



## An examination of muscle force control in individuals with a functionally unstable ankle

Sheng-Che Yen<sup>a,\*</sup>, Kevin K. Chui<sup>b</sup>, Ying-Chih Wang<sup>c</sup>, Marie B. Corkery<sup>a</sup>,  
Mohsen Nabian<sup>d</sup>, Amir Bahador Farjadian<sup>e</sup>

<sup>a</sup> Department of Physical Therapy, Movement and Rehabilitation Sciences, Bouvé College of Health Sciences, Northeastern University, United States

<sup>b</sup> School of Physical Therapy and Athletic Training, College of Health Professions, Pacific University, United States

<sup>c</sup> Department of Occupational Science & Technology, College of Health Sciences, University of Wisconsin Milwaukee, United States

<sup>d</sup> Harvard Medical School, Broad Institute of MIT and Harvard, Brigham Women Hospital, United States

<sup>e</sup> TAVANA LLC, United States



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### ABSTRACT

Previous studies suggest that functional ankle instability (FAI) may be associated with deficits in the ability to sense muscle forces. We tested individuals with FAI to determine if they have reduced ability to control ankle muscle forces, which is a function of force sense. Our test was performed isometrically to minimize the involvement of joint position sense and kinesthesia. A FAI group and a control group were recruited to perform an ankle force control task using a platform-based ankle robot. They were asked to move a cursor to hit 24 targets as accurately and as fast as possible in a virtual maze. The cursor movement was based on the direction and magnitude of the forces applied to the robot. Participants underwent three conditions: pre-test (baseline), practice (skill acquisition), and post-test (post skill acquisition). The force control ability was quantified based on the accuracy performance during the task. The accuracy performance was negatively associated with the collision count of the cursor with the maze wall. The FAI group showed reduced ability to control ankle muscle forces compared to the control group in the pre-test condition, but the difference became non-significant in the post-test condition after practice. The change in performance before and after practice may be due to different degrees of reliance on force sense.

### 1. Introduction

Chronic ankle instability is a common residual problem following an ankle sprain (Hertel, 2002). It is characterized by episodes of ankle giving way and/or recurrent ankle sprains. Chronic ankle instability has often been categorized into mechanical instability and functional instability (Gutierrez, Kaminski, & Douex, 2009; Hertel, 2000). Mechanical instability refers to joint laxity due to damage to the supporting ligamentous structures. Functional ankle instability (FAI) refers to a wide range of sensorimotor control issues such as deficits in proprioception, neuromuscular control, postural control, and muscle strength (Holmes & Delahun, 2009). The study of FAI was initiated by the classic work of Freeman et al (Freeman, Dean, & Hanham, 1965). They hypothesized that damage to ankle proprioceptors caused by a sprain creates a void in the proprioceptive feedback to the central nervous system, which in turn causes

\* Corresponding author at: Department of Physical Therapy, Movement and Rehabilitation Sciences, Bouvé College of Health Sciences, Northeastern University, 301 Robinson Hall, 360 Huntington Avenue, Boston, MA 02115, United States.

E-mail address: [s.yen@northeastern.edu](mailto:s.yen@northeastern.edu) (S.-C. Yen).

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individuals to have episodes of ankle giving way. To test this hypothesis, a number of researchers have examined joint position sense (Boyle & Negus, 1998; Gross, 1987; Jerosch & Bischof, 1996; Konradsen & Magnusson, 2000) and kinesthesia (Garn & Newton, 1988; Lentell et al., 1995; Refshauge, Kilbreath, & Raymond, 2000) in individuals with FAI. While the majority of the studies found that these two types of proprioception were reduced in individuals with FAI (Boyle & Negus, 1998; Garn & Newton, 1988; Jerosch & Bischof, 1996; Konradsen & Magnusson, 2000; Lentell et al., 1995), some studies showed contradictory findings (Gross, 1987; Refshauge et al., 2000).

Force sense, referring to the ability to detect changes in muscle and joint tension, is another type of proprioception (Lundberg & Winsbury, 1960). Force sense has received less attention in the field of FAI research, although it may play an important role in joint stability (Arnold & Docherty, 2006; Docherty & Arnold, 2008). Force sense is needed to detect the external force applied to the joint before the motor control system can plan and generate counteracting internal (muscle) forces to stabilize the joint. In addition, force sense is needed to detect discrepancy between the planned and actual muscle force generation (i.e., force control error) before the motor control system can make a correction. When there are deficits in force sense, the internal force cannot be generated effectively to counteract the external force, which can lead to joint instability and injury.

A few studies examined individuals with FAI using a force reproduction task and found this population may have deficits in force sense (Arnold & Docherty, 2006; Docherty & Arnold, 2008; Simon, Garcia, & Docherty, 2014). In these studies, participants first learned to produce a certain amount of target muscle force with the aid of augmented visual feedback. Then they were asked to reproduce the target force without the visual feedback. The results showed that the reproduction error in ankle eversion force was larger in the FAI group compared to the control group (Docherty & Arnold, 2008; Simon et al., 2014), and the error was positively associated with episodes of ankle giving way (Arnold & Docherty, 2006). These findings provided initial evidence to support that force sense may be compromised in individuals with FAI.

