affecting peripheral motor neuron excitability and proprioception [8,9]. The passive stiffness of ankle braces might be an important protective factor limiting inversion at ankle and subtalar joints [10–13].

The effectiveness of ankle braces is assessed on the basis of range of motion restriction [14]. Previous in vitro studies on ankle braces indicate semi-rigid ankle brace cannot restore the rotational stability of subtalar joints [11]. In vivo kinematics studies may provide good insight into the mechanisms behind the application of semi-rigid braces in patients with CAI and guide the design of ankle braces.

Brace application reduces hind foot rotation in coronal and sagittal planes [15,16]. However, many kinematics studies about the brace utilized skin markers and motion capture [5,15], which revealed overall movement strategies, but failed to study hindfoot joint kinematics accurately [17]. The in vitro joint kinematics of patients with braces has been reported, but can only represent the passive range of motions, and not the effect of dynamic mechanisms [12]. Fluoroscopic imaging systems can detect in vivo joint kinematics with an accuracy on the millimeter and degree level [18,19]. A study that utilized a

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https://doi.org/10.1016/j.gaitpost.2019.06.020
Received 6 December 2018; Received in revised form 16 June 2019; Accepted 25 June 2019
0966-6362/

fluoroscopic imaging system found that the in vivo kinematics in patients with CAI did not significantly change after the application of a semi-rigid brace [20]. However, it was a single fluoroscopic imaging study with large out-of-plane errors [20].

In this study, we utilized a dual fluoroscopic imaging system to detect the in vivo tibiotalar and subtalar joint kinematics in patients with CAI during the stance phase of walking before and after the application of a semi-rigid brace. We hypothesized that brace application can reduce the increased tibiotalar and subtalar inversion demonstrated by patients with CAI when walking on an inversion platform.

2. Methods

This cross-sectional study was approved by the Institutional Review Board of Huashan Hospital, Fudan University. Written informed consent was collected from all participants.

2.1. Subjects

Patients with unilateral CAI were recruited in accordance with the following inclusion criteria: (1) an initial lateral ankle sprain that occurred over 12 months prior and resulting in at least 3 days of immobilization and/or non-weight bearing; (2) symptoms of recurrent ankle sprains (more than twice in the same ankle during the past 6 months), giving way (more than twice in the same ankle during the past 6 months) or feelings of instability; (3) a Cumberland Ankle Instability Tool (CAIT) score of less than 24; and (4) no history of ankle sprain on the contralateral side that has resulted in at least 1 day of interruption in physical activities.

Subjects were excluded on the basis of the following exclusion criteria: (1) history of bilateral ankle sprains; (2) experience of acute ankle sprains within 3 months or acute lower extremity trauma on either side; (3) general joint hypermobility (i.e., Beighton and Horan score higher than 4); (4) trauma in either lower extremity requiring realignment or surgery; and (5) head trauma, inner ear disease, pregnancy, muscular atrophy or other conditions that may affect normal gait.

The entire lower extremity X-ray of both lower limbs was required to rule out histories of trauma or surgery. Eleven subjects with unilateral CAI were recruited, among whom six were males and five were females. Nine subjects were the same individuals as in a previous study [28]. The average age of the subjects was 24.5 years (range: 19–39 years). The average BMI of the subjects was 21.1 (range: 17.4–24.4). The average CAIT score of the subjects was 16.7 (range: 8–21), and the average duration from initial sprain to study commencement was 38.3 months (range: 21–57 months).

2.2. 3D model reconstruction

Computer tomography (CT) scans (Light Speed, GE, USA) were acquired for each subject from 10 cm above the tibiotalar joint through the toe tip. Scans were taken with the thickness, in-plane resolution, voltage, current, and matrix of 0.67 mm, 0.35 mm, 120 kV, 200 mA, and 512 × 512 pixels, respectively. CT images were segmented via thresholding and subsequent manual gap filling through a previously published method [21]. Segmented CT images were imported into Amira (Amira 5.3.2, Visage Imaging Inc., Germany) to reconstruct the 3D models of the tibia, talus, and calcaneus. Bone models from different subjects were placed in the same orientation and position by using the Iterative Closest Point algorithm prior to coordinate system establishment [22]. Coordinate systems were established and grouped with 3D bone models in a solid modeling software (Rhinoceros 5.0, McNeel & Associates, USA) in accordance with anatomic landmarks of each bone as described by Yamaguchi et al [23]. This process was conducted to facilitate subsequent kinematics calculation.

