

Effect of a Semi-rigid Ankle Brace on the In Vivo Kinematics and Muscle Activity of Patients with Functional Ankle Instability During Simulated Ankle Sprain

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Research Article

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Abstract

Background

Ankle braces can effectively decrease the incidence of recurrent ankle sprain; however, whether the brace can decrease the severity of sprain and its related mechanism during sprain remain unknown.

Methods

12 patients with functional ankle instability (FAI) (7 males and 5 females) and 10 healthy subjects (5 males and 5 females) were enrolled in this study. All of the subjects walked on a custom-built tilting platform that offered a 30° inversion to mimic the inversion of ankle sprain. We collected the kinematic and sEMG data of patients with FAI with or without ankle brace and normal controls six times.

Results

The FAI without brace group showed significantly higher maximum inversion angles and average inversion velocities than the control group ($P < 0.001$). The FAI with brace group revealed significantly lower maximum inversion angles and average inversion velocities than the FAI without brace group ($P < 0.001$); this group also showed significantly higher maximum external rotation angle and average external rotation velocities than the FAI with brace ($P < 0.001$) and control ($P < 0.001$) groups. The FAI with brace group indicated significantly lower average EMG_{Prep} ($P = 0.047$), EMG_{Tilt} ($P = 0.037$), and $EMG_{afterTilt}$ ($P = 0.004$) of the peroneus longus (PL) than the FAI without brace group.

Conclusions

The ankle brace could effectively decrease inversion angles and their velocities and increase external rotation angles and their corresponding velocities during ankle sprain in patients with FAI. It could also decrease the activity of the PL muscle during ankle sprain.

1. Background

Numerous studies have focused on the mechanism of ankle sprain, recurrent ankle sprain, and subsequent functional ankle instability (FAI). [1] [2] [3] [4] Evidence reveals that ankle sprain is directly related to ankle inversion combined with extreme internal rotation but not ankle dorsiflexion or plantarflexion [2] [3]. When the external load exceeds the self-control of ankle joints, lateral ligament injuries may occur. [4] Restriction of above-ankle rotation, such as by application of an external mechanical support brace, is widely believed to decrease the incidence of ankle sprain. However, the specific kinematics and neuromuscular control of the ankle joint complex during the whole sprain is still

unclear. Naturally, we could probably not know the effect and mechanism of external mechanical support like brace during the sprain.

Induced ankle inversion is a good solution to simulate the ankle sprain. Several studies have assessed kinematics and neuromuscular control during artificially induced ankle inversion. [5] [6] [7] [8] [9] Based on these studies, some researchers believe that humans can resist excessive ankle inversion through the related neuromuscular control. The findings in these experiments have prompted researchers to consider the influence of the self-protection mechanism of subjects during simulated ankle sprain studies. Furthermore, most patients with FAI are afraid to walk on uneven ground, thus indicating that these patients have a degree of ego defense at the central level.

However, there were several defects of those studies. Most reports are based on standing rapidly induced ankle inversion, which cannot simulate the real conditions surrounding sprain. Moreover, whole body movement during ankle sprain cannot be studied. [6] A number of scholars have conducted research featuring improved experimental conditions in which ankle sprain is simulated under more realistic conditions, such as walking or landing. [7] [8] [9] However, in these studies, the subjects knew that either the trapdoor will definitely tilt and ankle inversion would be induced. [7] [8], which resulted in a more cautious gait of subjects. Moreover, most current simulative ankle sprain studies do not measure kinematics synchronously; indeed, only one recent study has considered the kinematics of FAI. [9] In this work, the authors found that the ankle joint inversion angle and velocity at the ground contact phase are significantly lower in the expected condition than in the unexpected condition.

A brace is one of the most common ways to treat FAI and has been proven to decrease the recurrence rate of ankle sprain effectively. However, whether wearing an ankle brace can reduce the degree of injury in occurrent ankle sprain remains unknown. In addition, the mechanism of the brace during sprain is unclear. We believe that induced ankle inversion under functional conditions is a valuable study method. Hence, the current study aims to induce ankle inversion suddenly under unexpected conditions among subjects with and without FAI. In this work, we measure kinematic and neuromuscular control data synchronously before and after a semirigid ankle brace is worn.

