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Original Research

H-reflex in abductor hallucis and postural performance between flexible flatfoot and normal foot

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ABSTRACT

Objective: Morphological changes of the abductor hallucis muscle (AbH) in flexible flatfoot (FF) individuals influence regulations of the medial longitudinal arch (MLA). Prolonged and repeated stretching of AbH in flexible flatfoot may cause changes in muscle reflex properties and further influence postural performance. However, AbH muscle reflex under different postural conditions have never been examined. The purpose of this study was to investigate differences in AbH H-reflex and postural performance between individuals with normal foot (NF) alignment and FF under prone, double-leg stance (DLS), and single-leg stance (SLS) conditions.
Design: Cross-sectional study.
Setting: University laboratory.
Participants: Individuals with FF (n = 12) and NF (n = 12).
Main outcome measures: AbH H-reflex, AbH EMG and center of pressure (CoP) displacement.
Results: Under all postural conditions, AbH H-reflex was significantly lower in the FF group ($P < .05$). Under the SLS condition, AbH EMG was significantly higher in the FF group ($P < .05$), and CoP displacement for the medial-lateral and anterior-posterior directions were significantly higher in the FF group ($P < .05$).
Conclusions: With increased postural demand, FF individuals maintained their postural stability by recruiting greater AbH activities than through automatic stretch reflex, but FF individuals still showed inferior posture stability.

1. Introduction

Flexible flatfoot is a common foot condition characterized by partial or complete collapse of the medial longitudinal arch (MLA) when in bearing weight condition(Lee, Vanore, Thomas et al., 2005). Flexible flatfoot has been proposed to be associated with many factors including improper biomechanics (e.g., uneven pelvis position, scoliosis or leg length discrepancy) or muscle-related issues (e.g., calf muscle tightness, hip external rotators weakness or foot muscle weakness) (DiGiovanni & Langer, 2007, Chuter & Janse de Jonge, 2012).

Deviated joint position and posture in flexible flatfoot can lead to musculoskeletal problems in other body regions, including anterior cruciate ligament tear, patella tendinitis, and iliotibial band syndrome(Allen & Glasoe, 2000; Loudon, Jenkins, & Loudon, 1996; Nester, van der Linden, & Bowker, 2003; Tateuchi, Shiratori, & Ichihashi, 2015; Williams, McClay, & Hamill, 2001). It is also commonly associated with clinical symptoms (eg, foot and ankle pain, instability, and disorders of the lower back and lower extremities) and health-related hazards that can directly or indirectly affect quality of life(Lever & Hennessy, 2016).

Postural sways in upright stance posture resembles an inverted

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pendulum with ankle and foot acting as the crucial role, thus poor ankle and foot control would lead to postural instability.(D.A. 1995) Although ankle plantar flexors are the major muscles to regulate anterior-posterior postural sway (Loram, Maganaris, & Lakie, 2005; Tokuno, Carpenter, Thorstensson, Garland, & Cresswell, 2007), previous researchers found that plantar intrinsic foot muscle dysfunction is also a contributing factor to postural instability(Kelly, Kuitunen, Racinais, & Cresswell, 2012; Menz, Morris, & Lord, 2005). Intrinsic foot muscles are essential for postural control and their activities escalates under circumstances with increasing postural instability, for example, single leg standing (Kelly et al., 2012), thus plantar intrinsic foot muscle dysfunction would lead to poorer postural control.

The Hoffmann reflex (H-reflex) is a monosynaptic reflex that is electrically homogenous to the spindle stretch reflex. It resamples spindle inputs to a motoneuronal pool that indicates alpha-motor neuron excitability(Palmieri, Ingersoll, & Hoffman, 2004; Zehr, 2002). The H-reflex is assessed as a reflection of nervous responses from the spinal level in various conditions, including neurologic disorders, musculoskeletal injuries, treatment effects of exercise, and motor task performance(Aagaard, Simonsen, Andersen, Magnusson, & Dyhre-Poulsen, 2002; Silva et al., 2016; Vila-Cha, Falla, Correia, & Farina, 2012). Previous study showed muscle reflex sensitivity altered after passive muscle stretching (Avela, Kyrolainen, & Komi, 1999). It may highlight the possible stretch reflex contributions of plantar intrinsic foot muscles to the passive tension under the foot, and to plantar aponeurosis during the propulsion phase of ambulation. Current data supports that morphological alternations of foot muscles (e.g., changes in muscle size) in flatfoot individuals (Angin, Crofts, Mickle, & Nester, 2014), but little attention has been paid to their muscle reflex performances.