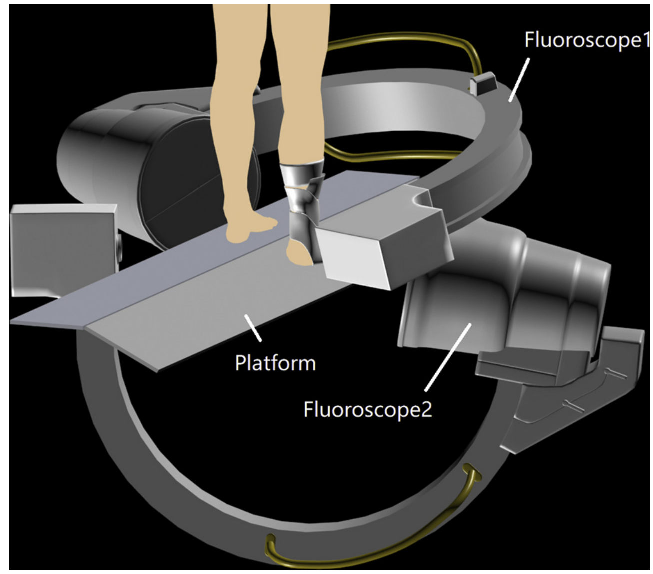

Fig. 1. Dual fluoroscopic system and walking with ankle brace on the 15° inversion platform.

2.3. Dual fluoroscopic imaging

Two approximately orthogonally placed fluoroscopes (BV Pulsera, Phillips Medical, USA) were used for imaging at a frame rate of 30 Hz with the resolution of 1024 × 1024 pixels and beam energy settings of 75 kV and 40 mA. A pair of custom-made calibrators was placed on the receivers of the fluoroscopes before the experiment, to obtain a pair of calibration images [24]. The calibration images were utilized to correct the distortions of fluoroscopic images before model-image registration. The subjects walked barefooted for two continuous steps on a custom-built tilt platform with an embedded force plate. The second step was on a marked position to maintain the tested foot within the narrow view of the fluoroscopes. Dual fluoroscopy images were acquired during the stance phase as subjects completed three tasks: barefoot walking on a level platform, barefoot walking on a 15° inversion platform, and walking with an ankle brace (Aircast A60, DJO Global, USA) on the 15° inversion platform (Fig. 1). The semi-rigid ankle brace used in the current study was comprised of two sleek splints located on either side of the ankle with a strap to hold them in place, which formed a stirrup structure. It was specifically designed to prevent inversion/eversion while allowing sagittal motions and is commonly prescribed for prophylactic protection against ankle sprains. Before testing, the subjects were allowed to practice and familiarize themselves with the testing procedures. Three satisfactory walking trials were performed for each subject. Only the injured ankles of the subjects were imaged. Seven key poses during the stance phase of walking were selected on the basis of the force plate data as follows: the heel strike of the tested foot (pose1), the foot flat of the tested foot (pose2), the toe off of the contralateral foot (pose3), the midstance of the tested foot (pose4), the heel off of the tested foot (pose5), the heel strike of the contralateral foot (pose6) and the toe-off of the tested foot (pose7). The images of the seven key poses were selected for subsequent analysis.

2.4. Data processing

Each pair of fluoroscopic images and bone models were imported into solid modeling software (Rhinoceros 5.0, McNeel & Associates, USA) to create a virtual experimental environment. All coordinate systems were established by the same author. The x, y, and z axes were aligned with the anterior/posterior, lateral/medial, and proximal/distal axes, respectively. The inversion/eversion, dorsiflexion/plantarflexion, and external/internal rotation were around the x, y, and z axes, respectively. The axes were aligned with the local bone anatomical directions. The tibia, talus, and calcaneus had different x, y, and z orientations. The relative rotation between any two bones was determined by using Euler angles. Joint translations were calculated by subtracting the origin location of one bone from the origin location of adjacent bone. These values were offset from an initial static position. The initial static position was determined by weight-bearing CT of one subject. Positive values referred to anterior, lateral, proximal, eversion, dorsiflexion and external rotation, whereas negative values corresponded to opposite directions. The bone models with the coordinate systems were moved and rotated independently at increments of 0.01 mm and 0.01°, and were semi-automatically matched to overlap their silhouettes on the images [25]. Tibiotalar joint angles were determined by using the talus coordinate system relative to the tibia coordinate system and those of subtalar joints were determined by using the calcaneus coordinate system relative to the talus coordinate system. The kinematics data of three satisfactory walking trials for each subject were averaged.