2. Methods

2.1 Subjects characteristics

A total of 12 patients with FAI (7 males and 5 females, 12 feet) as FAI group and 10 subjects without FAI (5 males and 5 females, 10 feet) as control group were recruited (Table 1). For the FAI group, all of the following inclusion criteria had to be met: [10] (1) aged 18–40 years and BMI between 17 to 25; (2) a history of at least one ankle sprain that resulted in pain, swelling, and stiffness, prohibiting participation in sports and recreational or other activities for at least 3 weeks; (3) recurrent ankle sprain (2 or more sprains in the same ankle) or giving way (more than 2 times in the past 6 months) or feeling of instability during daily life activities in the previously injured ankle; and (4) Cumberland ankle instability tool (CAIT)

scores lower than 24. The control group had no history of ankle sprain in the last 2 years and a CAIT scores no less than 24. Overall exclusion criteria were a history of fracture or surgery in lower extremities, lower limb pain unrelated to ankle sprain, an ankle sprain in last 3 months, positive talar tilt test or anterior drawer test findings, and equilibrium deficits. All subjects were screened carefully to ensure that they satisfied the inclusion and exclusion criteria. This descriptive laboratory study was approved by the Institutional Review Board of Huashan Hospital, and informed consent was collected from all subjects prior to their participation in this research.

Table 1
Subject characteristics

	Control	FAI
Number of subjects	10	12
Number of feet	10	12
Gender	5M/5F	7M/5F
Age (years)	22.2(1.8)	21.4(1.6)
BMI (kg/m ²)	20.5(1.4)	21.6(1.7)
CAIT scores	28.7(0.9)	16.6(4.1)

2.2 Custom-built tilting platform setup

We independently designed a custom-built tilting platform that included a wooden testing platform, a bilateral trapdoor with wireless electromagnetic switch, and a matched high-speed camera (Fig. 1). The platform had enough height and width for the trapdoor and a total length of over 5 m for at least 2 entire gait cycles. The trapdoor was controlled by a wireless electromagnetic switch and induced an inversion deflection of 30°. A high-speed camera was placed besides the platform to divide the gait cycle. A trigger control device connected the upstream high-speed camera and the downstream wireless electromagnetic switch. A computer program ensured that tilts occur as soon as the heel-strike occurred.

2.3 Data process

Kinematic data were collected by an optical motion capture system including 10 cameras (Vicon Motion Systems, Oxford Metrics Ltd., Oxford, UK) with a collection rate of 100 Hz. Sixteen 14 mm retro-reflective markers, which enabled assessment of ankle joint angles, were placed on the bilateral lower extremity of the subjects. [11] Marker trajectories were low-pass filtered with the fourth order zero-lag Butterworth filter at 15 Hz. Ankle joint angles were derived using the Joint Coordinate System approach, resulting in plantar/dorsiflexion, inversion/eversion, and internal/external rotation. [12] The static stance served as the basis of the definition of neutral joint alignment.

The EMG signals of the m. tibialis anterior (TA), the m. peroneus longus (PL), and the m. soleus (SOL) were recorded using wireless surface electromyography at 2000 Hz. [13] The skin was prepared to ensure an interelectrode impedance of less than 5 k Ω prior to data collection. The raw EMG data were filtered (10–750 Hz, fourth order Butterworth filter), rectified, and integrated at 80–250 Hz. The following time intervals were divided by the high-speed camera as follows: 100 ms before platform tilting (EMG_{Prep}), during platform tilting (EMG_{Tilt}), and 100 ms after platform tilting (EMG_{afterTilt})

Each subject walked on the platform with normal speed (average = 1.2 m/s), and kinematic and sEMG data, called a valid collection, were collected synchronously (Fig. 2). Data from patients with FAI were collected with or without a brace, while those from the control group were collected without the brace. Six valid collections were conducted for each condition of each foot. The tilt sides of the six collections were generated randomly by a computer and contained at least three scheming sides. The subjects and researchers were double-blinded to the collections, and all subjects were trained to walk on the platform prior to data collection.