Plantar intrinsic foot muscles, especially the abductor hallucis muscle (AbH), are important for supporting and regulating the MLA during dynamic activities(Kelly et al., 2012). AbH muscle contraction leads to first metatarsal abduction and flexion, calcaneus inversion, and ankle supination, with corresponding changes in the navicular height(Wong, 2007). Prior studies demonstrated the increased navicular drops in association with anesthetization and fatigue of the AbH muscle, and arch height restoration upon stimulation of plantar intrinsic foot muscles beyond their natural muscle activation levels(Goo, Heo, & An, 2014; Headlee, Leonard, Hart, Ingersoll, & Hertel, 2008; Kelly, Cresswell, Racinais, Whiteley, & Lichtwark, 2014).

Current available data suggests that the AbH muscle controls the MLA thus contributing to postural stability (Zhang, Schutte, & Vanwanseele, 2017); however, no prior studies investigated the reflex properties of the AbH muscle under different postural conditions and compared between normal foot and flexible flatfoot. Thus, in the present study, we aimed to investigate the differences in neuromuscular control and postural performance—including AbH H-reflex, EMG, and center of pressure (CoP)-related parameters—under different postural conditions and between individuals with normal foot (NF) alignment and flexible flatfoot (Palmieri et al.).

2. Methods

2.1. Participants

We recruited 15 participants with FF and 15 with NF alignments. Participants were included as FF or NF according to their Foot Posture Index (FPI-6) and navicular drop (ND) scores measured in the laboratory(Cornwall, McPoil, Lebec, Vicenzino, & Wilson, 2008; Mueller, Host, & Norton, 1993). Individuals with bilateral FPI-6 scores ranging from 0 to +5 and ND of 5–9 mm were categorized as the NF group, and those with FPI-6 scores ranging from +6 to +12 and ND of greater than 10 mm were categorized as the FF group. Exclusion criteria were: history of ankle injury within the previous 6 months, diagnosed lower extremity injuries, leg length discrepancy greater than 1.5 cm, or severe scoliosis. However, six individuals (three in each group) were excluded because biphasic motor responses were unable to identify from their AbH muscles. Written informed consents were given to all participants with regards to the experimental procedure, and it was approved by the National Taiwan University Hospital Research Ethics Committee (no. 201607074RIN).

2.2. Procedures

Demographic and baseline data were collected from each participant at the beginning of the study (Table 1). We recorded AbH H-reflex, EMG, and center-of-pressure (CoP) parameters under three postural conditions with increasing demands, such as: prone, double-limb stance (DLS), and single-limb stance (SLS)(Taube, Gruber, & Gollhofer, 2008).

2.2.1. Postural conditions

In the prone condition, participants were positioned on the testing table with their arms resting at their sides, eyes closed lightly, and heads turned to the side opposite of the testing (dominant) foot. Knees were positioned at 20° flexion, and ankles were maintained in a neutral position (Fig. 1A). Participants were instructed to relax as much as possible, and to not voluntarily contract their muscles (Versino et al., 2007).

In the DLS condition, the participants stood upright on a force platform, with their bare feet shoulder-width apart. They were instructed to keep their head faced forward, and to remain as steady as possible. In the SLS condition, participants were asked to stand on their dominant foot only and to keep their upper body steady. For each trial under both weight-bearing postural conditions, the participants were encouraged to maintain a steady stance throughout the experiment.

2.2.2. EMG and H-reflex assessments

AbH reflexes were elicited by 1-ms rectangular pulses delivered using an electrical stimulator (Model S88; Grass Instruments, USA). An adhesive anode electrode was placed over the patella, and a bar cathode electrode was fixed on the skin surface over the posterior tibial nerve at the popliteal fossa (Fig. 1A). AbH activity was recorded using a wireless EMG system (BIOPAC Systems, Inc. Santa Barbara, CA) with a gain of 500, a 4,000-Hz sampling frequency, and a band-pass filter of 10–500 Hz. Two 1-cm-diameter adhesive Ag/AgCl electrodes were attached onto the AbH muscle belly and at the medial side near the base of the big toe's proximal phalanx (Fig. 1B). A ground electrode was placed over the lateral malleolus(Huang,

Table 1
Participant characteristics.