2.5. Statistical analysis

Statistical analysis was performed by utilizing SPSS software (SPSS 19.0, SPSS Inc., USA). Figures were created by applying GraphPad Prism 6 software (GraphPad Prism 6, GraphPad Software, USA). The joint translations and joint angles of 11 patients with CAI were averaged and presented as the mean value with standard deviation. The joint positions of three walking conditions were compared by utilizing the Friedman test. P value < 0.05 was considered statistically significant. Wilcoxon signed rank tests were applied as post-hoc tests when comparisons reached statistical significance. The significance level of post-hoc tests was adjusted to 0.017 through Bonferroni correction.

3. Results

The tibiotalar joint position values of the seven key poses are shown in Fig. 2 and supplementary table 1. The anterior/posterior translation, lateral/medial translation, proximal/distal translation, dorsiflexion/plantarflexion, and external/internal rotation of the tibiotalar joints of the patients with CAI did not significantly differ among the three walking conditions. During foot flat, tibiotalar joints were more inverted while walking barefooted on the inversion platform then while walking barefooted on the level platform (pose 2, p = .004).

The subtalar joint position values of the seven key poses are shown in Fig. 3 and supplementary table 2. During foot flat to heel off, subtalar joints were more anteriorly translated walking barefooted on the inversion platform than while walking barefooted on the level platform (pose 2, p = .003; pose 3, p = .003; pose 4, p = .003; pose 5, p = .003; pose 6, p = .003). During midstance to heel off, subtalar joints were more anteriorly translated while walking with a brace on the inversion platform than while walking barefooted on the level platform (pose 3, p = .006; pose 4, p = .006; pose 5, p = .016).

During foot flat and heel off, subtalar joints were more dorsiflexed during while walking barefooted on the level platform than while walking barefooted on the inversion platform (pose 2, p = .008; pose 3, p = .013; pose 5, p = .008; pose 6, p = .016). During foot flat, subtalar joints were more dorsiflexed while walking barefooted on the level platform than while walking with the brace on the inversion platform (pose 2, p = .003; pose 3, p = .006).

During heel strike to heel off, subtalar joints were more inverted while walking barefooted on the inversion platform than while walking barefooted on the level platform (pose 1, p = .003; pose 2, p = .003; pose 3, p = .003; pose 4, p = .003; pose 5, p = .003; pose 6, p = .013). During midstance and toe off, subtalar joints were more inverted while walking barefooted on the inversion platform than while walking with the brace on the inversion platform (pose 2, p = .003; pose 3, p = .003; pose 4, p = .003; pose 5, p = .004; pose 7, p = .016). During