Force sense, along with other types of sensory feedback, are the foundation of motor control. Motor control consists of feedback and feedforward mechanisms that work closely with each other. When individuals perform a novel motor task, they tend to rely more on the feedback mechanism to detect and correct movement errors (Mulder & Hulstijn, 1985; Sober & Sabes, 2005). Over multiple trials of practice, however, the reliance on the feedback mechanism will be gradually reduced as a feedforward model is formed based on the sensory information, to guide the motor performance (Bastian, 2008; Kawato, 1999; Yen, Landry, & Wu, 2014; Yen, Landry, & Wu, 2013). One approach investigates if a feedforward model occurs through inter-limb transfer, referring to the phenomenon that learning a motor skill in one limb can transfer to the opposite limb (Morris, Newby, Wininger, & Craelius, 2009; Yen et al., 2018). From a perspective of generalized motor program theory, inter-limb transfer occurs because a feedforward model was formed through the practice of one limb, and is available for use to produce the motor task with the opposite limb (Perez et al., 2007).

While previous studies found evidence to support that FAI is associated with reduced force sense (Arnold & Docherty, 2006; Docherty & Arnold, 2008; Simon et al., 2014), we were not aware of any studies examining if individuals with FAI have reduced ability to control the magnitude and direction of muscle forces in a novel or an experienced motor task. Clarifying these questions will advance our knowledge in motor control in individuals with FAI. Thus, the purpose of this study was to compare the ability to control the magnitude and direction of ankle muscle forces in a novel task (force control task) before and after multiple trials of practice between individuals with FAI and their healthy counterparts. The force control test was performed isometrically (without ankle motion) as we wanted to isolate the contribution of force sense and minimize the involvement of joint position sense and kinesthesia. The reason for testing force control both before and after the practice was because participants may rely more on a feedback mechanism before the practice and more on a feedforward mechanism after the practice. We used the inter-limb transfer paradigm to verify if a feedforward model was formed. We hypothesized that individuals with FAI will show worse performance in the force control task compared to their healthy counterparts before and after practice of a force control task.