The semirigid ankle brace (Aircast A60 Ankle Support, DJO, Europe) used in our current study was composed of nylon supporters and polyethylene lace and designed to resist inversion/eversion and internal/external rotation movements while allowing dorsiflexion/plantar flexion.

2.4 Statistical analysis

The joint position was defined as three rotation DOFs during different phases of ankle title. These phases were summarized as follows: dorsiflexion/plantarflexion (DF+/PF-), inversion/eversion (IV+/EV-), internal rotation/external rotation (IR+/ER-). The maximum angles of the ankle complex during tilt were defined as the difference between the maximum and minimum rotation angles in each DOF. The Average velocities of the ankle complex during tilt was defined as the ratio between the maximum angle and time. The final output index of EMGs, which was defined as the average EMG, was the integral average of the EMG amplitude obtained during testing. The results of all groups were converted into the corresponding values with reference to those of the FAI without brace group, which were assigned a value of 100 in all comparisons. Statistical analysis was conducted using SPSS 22.0. The Maximum Angles, average Velocities and average EMG were checked via Kolmogorov–Smirnov tests, and both of them did not meet the normal distribution criterion. Therefore, the data of two related samples of FAI without a brace and FAI with a brace were statistically analyzed using a Wilcoxon signed-rank test, and the data of the two independent samples were statistically analyzed using Mann–Whitney U test. Differences were considered statistically significant when $P < 0.05$.

3. Results

3.1 Average ankle position

The average ankle position–time curves during tilt are listed in Fig. 3. Tilts began at 0 ms.

No significant difference was observed among the three groups in terms of DOF of ankle dorsiflexion/plantarflexion. In terms of inversion/eversion DOF, we found that all three groups show the same trend, which started from the neutral position, progressed to gradual inversion, and then returned to the neutral position. Furthermore, the FAI without brace group revealed more inversion positions at 40–100 ms compared with the control group and significantly more inversion positions than the FAI with brace group at 0, 40, 80, and 100 ms. The FAI with brace group revealed more eversions than the control group at 0 ms; this finding was the only difference observed between the FAI with brace and control groups at 0 ms. In terms of internal/external rotation DOF, the FAI with brace group showed more external rotation positions than the FAI without brace and control groups at 0–80 ms. The trend of the curve started from the neutral position, progressed to gradual external rotation, and then returned to the neutral position. Maximum external rotation occurred at 60 ms.

3.2 Average Maximum Angles of The Ankle Complex During Tilt

Maximum angles of the ankle complex during tilt are listed in Table 2 and presented in Fig. 4. No significant difference was observed among the three groups in terms of DOF of ankle dorsiflexion/plantarflexion. In terms of the inversion/eversion DOF, the FAI without brace group revealed significantly larger angles than the control group ($p < 0.001$) and significantly more angles than the FAI with brace group ($p < 0.001$). In terms of internal/external rotation DOF, the FAI with brace group showed significantly larger angles compared with the FAI without brace ($p < 0.001$) and the control ($p < 0.001$) groups.

Table 2
The Maximum Angles of The Ankle Complex During Tilt

Maximum Angles (°)			
	DF+/PF-	IV+/EV-	IR+/ER-
Control	4.26(5.70)	11.59(1.71)	-4.47(3.96)
FAI without brace	1.29(5.05)	16.27(1.94)	-3.44(5.03)
FAI with brace	1.73(2.82)	11.46(0.84)	-14.18(2.02)
DF+/PF-, dorsiflexion/plantarflexion; IV+/EV-, inversion+/eversion-; IR+/ER-, internal rotation+/external rotation-			

3.3 Average Velocities of The Ankle Complex During Tilt

Average velocities of the ankle complex during tilt are listed in Table 3 and Fig. 5. No significant difference was observed among the three groups in terms of DOF of ankle dorsiflexion/plantarflexion. In terms of inversion/eversion DOF, the FAI without brace group had significantly higher velocities than the control ($p < 0.001$) and FAI with brace ($p < 0.001$) groups. In terms of internal/external rotation DOF, the FAI with brace group showed significantly higher velocities compared with the FAI without brace ($p < 0.001$) and control ($p < 0.001$) groups.