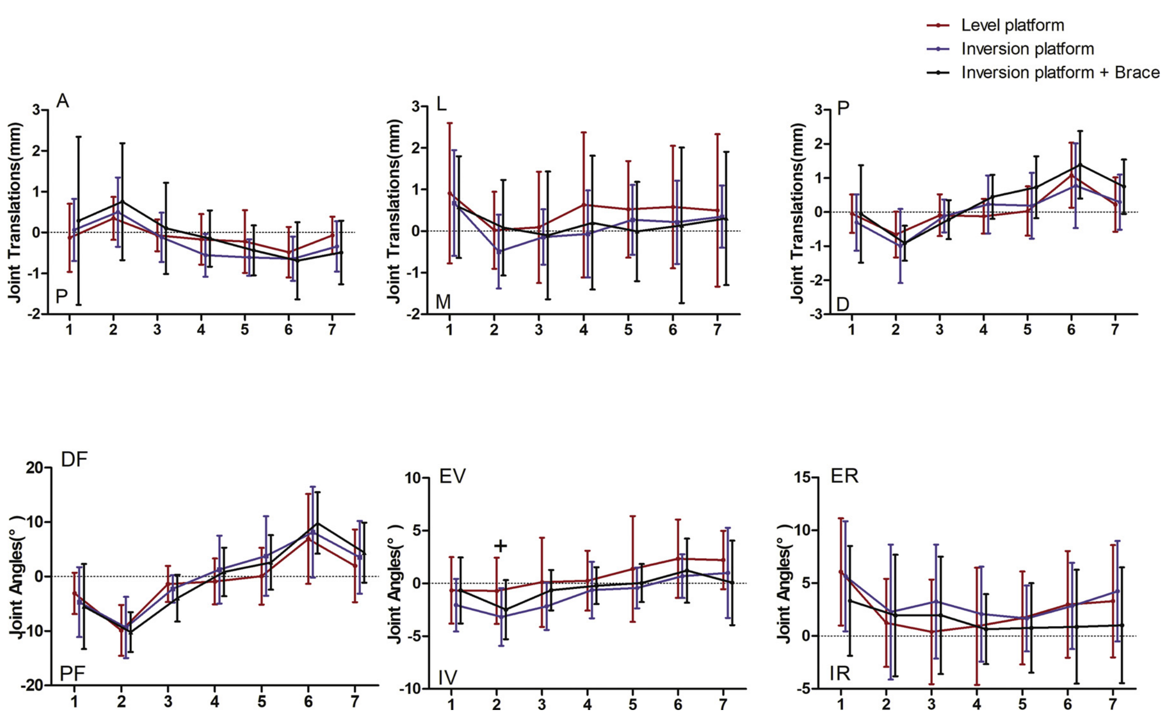

Fig. 2. Tibiotalar joint positions during three walking conditions, including walking barefooted on the level platform, walking barefooted on the inversion platform, and walking with an ankle brace on the inversion platform. Data are presented as mean values with standard deviations. A/P: anterior/posterior translation; L/M: lateral/medial translation; P/D: proximal/distal translation; DF/PF: dorsiflexion/plantarflexion; EV/IV: eversion/inversion rotation; ER/IR: external/internal rotation. +, significant difference between level platform and inversion platform; #, significant difference between inversion platform and inversion platform with brace; *, significant difference between level platform and inversion platform with brace.