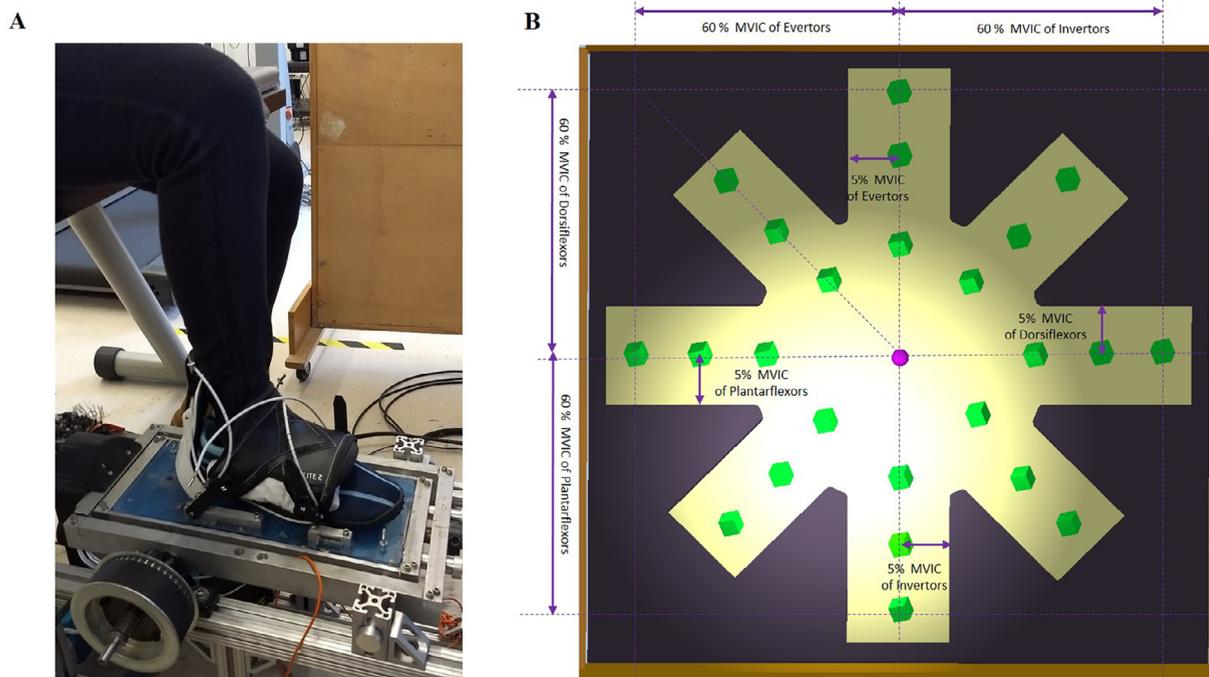
## 2. Methods

### 2.1. Participants

A total of 20 participants were conveniently recruited on a university campus. The sample consisted of 10 participants with FAI (6 females and 4 males; age =  $22.5 \pm 1$  years old) and 10 control participants (6 females and 4 males; age =  $22.3 \pm 1$  years old). The FAI and the control groups were matched by gender and age. Participants were determined to have FAI if they scored 24 or lower in the Cumberland Ankle Instability Tool (CAIT) (Hiller, Refshauge, Bundy, Herbert, & Kilbreath, 2006), had more than one event of ankle giving way in the past six months prior to study enrollment, and had a history of at least one significant ankle sprain, with the initial sprain occurring at least one year prior to study enrollment (Gribble et al., 2014). The number and determination of FAI participants was not changed when we alternatively used Wright et al.'s recalibrated CAIT cutoff score ( $\leq 25$ ) (Wright, Arnold, Ross, & Linens, 2014). Those who had a recent ankle sprain (three months prior to study enrollment) were excluded from study participation. Control participants were included if they scored 28 or higher in the CAIT and had no history of major ankle sprains. Informed consent was obtained from all participants, and all procedures were conducted in accordance with the Helsinki Declaration of 1975 and approved by the local Institutional Review Board.

### 2.2. Instrumentation

We used the virtually interfaced Robotic Ankle and Balance Trainer (vi-RABT, Fig. 1A) to test ankle muscle force control (Farjadian, Nabian, Hartman, & Yen, 2017). The main component of the vi-RABT was a motorized footplate. The footplate was



**Fig. 1.** (A) The setup of the vi-RABT during data collection. The test foot was affixed to the vi-RABT with a shoe brace. The ankle was in a neutral position during the test. (B) The layout of the maze game and the placement of targets for testing the right side. The setup was based on each individual participant's maximum voluntary isometric contraction (MVIC) of ankle muscles.

embedded with four load cells (one at each corner) for measuring forces in the sagittal plane (dorsiflexion and plantarflexion) and the frontal plane (inversion and eversion). During the force control test, the motor of the robot was turned off, the footplate was locked in parallel to the floor, and the participant's test foot was affixed on the top of the footplate. The footplate measured forces exerted from the test foot in real time, and the force signals were fed to a customized force control task program written in the Unity language (v4.3, Unity Technologies, CA).

### 2.3. Force control task

The force control task was essentially an interactive videogame. The interface of the program (Fig. 1B) consisted of an eight-tunnel maze, 24 static targets (green boxes, three in each tunnel), and a moving cursor (pink ball). The cursor movement was controlled by the magnitude and direction of the participant's force exertion. For both legs, dorsiflexion and plantarflexion forces moved the cursor up and down, respectively. For the right leg, inversion and eversion forces moved the cursor to the left and right, respectively. For the left leg, the direction of cursor movement was reversed for inversion and eversion forces. Exerting forces across the planes moved the cursor in diagonal directions. The moving distance of the cursor is proportional to the magnitude of the force applied on the foot plate.

The targets were placed in the maze based on each individual participant's maximum voluntary isometric contraction (MVIC) following our previous setup (Yen et al., 2018), which is shown in Fig. 1B. A participant could reach the farthest target in the horizontal or vertical tunnel by exerting 60% of MVIC in the corresponding direction. Each diagonal tunnel has a 45° of intersection angle with the horizontal and vertical tunnels. The distance from the center of the maze to the farthest target in each diagonal channel is 10% shorter than that in the vertical/horizontal direction, as we intended to reduce the level of difficulty in controlling forces across two directions. The participant could reach the farthest target in a diagonal tunnel by exerting approximately 37.5% of the MVIC in the vertical direction ( $60\% \text{ of MVIC} \times 90\% \times \cos 45^\circ$ ) and approximately 37.5% of the MVIC in the horizontal direction.

In the vertical channels, the perpendicular distance from the center of the tunnel to the lateral maze wall was set at 5% of the corresponding MVIC in the inversion/eversion direction. In the horizontal channels, the perpendicular distance from the center of the tunnel to the maze wall above was set at 5% of the MVIC in the dorsiflexion direction, and that to the maze wall below was set at 5% of the MVIC in the plantarflexion direction.

### 2.4. Data collection procedures

For the FAI group, we started data collection with identifying which side of the ankle was the affected side (for those with unilateral FAI,  $N = 5$ ) or the more unstable side (for those with bilateral FAI,  $N = 5$ ) based on the CAIT score. The performance of the

affected/more unstable side was of the primary interest of this study. This side went through all the test procedures including a practice condition, and therefore we called it “the practiced side.” The opposite side went through all test procedures except the practice condition, and thus we called it “the non-practiced side.”