Table 3
The Average Velocities of The Ankle Complex During Tilt

Average Velocities (°/s)			
	DF+/PF-	IV+/EV-	IR+/ER-
Control	80.74(39.24)	189.15(38.16)	63.55(51.23)
FAI without brace	101.88(35.70)	264.06(38.65)	73.12(29.80)
FAI with brace	88.01(40.65)	212.27(12.89)	231.26(46.83)
DF+/PF-, dorsiflexion/plantarflexion; IV+/EV-, inversion+/eversion-; IR+/ER-, internal rotation+/external rotation-			

3.4 The average EMG of the lower extremity during tilt.

The average EMGs of the lower extremity during tilt are listed in Table 4. Compared with the FAI without brace group, the FAI with brace group revealed significantly increased EMG_{Prep} ($P = 0.047$), EMG_{Tilt} ($P = 0.037$), and $EMG_{afterTilt}$ ($P = 0.004$) of the PL. Significant differences were not observed in other muscles.

Table 4
The Muscular Activity of Lower Extremity During the Tilt

	FAI without brace	FAI with brace
m. tibialis anterior		
- EMG _{Pre}	100(0.0)	83.8(27.8)
- EMG _{Tilt}	184.3(0.0)	169.5(59.1)
- EMG _{afterTilt}	126.1(0.0)	112.4(22.6)
m. peroneus longus		
- EMG _{Pre}	100(0.0)	88.3(13.4) *
- EMG _{Tilt}	324.8(27.6)	273.5(39.3) *
- EMG _{afterTilt}	212.7(13.8)	182.3(19.9) **
m. soleus		
- EMG _{Pre}	100(0.0)	93.5(23.2)
- EMG _{Tilt}	275.6(70.6)	285.5(78.1)
- EMG _{afterTilt}	189.9(56.8)	166.9(32.9)
***means $P < 0.001$, ** means $P < 0.01$, * means $P < 0.05$		

4. Discussion

The ankle brace is widely used among patients with FAI and can effectively reduce the incidence of sprain recurrence, especially among athletes. [14] However, whether ankle braces can reduce the degree of injury is unknown. McGuine et al found that use of lace-up ankle braces reduced the incidence but not the severity of acute ankle injuries in male and female high school basketball athletes both with and without a previous history of an ankle injury. [15] Current research suggest that an ankle brace can prevent or reduce injuries by affecting proprioception during sudden inversion. [16] Unfortunately, previous studies are based on induced sudden ankle inversion in a standing or sitting position. [17] [18] [5] [6] Several studies simulating ankle sprain under more functional situations, such as walking or landing, conclude that the ankle brace or patient's mental preparation may reduce some of the muscle activation that occurs during ankle inversion. [7] [8] [9] The lack of data on synchronous kinematic changes after wearing an ankle brace also presents problems when interpreting results. Only one recent study has conducted coupled analysis of the neuromuscular functions and kinematics of the ankle complex; [19] in this work, the researchers induced rapid sudden ankle inversion on normal subjects and found that an ankle brace could simultaneously restrict inversion and reduce the activity of the PL. The

current study cannot fully illustrate the effect of ankle braces on patients with FAI because the subjects were healthy. Thus, our study aimed to reveal the effect of a semirigid ankle brace on the kinematic and neuromuscular functions of patients with FAI through induced ankle inversion during walking.

We studied the kinematics and neuromuscular function of the ankle simultaneously. This current study found some new mechanism of ankle brace during sprain. Ankle brace could effectively reduce the angles and velocities of patients with FAI under rapidly induced ankle inversion movement and synchronously reduce PL activity. We also primarily found a compensatory external rotation mechanism, except when under the direct restriction effect of ankle brace. These findings may provide novel insights into the mechanism of the ankle brace.