Group	NF (n = 12)	FF (n = 12)	*P* value
Sex	9 females, 3 males	8 females, 4 males	
Age (yrs)	24.83 ± 2.98	26.75 ± 4.99	.25
Height (cm)	166.23 ± 9.80	164.38 ± 7.07	.60
Weight (kg)	61.83 ± 8.27	61.67 ± 19.35	.98
FPI-6	2.33 ± 1.61	10.92 ± 1.16	<.01[a]
ND (mm)	3.75 ± 1.60	14.25 ± 2.83	<.01[a]

Data are presented as mean ± standard deviation. Abbreviations: FF, flexible flatfoot; NF, normal foot; FPI-6, Foot Posture Index-6; ND, Navicular drop.
[a] Statistically significant difference between groups.

Fig. 1. H-reflex assessment in prone position (A), AbH EMG electrode placements (B).

Cherng, Yang, Chen, & Hwang, 2009; Versino et al., 2007).

For muscle electromyography normalizations, we recorded maximum voluntary isometric contractions (MVIC). The subjects sat with their ankles in a neutral position and their knees flexed to 90° and then pushed their first metatarsal joints downward without bending the interphalangeal joint or lifting their heels. Simultaneously, the examiner applied an adduction force to the medial side of the first proximal phalanxes and asked the individual to contract as hard as they could for 5 s(Headlee et al., 2008). Three MVICs were recorded with a 2-s build-up followed by 3 s of maximum effort, with a 1-min rest session between contractions. We used a middle 1-s window within the 3-s period of maximum effort to calculate the average root mean square (RMS) from the three MVICs. All AbH EMG signals were normalized to MVICs and presented as %MVIC.

Before evaluating the AbH H-reflex in each postural condition, we obtained three maximum M responses (M_{max}) of the AbH muscle by gradually increasing the quantitative stimulus between individuals. We used the intensity that elicited 50% ± 10% of M_{max} (M_{sti}) as the stimulus intensity to record H-reflexes during each postural condition(Marquez, Morenilla, Taube, & Fernandez-del-Olmo, 2014). The electrical stimuli were first delivered at the targeted intensity (M_{sti}), with a 10-s interval and with the subject in the prone position, and AbH H-reflexes were recorded. For the DLS and SLS conditions, an electrical stimulus was delivered after 20 s of CoP and EMG recording. We recorded eight H-reflexes under each postural condition. To investigate the possible influence of muscle contractions on H-reflexes during dynamic postural tasks, we recorded AbH EMG activities 50 ms prior to stimulus delivery for each trial, and used these EMG data to adjust for the influence of active muscle contraction on H-reflex(Dietz, Faist, & Pierrotdeseilligny, 1990; Larsen, Mrachacz-Kersting, Lavoie, & Voigt, 2006).

2.2.3. CoP assessment

CoP displacements under the two weight-bearing conditions (DLS and SLS) were categorized into anterior-posterior (AP) and medial-lateral (ML) movements of the CoP. They were recorded using force platforms with four load cells (CRS03; Silicon Sensing, UK) installed on the bottom of the force plate at each of the four corners. All analog signals were obtained and recorded via the NI 9215 unit's compact data acquisition device (cDAQ-9172; National Instruments, USA). The load cell signals were analyzed using LabVIEW 2014 (National Instruments, USA).

2.3. Data processing

H-reflex amplitude rises with increasing muscle contraction, which may be due to increased neural drive from the supraspinal level(Nielsen, Petersen, Deuschl, & Ballegaard, 1993; Stein, Estabrooks, McGie, Roth, & Jones, 2007). To account for the influence of different muscle contraction levels, we presented the H-reflex value as the ratio of the peak-to-peak amplitudes of the AbH muscle H-reflex (%M_{max}) divided by the AbH background EMG (50 ms prior to the testing stimuli)(Capaday, 1997; Pinar, Kitano, & Koceja, 2010). The electrical stimulus consistency under each postural condition was checked with the M_{sti}, expressed as a percentage of M_{max}. We calculated the mean AbH EMG RMS for the entire duration of each condition, and it was normalized and represented as %MVIC.

CoP data were sampled at 1000 Hz and filtered with a low-pass Butterworth filter with a cut-off frequency of 6 Hz. We calculated the RMS of stable CoP from the stable 20 s in the AP and ML directions under both weight-bearing conditions.

Mean H-reflex, M_{sti}, and AbH EMG of each postural condition, and the mean CoP displacement under the two weight-bearing conditions were processed and analyzed using Matlab v. 20 (Mathworks, Inc. Natick, MA, USA).