The non-practiced side was used to examine inter-limb transfer. We were not aware of any previous study examining inter-limb transfer in individuals with either unilateral or bilateral FAI, and therefore we recruited both types of patients to be inclusive. Among the 10 participants with FAI, five had the right side as the practiced side and five had the left side. Each control participant had the same practiced side as his/her matched participant with FAI.

Each participant went through four conditions: (1) MVIC test; (2) pre-test; (3) practice; (4) post-test. In all conditions, the participant was in a seated position with the test foot affixed to the vi-RABT with the ankle in a neutral position (Fig. 1A). In the MVIC test condition, we measured each participant’s MVIC of the dorsiflexors, plantarflexors, invertors, and evertors of both legs using the vi-RABT. The MVIC was tested three times and averaged for each side. The mean MVIC was used for maze construction and target placement as shown in Fig. 1B.

In the pre-test condition, participants performed three trials of the force control task with each foot, and the test order for the left and right sides was randomized. Participants’ goal in the task was to hit the 24 targets as fast as possible with the moving cursor, while avoiding the cursor colliding with the wall. When wall collision occurred, participants received a beep as error feedback. Participants had the freedom to plan and execute the sequence of target hitting. The same task goal was applied to the practice condition and the post-test condition. In the practice condition, participants practiced the same task 15 times with the practiced side (FAI group) or the matched side (control group). In a previous study, we found healthy individuals were able to significantly improve their performance in the same force control maze game over 15 trials of practice without fatiguing the ankle muscles (Yen et al., 2018). In the post-test condition, participants repeated the same procedures in the pre-test condition with both sides being tested.

## 2.5. Outcome variable and covariates

The outcome variable for this study was a customized ankle force control index. The index measured the ability to accurately control muscle forces during the task and had an inverse relationship with the number of times that the cursor collided with the wall (i.e., error). The index was calculated as:  $\frac{\text{Targets}}{\text{Targets} + \text{Collisions}} \times 100\%$ , where Targets is a constant of 24 that indicates the number of targets to be hit in a task trial, and Collisions is the collision counts. The Targets term in the formula served two purposes: (1) to avoid 0 in the denominator when the participant made no collision and (2) to make the index = 100% when the participant made no collision. With this arrangement, fewer wall collisions led to a greater ankle force control index, which indicated a more accurate force control.

There were three potential covariates in this study. The first one was the task completion time, which was measured as the time required for a participant to hit all 24 targets in the maze during a trial. Based on speed-accuracy trade off (Fitts, 1992), task completion time was likely to be negatively associated with the error (collisions) and affect the study outcome. The second one was the MVIC of the ankle muscles that showed a significant between-group difference. Previous studies have shown that individuals with FAI have lower strength in ankle evertors compared to their healthy counterparts (Arnold, Linens, de la Motte, & Ross, 2009). The third one was the trials within each condition. We expected that the participant’s performance will improve over the trials due to learning effects.

## 2.6. Statistical analysis

We first compared the MVIC in the practiced side between the FAI and control groups using either the independent *t*-test or the non-parametric Mann-Whitney *U* test, depending on whether the data were normally distributed. The normality was tested using the Shapiro-Wilk test. When the MVIC for a direction was found to be significantly different between the control and FAI groups, it was treated as a covariate and controlled for in the statistical model that compared the ankle force control index between the two groups.

A linear mixed models (LMM) was conducted to compare the ankle force control index of the practiced side between the groups (FAI versus control) in each of the pre-test and post-test conditions. The model examined the main effect of group. The following covariates were introduced to the model: task completion time, the MVIC that had a significant between-group difference, and trials within each condition. The covariance structure between the three trials within each condition was set as “unstructured.”

Another LMM was used to analyze the performance in the practice condition. This analysis was performed on the practiced side and included the main and interaction effects of group and practice trials. Covariates included in the model were task completion time and the MVIC that had a significant between-group difference. The covariance structure between trials was set as “unstructured.”

A third LMM was conducted to compare the ankle force control index of the non-practiced side between the conditions (pre-test versus post-test) in each of the FAI and control groups. The model examined the main effect of condition. Task completion time and trials within each condition were introduced to the model as covariates. The covariance structure between conditions and trials was set as “unstructured.” All statistical comparisons were performed using SPSS v.23 (IBM Corp., Armonk, NY). The alpha level was set at  $p = 0.05$ .