When tilt began, the time-related inversion angle of the three groups rapidly increased and then slowly decreased. We found no difference in the peak angles of the three groups. The FAI without brace group had larger maximum inversion angles, larger maximum inversion velocities, and steeper average ankle position–time curves than the two other groups. However, maximum inversion angles and velocities significantly decreased after wearing of the ankle brace. These findings are in accordance with previous studies. Lower inversion angles result in less ATFL and CFL strain, which indicates that the ankle brace can decrease the strain of lateral ligaments at the instance of sprain. [20] The decrease in ligament strain may contribute to a reduction in the severity of injury when sprain occurs. Besides, significant external rotation synchronous with inversion was observed in the FAI with brace group. A previous biomechanics study showed that compensatory external rotation of the talocrural joint occurs during extreme ankle inversion; this rotation probably occurs against the inversion and adjusts the position of the angle. However, the largest tilt angle observed in the current study was 30°, and results showed no inversion angles over 20°. Considering that compensatory external rotation may not occur under our experimental conditions, we did not find external rotation in the FAI without brace and control groups. Nevertheless, we suppose that the external rotation occurring in the FAI with brace group was activated in advance by the restriction and proprioception regulation of the ankle brace, thus confirming that injury may be reduced after the brace is worn. Moreover, increases in external rotation may decrease the strain of ATFL, which may be another protective mechanism of the brace. [21]

The sEMG data showed significantly less activation of the PL in the FAI with brace group compared with that in the FAI without brace group. The mechanical support provided by the ankle brace may reduce the demand for muscles when walks or sprain occurs. However, these results contradict previous studies showing increased peroneal stretch-reflex sensitivity [5] [22] and motoneuron pool excitability [23] after wearing a brace. Considering that the subjects were tested under sitting or standing conditions in those studies, we feel that our study is more reflective of the actual situation. While our conclusions are similar to those of Barlow [24], Gehring [19] and Feger. [25] Barlow G showed that ankle bracing resulted in lower pre-contact amplitude of the peroneus longus comparing with no brace during walking in patients with chronic ankle instability. Gehring induced rapid sudden ankle inversion on normal subjects and found that an ankle brace could reduce the activity of the PL. In Feger's research, patients with chronic ankle instability demonstrated decreased muscle activity of ankle, knee, and hip musculature during common

functional rehabilitative tasks. In the current study, we consider the combined existence of feedforward and feedback regulations when the sEMG of the PL is reduced. On the one hand, the restriction provided by the ankle brace stimulates cutaneous sensation and sends these impulses to the nerve center; thus, regulation starts before the myotatic reflex of the PL, which corresponds to sEMG reductions before tilt. On the other hand, after tilt begins, the nerve center controls the reflex to an appropriate level according to the subject's needs, which corresponds to sEMG reduction during tilt, due to the weaker myotatic reflex caused by restriction of the ankle brace. We believe that the relatively low activation of the PL during rapidly induced ankle inversion could relieve muscle fatigue, which contributes to further injury. [26]

Some methodological limitations should be considered when interpreting our results. First, some risks resulting in injury during rapidly induced ankle inversion exist. Fortunately, no accident occurred during our experiment. Second, the Vicon Motion System is not as accurate as the 3D–2D fluoroscopy image registration technique used in our previous studies, [27] [28] [29] Thus, the kinematics of the talocrural and subtalar joints were not studied separately. Third, considering the large individual differences in sEMG observed, we only conducted self-control before and after patients in the FAI group wore their ankle brace. Finally, accurate comparisons between different groups require a larger sample size.

5. Conclusions

Patients with FAI revealed larger inversion angles and velocities than normal controls during ankle sprain. Ankle braces can effectively decrease inversion angles and velocities during ankle sprain in patients with FAI and simultaneously increase external rotation angles and velocities. Moreover, braces can decrease the activity of the PL muscle during ankle sprain.