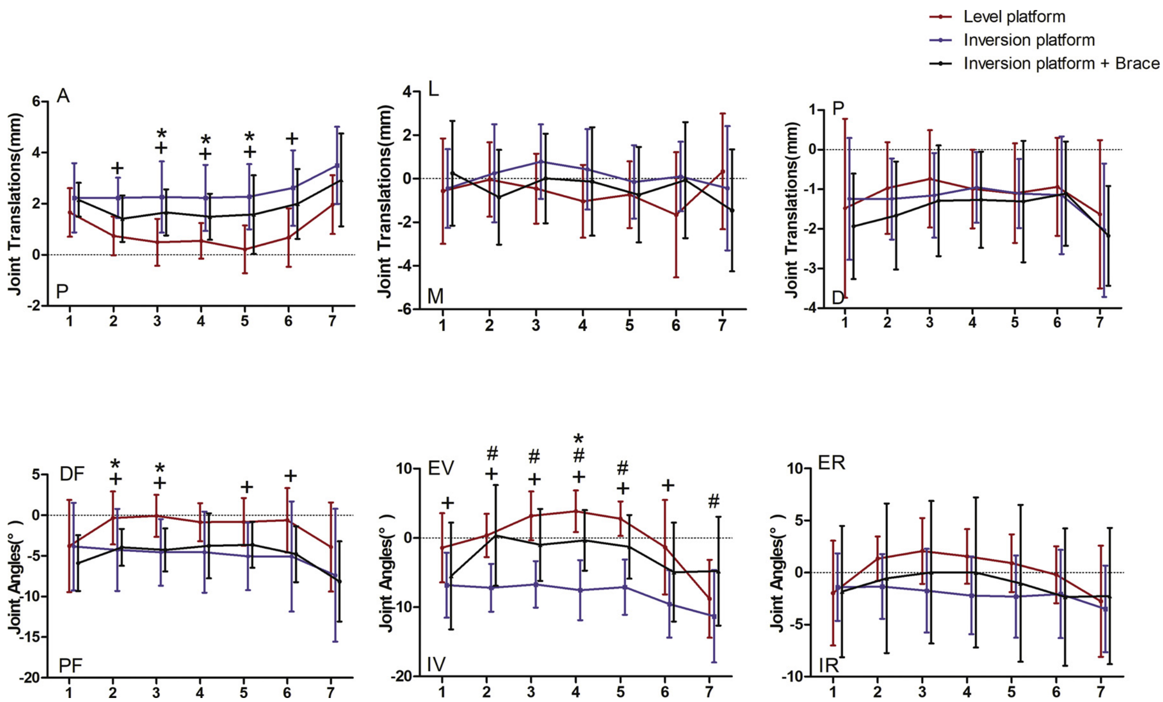

Fig. 3. Subtalar joint positions during three walking conditions, including walking barefooted on the level platform, walking barefooted on the inversion platform, and walking with an ankle brace on the inversion platform. Data are presented as mean values with standard deviations. A/P: anterior/posterior translation; L/M: lateral/medial translation; P/D: proximal/distal translation; DF/PF: dorsiflexion/plantarflexion; EV/IV: eversion/inversion rotation; ER/IR: external/internal rotation. +, significant difference between level platform and inversion platform; #, significant difference between inversion platform and inversion platform with brace; *, significant difference between level platform and inversion platform with brace.

midstance, subtalar joints were inverted while walking with the brace on the inversion platform than while walking barefooted on the level platform (pose 4, $p = .013$).

4. Discussion

In the current study, we compared the in vivo tibiotalar and subtalar joint kinematics of patients with CAI under three walking conditions. Subtalar joints were significantly more anteriorly translated, plantarflexed, and inverted while walking barefooted on the inversion platform than while walking on the level platform. Brace application reduced the increased subtalar inversion induced by the inversion platform. Subtalar anterior translation and plantarflexion increased on the inverted platform. Nevertheless, increased subtalar anterior translation and plantarflexion persisted even after brace application.

A previous single fluoroscopic imaging study did not identify significant differences in unilateral CAI ankles before and after bracing [20]. However, the single fluoroscopic system used in the previous study had large out-of-plane errors. Another comparable dual fluoroscopic study detected decreased inversion and increased dorsiflexion in tibiotalar and subtalar joints after bracing during level walking [26]. But they failed to study the effects of bracing under different walking conditions. By contrast, we utilized a dual fluoroscopic imaging system to quantify the effect of ankle bracing during walking on an inversion platform.

Alterations in subtalar joint kinematics in patients with CAI have been reported in previous studies [27,28]. In the present study, we showed that patients with CAI demonstrated the significantly increased anterior translation, plantarflexion, and inversion of subtalar joints while walking on the inversion platform. These kinematic changes induced by walking on the inverted platform may be the result of compromised subtalar stability, which has been found previously to affect individuals with CAI [27,28]. Several cadaveric studies have identified similar kinematics changes in subtalar joints in ligament-compromised ankles. Ringleb et al [29] reported that subtalar joints underwent excessive anterior translation after the interosseous ligament was severed during maximum range of motion on a six degree-of-freedom positioning and loading device. The severance of the calcaneofibular ligament may increase subtalar inversion [30]. Alterations in subtalar kinematics while walking on the inversion platform might reflect that the subtalar-stabilizing structure in patients with CAI has been compromised.

Several cadaveric studies wherein the calcaneofibular ligament, the cervical ligament, and the interosseous ligament were severed to simulate subtalar instability showed that the inversion/eversion range of motion of the subtalar joints became restricted after brace application [11,12]. During weight loading phase in the current study, subtalar inversion significantly reduced after ankle brace application. The reduction in subtalar inversion might be an important mechanism underlying the ability of ankle braces to prevent ankle sprains.

Increased subtalar inversion during barefoot walking on the inversion platform persisted through preparatory phase (pose 1) to weight loading phase (pose 2–6). In comparison with barefoot walking, brace application did not decrease preparatory subtalar inversion (pose 1). During weight loading phase (pose 2–6), reducing inversion at subtalar joints might attribute to passive stiffness of ankle braces [5]. Webster et al. reported that after muscle fatigue, the joint stiffness of unbraced ankles decreased, whereas that of braced ankles increased [13]. This finding also indicates that the passive structural factors may exert stabilizing effects [10]. The passive stiffness of the semi-rigid brace might contribute to the restricted inversion/eversion range of motion of the subtalar joints.