### MVIC: Practiced Side

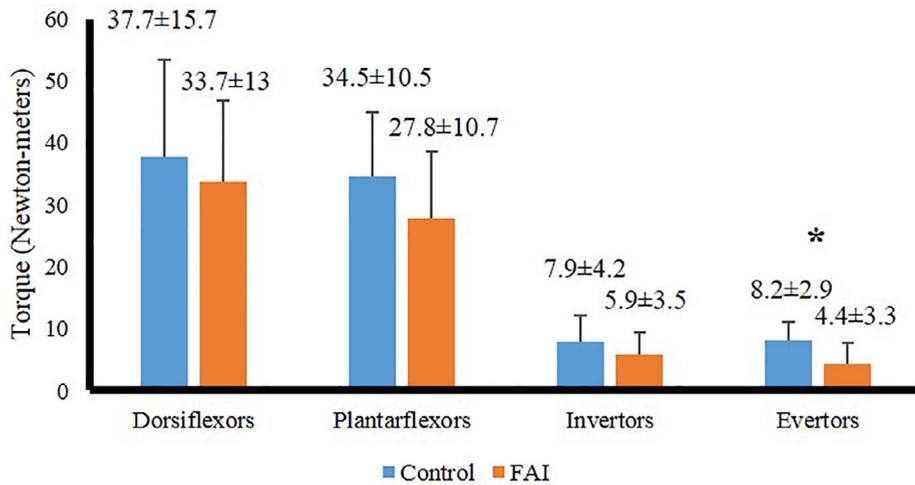


Fig. 2. A comparison between the functional ankle instability (FAI) and control groups in the maximum voluntary isometric contraction (MVIC) of the dorsiflexors, plantarflexions, invertors, and evertors of the practiced side. Error bars represent standard deviation. \*p < 0.05.

### 3. Results

#### 3.1. MVIC of ankle muscles: practiced side

We found a significant between-group difference in the MVIC of ankle evertors in the practiced side [ $t(17.7) = 2.8, p = 0.01$ ], with the FAI group demonstrating lower MVIC (Fig. 2). In contrast, there was no between-group difference in the MVIC of the ankle dorsiflexors, plantarflexors, and invertors. Based on these results, we adjusted for the MVIC of the ankle evertors in the LMM model that compared the ankle force control index between the FAI and control groups in the practiced side.

#### 3.2. Pre-test and post-test conditions: practiced side

Fig. 3 shows the descriptive statistics (mean and standard deviation) of the ankle force control index of the control and FAI groups in the pre-test and post-test conditions. In the pre-test condition (the two bars on the left side of Fig. 3), the mean index value was lower in the FAI group compared to the control group. Inferential statistics suggested that this observed between-group difference

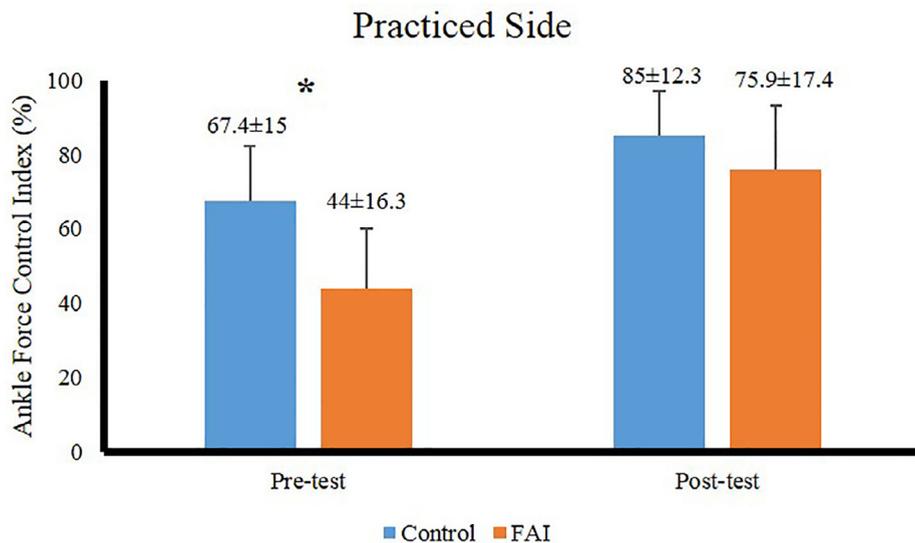
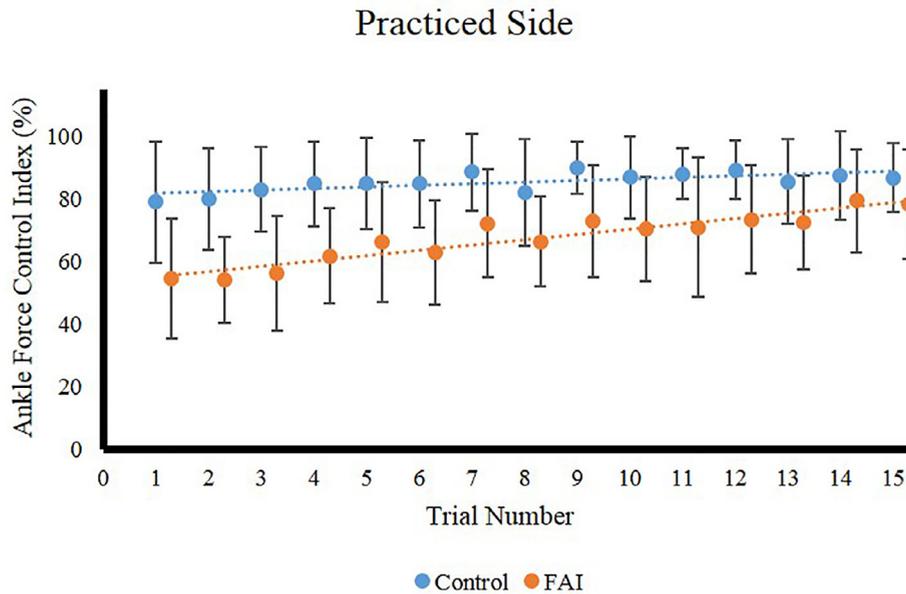