Declarations

Ethics approval and consent to participate

This study was conducted in accordance with the Declaration of Helsinki. The protocol was approved by the Ethics Committee of Tongren Hospital Shanghai Jiao Tong University School Of Medicine (No. 2022-050).

Consent for publication

Not applicable.

Availability of data and materials

All data generated or analysed during this study are included in this published article.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

Gonghao Zhang and Shengxuan Cao contributed to the data analysis and preparation of the manuscript. Guoning Zhang and Yangyang Zhang contributed to the methodology. Li Xiong and Ping Huang contributed to the gait data collection. Yunhan Ji and Xin Ma contributed to the study design. Chao Zhang contributed to the recruitment of volunteers. Chen Wang contributed to the statistical analysis.

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Figures

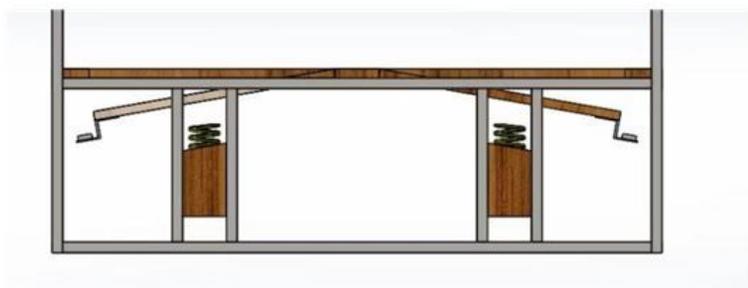


Figure 1

Custom-Built Tilting Platform

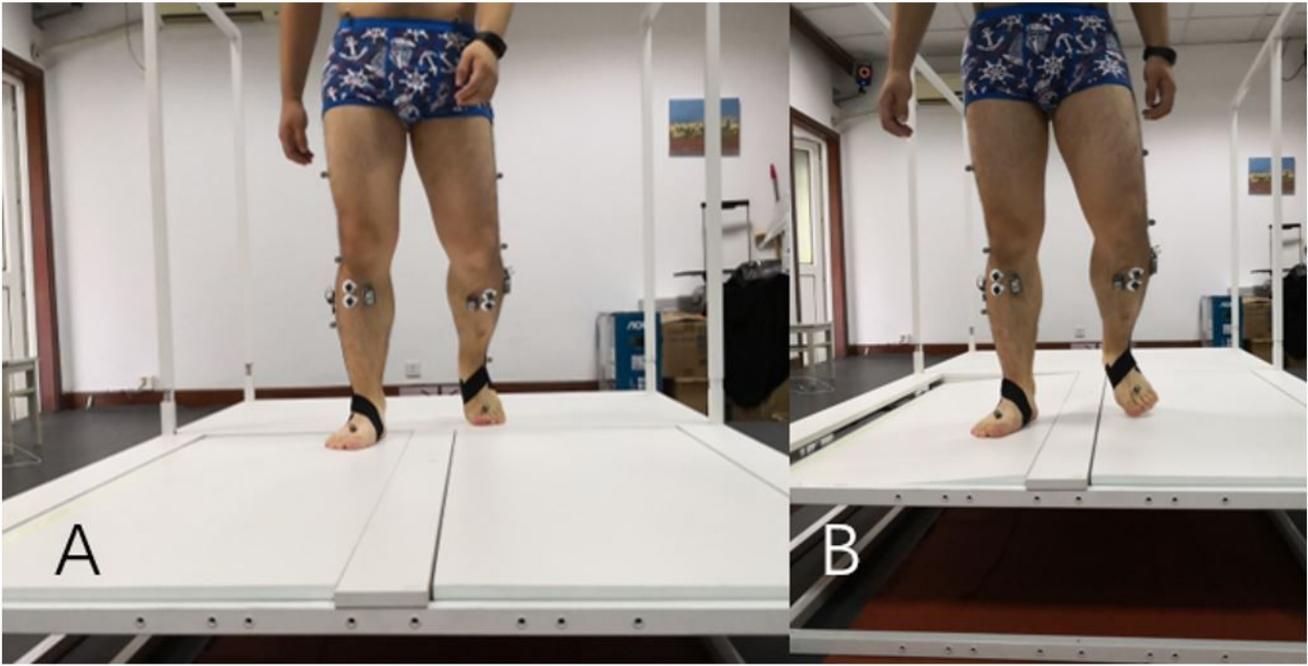


Figure 2

A Valid Collection

(A. The collection starts; B. platform title)