2.4. Statistical analysis

Demographics characteristics, FPI-6 scores, and ND (mm) were compared between the NF and FF groups using independent-sample *t*-tests. To compare the differences in response amplitudes—including H-reflex, M_{max}, M_{sti}, EMG for AbH muscles for each postural condition, a 2 (group: NF and FF) × 3 (posture: prone, DLS, and SLS) mixed model analysis of variance (ANOVA) was used. Next, we examined the weight-bearing effect on AbH H-reflex and AbH EMG by performing post-hoc analysis (Bonferroni corrections) between prone and DLS conditions. We also analyzed the postural-difficulty effect on AbH H-reflex, and AbH EMG by performing post-hoc analysis (Bonferroni corrections) between DLS and SLS conditions. We then used independent-sample t-tests to compare CoP displacement (CoPAP, CoPML) for DLS and SLS conditions between the two groups. Lastly we used paired-t-test to compare CoP displacement between DLS and SLS trials. Statistical analyses were performed using SPSS software (version 20.0; IBM Corp., Armonk, New York). The threshold for statistical significance was set at $P < .05$.

3. Results

Fig. 2 presents examples of the H-reflexes under three postural conditions in both groups. Under all postural conditions, the AbH H-reflex was significantly lower in the FF group compared to the NF group (Prone: $F_{1,22} = 37.90$, $P < .01$; DLS: $F_{1,22} = 5.68$, $P < .01$; SLS: $F_{1,22} = 9.53$, $P < .01$; Fig. 3). In both FF and NF groups, we found significant lower AbH H-reflex in DLS condition when compared to prone condition (weight bearing effect), and significant lower AbH H-reflex in SLS condition when compared to DLS condition (postural difficulty effect) ($P < .01$, Fig. 3). The stimulation consistency was verified, showing insignificant differences in M_{sti} and M_{max} among all experimental conditions in both groups ($P > .05$, Table 2).

AbH EMG was significantly higher in the FF group (130.31 ± 8.41%MVIC) compared to the NF group (74.44 ± 10.79% MVIC) in SLS condition. Regarding the postural difficulty effect, AbH EMG was significantly higher under SLS condition compared to DLS condition in both participant groups ($P < .01$, Table 3).

Single limb stance task induced a higher level of postural difficulty on postural sway, and larger CoP_{ML} and CoP_{AP} displacements

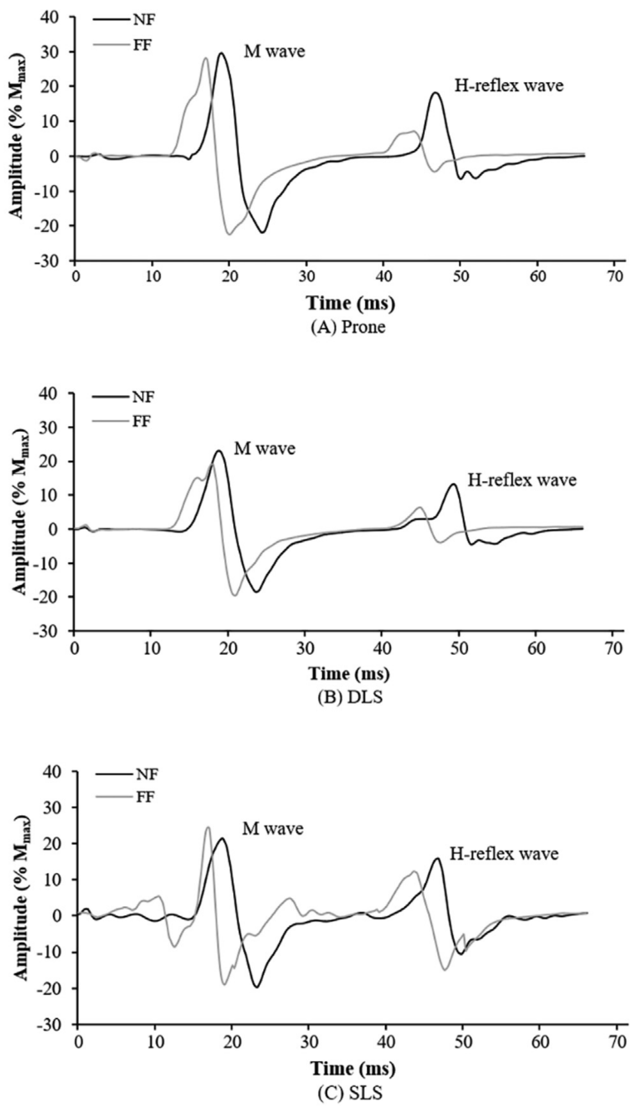

Fig. 2. Sample recordings of the abductor hallucis H-reflex from a normal foot (NF) participant and a flatfoot participant under the three postural conditions: prone (A), single-leg stance (SLS) (B), and double-leg stance (DLS) (C).