Fig. 3. A comparison between the functional ankle instability (FAI) and control groups in the ankle force control index of the practiced side in the pretest and post-test conditions. Error bars represent standard deviation. \*p < 0.05.



**Fig. 4.** A comparison between the functional ankle instability (FAI) and control groups in the ankle force control index over the 15 trials of practice. The dashed lines are the fitting lines for each group. Error bars represent standard deviation.

reached statistical significance. Specifically, the LMM detected a significant main effect of group on the ankle force control index, controlling for the covariates [ $F(1,18) = 18.7, p < 0.01$ ]. All covariates had significant impact on the ankle force control index. The ankle force control index had a negative relationship with the task completion time [ $F(1,36.2) = 23.3, p < 0.01$ ], and had a positive relationship with the trial numbers [ $F(2,18.3) = 6.7, p < 0.01$ ] and with the MVIC of the ankle evertors [ $F(1,17.7) = 5.3, p = 0.03$ ].

In the post-test condition (two bars on the right side of Fig. 3), the mean index value in the practiced side was slightly lower in the FCI group compared to the control group. However, inferential statistics suggested that this observed between-group difference did not reach statistical significance. Specifically, the LMM did not detect a significant main effect of group, controlling for the covariates [ $F(1,13.7) = 1, p = 0.3$ ]. Also, none of the covariates had a significant impact on the ankle force control index.

### 3.3. Practice condition

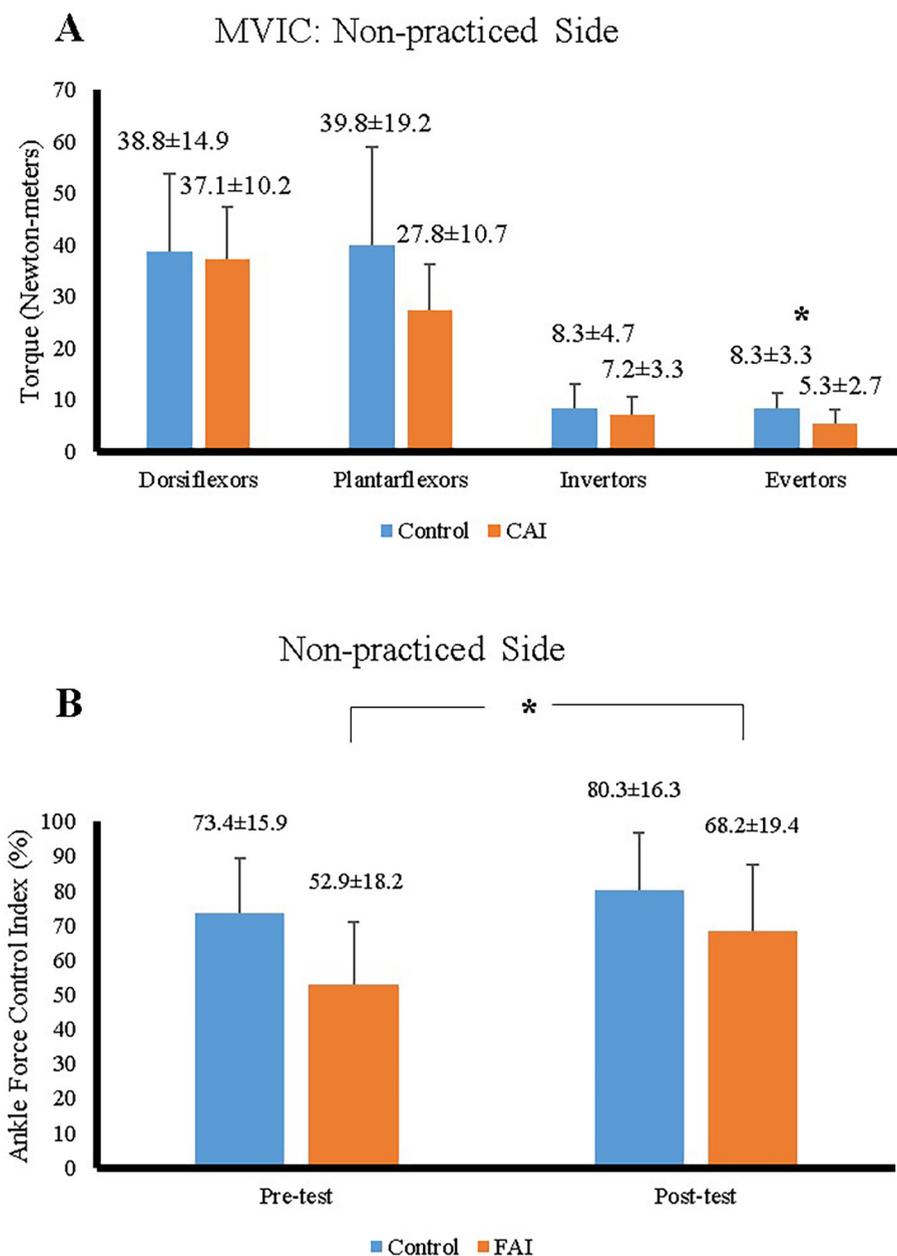
Fig. 4 shows the descriptive statistics (mean, standard deviation, and fitting line) of the ankle force control index of the control and FAI groups across the 15 trials in the practice condition. Based on the mean values observed in Fig. 4, the ankle force control index was lower in the FAI group than that in the control group in the practice condition. Fig. 4 also shows that both groups demonstrated a rising trend in the ankle force control index over the 15 trials of practice, although the rate of change was faster in the FAI group than that in the control group (see the slope of the fitting lines). Inferential statistics suggested that this observed difference in the rate of change reached statistical significance. Specifically, the LMM detected a significant group by trial interaction effect on the ankle force control index (i.e., the slopes of the fitting lines were significantly different), controlling for the covariates [ $F(14,17.7) = 17.3, p < 0.01$ ]. Since the interaction effect was significant, we did not report the main effects of group and trial as they can be misleading (Weinberg & Abramowitz, 2008).