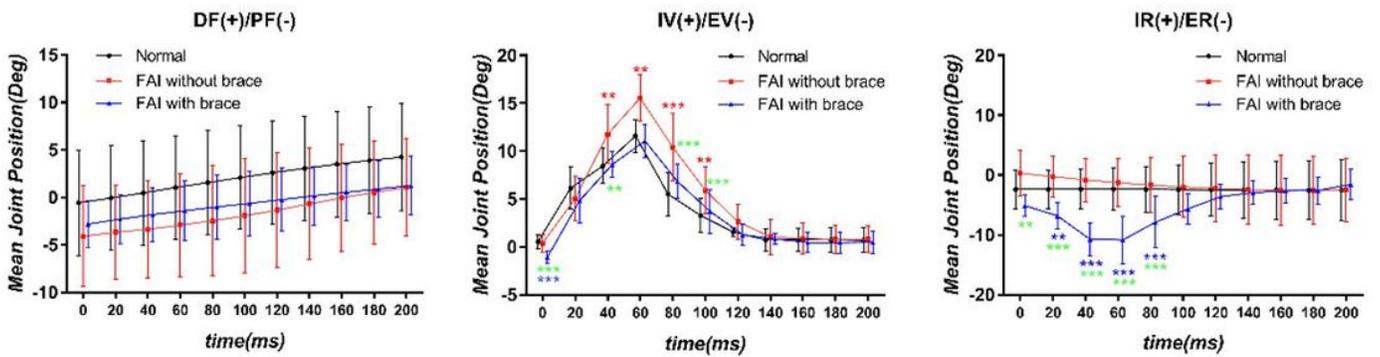


Figure 3

The Mean Joint Position of The Ankle Complex During Tilt

(* (red), comparison between FAI without brace and normal; *(blue), comparison between FAI with brace and normal; *(green), comparison between FAI without brace and FAI with brace; *** means $P < 0.001$, **

means $P < 0.01$, * means $P < 0.05$); DF+/PF-, dorsiflexion/plantarflexion; IV+/EV-, inversion+/eversion; IR+/ER-, internal rotation+/external rotation-)