The increased plantarflexion of feet with CAI found in this study suggests more plantarflexion was required during the inverted platform condition. In the present study, we found that brace application did not reduce the plantarflexion of the subtalar joint. Contrary to healthy individuals, patients with CAI are more plantarflexed at ankle joints during walking and running according to previous kinematics studies

[31]. Increased plantarflexion might predispose the subtalar joint to an increased risk of inversion injury. Ankle brace application did not fully attenuate kinematics alterations during foot flat to midstance. The increased subtalar plantarflexion induced by the inversion platform continued to persist. This is different from previous studies that reported restriction of sagittal motion after brace application during drop landing tasks [15,16]. Differences between these two studies and the current study could be attributed to the different activities investigated. These differences could also be attribute to the design of braces. In contrast to the semi-rigid stirrup braces used in the current study, which prevent inversion/eversion while allowing sagittal motions, the soft braces and lace-up braces used in the two previous studies offer better compression around hindfoot, and thus better restriction on sagittal joint motions [15,16]. A previous study using stirrup braces also reported no significant restriction on ankle plantarflexion after brace application [5]. Brace design might be changed to lift the restriction on plantarflexion to stabilize the subtalar joint during walking on the inverted platform. The addition of lace-up or compressive structures might effectively protect patients with CAI from injury.

The brace application failed to reduce subtalar anterior translation in the current study. Increased anterior translation in subtalar joint was detected after the interosseous ligament was severed in a previous study [29]. No previous studies reported translational kinematic changes in subtalar joints after brace application. Both the increased anterior translation and increased plantarflexion in subtalar joints reflected sagittal hypermobility in subtalar joints. The addition of subtalar locking structures to braces might effectively reduce sagittal hypermobility in subtalar joints.

In the present study, we demonstrated that, the ankle brace stabilized the subtalar joints of patients with CAI against increased inversion rotation. Ankle bracing might complement the rehabilitation program of patients with CAI. Nevertheless, the ability of ankle bracing to restrict sagittal stability in subtalar joints is limited. Brace designs must be improved to restore the sagittal stability of the subtalar joint.

The current study has several limitations. First, only the immediate effects of ankle bracing were investigated. However, a previous study showed that long-term ankle brace application does not alter kinematics [16]. In addition, only the semi-rigid brace, Aircast A60, was investigated in this study. Previous studies categorized ankle braces in to different types, such as rigid, semi-rigid, brace and soft braces. Variable types of braces have slightly different effects [3,4]. Thus, further studies on different types of ankle braces are warranted. We only recruited 11 subjects with unilateral CAI on the basis of strict inclusion and exclusion criteria. Different groups of subjects, including patients with mechanical ankle instability or functional ankle instability, lateral ankle sprain copers, and healthy controls were ignored. Without comparison with other groups of subjects, it is not known whether these kinematic changes are specific to CAI subjects, or what the sagittal stability needs to be restored to. This limitation might have affected the generalizability of our results.

Future studies must determine if ankle braces with different designs can stabilize ankle and subtalar joints within six degrees of freedom. Studies on the immediate and long-term effects of braces during various activities and among different groups of subjects are also needed.

5. Conclusion

Subtalar joints were significantly more anteriorly translated, plantarflexed, and inverted in patients walking barefooted on the inversion platform than in patients walking on the level platform. Brace application attenuated the increased subtalar inversion induced by the inversion platform. Nevertheless, increased subtalar anterior translation and plantarflexion persisted. The ankle brace might be beneficial for clinical populations that exhibit increased subtalar inversion. The results of this study might help explain the mechanisms underlying the protective effects of ankle braces.

Author contributions

Shengxuan Cao contributed to the data analysis and preparation of the manuscript. Chen Wang contributed to the methodology. Gonghao Zhang contributed to the model reconstruction. Xin Ma contributed to the study design. Xu Wang and Jiazhang Huang contributed to the recruitment of volunteers. Chao Zhang contributed to the statistical analysis. Kan Wang contributed to the imaging.

Acknowledgements

The present study was supported by grants from the National Natural Science Foundation of China (Grant No. 81472037, Grant No. 81601862 and Grant No. 81772295), Program of Shanghai Subject Chief Scientist (Grant No. 17XD1401000) and Pioneering Project of Academy for Engineering and Technology, Fudan University.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.gaitpost.2019.06.020.

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