All covariates had a significant impact on the ankle force control index in the practice condition. The ankle force control index had a negative relationship with the task completion time [ $F(1,30.9) = 621.5, p < 0.01$ ] and had a positive relationship with the MVIC of the ankle evertors [ $F(1,16) = 26, p < 0.01$ ]. The ankle force control index was greater in the later trials than earlier trials [ $F(14,17.8) = 13, p < 0.01$ ].

### 3.4. Performance in the non-practiced side

In the non-practiced side, we found a significant between-group difference in the MVIC of the ankle evertors [ $t(18) = 2.3, p = 0.03$ ], with the FAI group demonstrating lower MVIC (Fig. 5A). In contrast, there was no between-group difference in the MVIC of the ankle dorsiflexors, plantarflexors, and invertors. Based on these results, we adjusted for the MVIC of the ankle evertors in the LMM model that compared the ankle force control index between the FAI and control groups in the non-practiced side.

Both groups increased the ankle force control index from the pre-test condition to the post-test condition in the non-practiced side (Fig. 5B). In the control group, however, the increase did not reach statistical significance, controlling for the covariates [ $F(1,10) = 0.3, p = 0.6$ ]. In contrast, the increase reached statistical significance, controlling for the covariates [ $F(1, 8.9) = 8.1, p = 0.02$ ]. The task completion time had a significant impact on the ankle force control index in both the FAI group [ $F(1,10.3) = 263.4, p < 0.01$ ] and control group [ $F(1,14) = 116.7, p < 0.01$ ]. The effect of trials was not significant.



**Fig. 5.** (A) A comparison between the functional ankle instability (FAI) and control groups in the maximum voluntary isometric contraction (MVIC) of the dorsiflexors, plantarflexions, invertors, and evertors of the in the non-practiced side. (B) A comparison between the FAI and control groups in the ankle force control index of the non-practiced side in the pre-test and post-test conditions. Error bars represent standard deviation. \* $p < 0.05$ .

#### 4. Discussion

This study had three major findings on the practiced side (the affected side/more unstable ankle for the FAI group). First, the FAI group demonstrated a lower ankle force control index compared to the control group when the task was novel (i.e., before practice). Second, both FAI and control groups improved the ankle force control index over time in the practice condition, although the improvement was greater in the FAI group compared to the control group. Third, the between-group difference in the ankle force control index became non-significant after the practice. In addition to these major findings, we also found that the ankle force control index in the non-practiced side significantly increased from the pre-test to the post-test conditions in the FAI group, suggesting that inter-limb transfer occurred. While a similar increase was observed in the control group, the difference was not significant.