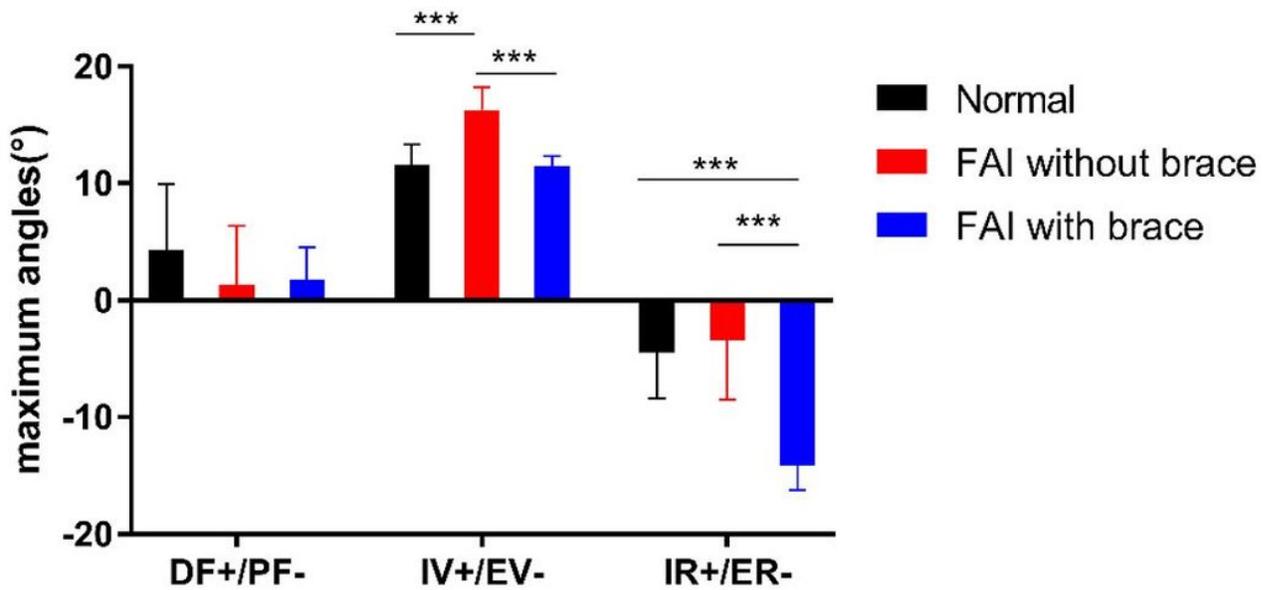


Figure 4

The Maximum Angles of The Ankle Complex During Tilt

(***means $P < 0.001$, ** means $P < 0.01$, * means $P < 0.05$); DF+/PF-, dorsiflexion/plantarflexion; IV+/EV-, inversion+/eversion; IR+/ER-, internal rotation+/external rotation-)

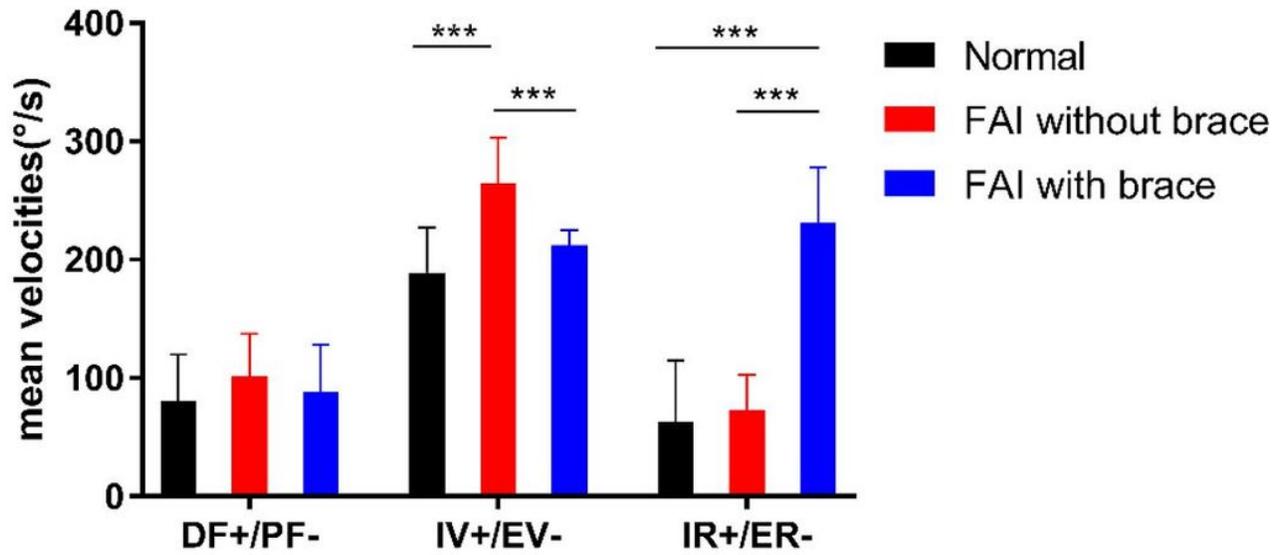


Figure 5

The Average Velocities of The Ankle Complex During Tilt

(***means $P < 0.001$, ** means $P < 0.01$, * means $P < 0.05$); DF+/PF-, dorsiflexion/plantarflexion; IV+/EV-, inversion+/eversion-; IR+/ER-, internal rotation+/external rotation-)