This current study was motivated by previous results that individuals with FAI may have deficits in ankle force sense, which was observed in force reproduction tasks (Arnold & Docherty, 2006; Docherty & Arnold, 2008; Simon et al., 2014). We advanced this

research to determine if individuals with CAI have deficits in force sense-based actions. The force control task used in this study required participants to adjust the magnitude and direction of the ankle muscle forces as accurately and as fast as possible. Our robotic technology enabled the test to be performed isometrically to minimize the involvement of position sense and kinesthesia in the task performance. The task was novel to the participants in the pre-test and therefore resulted in them largely relying on force sense to perform the task (Mulder & Hulstijn, 1985; Sober & Sabes, 2005). Thus, it is likely that the FAI group's inferior performance observed in the pre-test condition was due to deficits in their force sense.

It was interesting to observe that the between-group difference in ankle force control became smaller in the post-test condition. Compared to the pre-test condition, participants may have been more reliant on a feedforward than feedback mechanism to perform the task. A feedforward model can be formed to guide motor performance after multiple practice trials (Bastian, 2008; Kawato, 1999; Yen et al., 2014; Yen et al., 2013). The ability to use feedforward control can improve movement efficacy as it reduces sensory-motor delays (Kawato, 1999; Shimansky, 2000) and compensates for inadequate sensory feedback (Kuo, 2002). Thus, the FAI group's improved performance observed in the post-test condition was likely because a feedforward model had been established to guide the motor performance and their reliance on force sense was reduced. This interpretation can be confirmed by the results that the performance of the non-practiced side was improved in the post-test condition. From a perspective of generalized motor program theory, inter-limb transfer occurs because a feedforward model was formed through the practice of one limb, and is available for use to produce the motor task with the opposite limb (Perez et al., 2007). The increase in the ankle force control index in the non-practiced side was significant in the FAI group but not in the control group. A possible reason was that the control group's ankle force control index was already high in the pre-test condition (~73%), and it may be difficult to improve the performance simply through transfer of learning from the opposite limb.

The examination of inter-limb transfer in individuals with FAI was an innovation of our study. We were not aware of any previous study investigating this question. We had a mix of participants who had unilateral or bilateral FAI in this current study. We examined each individual participant's change in force control performance of the non-practiced side from the pre-test to post-test conditions. We found that all participants in the FAI group had an increase in the ankle force control index. The results suggested that individuals with FAI can achieve inter-limb transfer, regardless having unilateral or bilateral injuries. A larger scale study should be conducted to verify this study outcome.

Our study found that the FAI group had lower MVIC of the ankle evertors compared to the control group. The literature, at the individual study level, is inconsistent on whether FAI is associated with deficits in ankle evertor strength. While some studies suggested that individuals with FAI have eversion strength deficits (Munn, Beard, Refshauge, & Lee, 2003; Tropp, 1986; Willems, Witvrouw, Verstuyft, Vaes, & De Clercq, 2002), other studies found counterevidence (Bernier & Perrin, 1998; Kaminski, Perrin, & Gansnedter, 1999; McKnight & Armstrong, 1997). To address the contradictory findings, Arnold et al. (2009) performed a meta-analysis on the relevant literature, and concluded that individuals with FAI have weaker ankle evertor strength compared to their healthy counterparts, which was consistent with our result. A major difference between ours and previous studies was how strength was measured. Our study measured ankle strength isometrically with the ankle placed in the neutral position, while previous studies measured concentric strength with the ankle joint moving at different speeds. Future study may examine ankle muscle strength across different types of contraction in individuals with FAI.

This current study may have potential clinical application in the future. Limited clinical tools are available to objectively differentiate individuals with and without FAI. Many existing tools developed for this purpose, such as the CAIT (Hiller et al., 2006), are self-report surveys. The force control task used in this study could be developed into an objective tool for FAI assessment based on individuals' time and accuracy performance.

This study had a few limitations. First, the force control test was performed with the ankle placed in the neutral position. Different ankle positions can change the length-tension relationship of ankle muscles and may therefore change the results. Future study may examine the ankle force control ability when the joint is placed in an open-packed or a close-packed position. Second, we did not constrain the sequence of target hitting as we wanted the participants to find the most comfortable strategy to complete the task. Different target hitting sequences could potentially confound the results. Third, the ankle force control index was quantified based on participants' force control performance in all eight directions. There may be one particular direction that can best differentiate individuals with or without FAI. These questions will be addressed in our follow-up studies. Lastly, while the non-practiced side did not go through the 15 trials of practice, potential learning effects could occur during the three test trials in the pre-test condition. To address this potential confounding effect to inter-limb transfer, we will test if individuals with FAI can acquire, retain, and transfer the force control skill in three trials of test/practice in a future study.

## 5. Conclusion

In this study, we compared ankle muscle force control between individuals with FAI and their healthy counterparts. The force control ability was measured based on the accuracy performance when the participants adjusted the magnitude and direction of ankle muscle forces isometrically through the innovative use of robotic technology and a virtual maze game. The results showed that the FAI group had reduced ability to control ankle muscle forces compared to the control group when the task was novel. However, the between-group difference became non-significant after multiple trials of practice. The change in performance before and after practice may be due to different degrees of reliance on force sense.

## 6. Declarations of interest

None.

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