were observed in SLS condition when compared to DLS condition in both participant groups ($P < .05$, Fig. 4). Under SLS condition, significant larger CoP displacements in the ML and AP directions in FF group were observed when compared to NF group ($P < .05$; Fig. 4).

4. Discussion

The aim of this study was to investigate differences in AbH H-reflex, EMG and CoP-related parameters during three postural conditions between individuals with and without flexible flatfoot. Our results showed diminished AbH H-reflex, increased AbH EMG activities, and increased CoP displacements in individuals with flexible flatfoot when compared to those with normal foot alignment.

4.1. Lower AbH H-reflex in the FF group under each postural condition

Under all postural conditions, AbH H-reflex was significantly lower in the FF group than the NF group. The NF and FF groups showed the same levels of background EMG activities under the prone (NF: 8.52 ± 0.63 μV; FF: 9.57 ± 0.53 μV) and DLS (NF: background 17.77 ± 2.24 μV; FF: 19.37 ± 4.74 μV) conditions; thus, the lower H-reflex in the FF group may indicate lower AbH motor neuron excitability. H-reflex differences under non-weight-bearing conditions and DLS postural condition may result from “adaptive plasticity” in the spinal cord, via several possible causative mechanisms. Kim et al. reported that individuals with flexible ankle instability exhibit decreased ankle muscle H/M ratios, and proposed that arthrogenic muscle inhibition occurs due to mechanoreceptor damage within soft tissues, which interrupts neurologic feedback(Kim, Ingersoll, & Hertel, 2012; McVey, Palmieri, Docherty, Zinder, & Ingersoll, 2005). Koceja et al. described a reduced soleus H-reflex amplitude in elderly individuals, and a tendency for Ia presynaptic inhibition to increase with age, indicating chronic adaptive plasticity of the H-reflex(Koceja, Markus, & Trimble, 1995). It is also reported that changes in muscle fiber length affect the H-reflex during passive and active muscle actions(Koceja et al., 1995). Individuals with flexible flatfoot experience MLA collapse during weight-bearing tasks, potentially leading to repetitive or prolonged stretching of the AbH muscle under dynamic or static tasks, which could in turn influence the H-reflex. Avela et al. reported that the maximal H-reflex of the triceps surae muscle decreased by 43.38% following a repetitive passive stretching protocol, resulting in reduced activity of Ia afferents(Avela et al., 1999). To sum up, H reflex can be influenced by the changes of muscle length or mechanoreceptor properties through adaptive plasticity.

In our study, the FF group exhibited a lower AbH H-reflex with higher pre-existing background EMG activity under the SLS condition (NF: 229.12 ± 38.60 μV; FF: 576.04 ± 26.87 μV). The H-reflex differences between the two groups under the SLS postural condition may have been heavily influenced by differing levels of muscle activation. Under weight-bearing conditions, NF individuals regulate foot posture via slight contraction of the plantar intrinsic foot muscles, strengthening the MLA(Kelly et al. 2012, 2014). The higher AbH EMG activity observed in the FF group (130.31 ± 8.41 % MVIC) indicated greater muscle activity to control the foot arch under the SLS condition. Individuals with FF exhibit an excessive navicular drop that lengthens the MLA, and this in combination with a decreased base of support from single-leg standing would predispose the AbH muscle to actively contract more to elevate the foot arch(Kelly et al., 2014).

4.2. Decreased postural stability in the FF group

FF individuals exhibited greater CoP displacements with a decreasing base of support. Previous data indicate that foot postures and functions influence single-leg stability(Kelly et al., 2012; Sung, Zipple, Andraka, & Danial, 2017). Kelly et al. reported that plantar intrinsic foot muscle activities are correlated with mediolateral postural sway in a single-leg stance, suggesting that a central balance control mechanism regulates plantar intrinsic foot muscle activation in response to postural sway(Kelly et al., 2012). In the current study, increased AbH muscle activity in the SLS condition was more evident in the FF group, indicating that the spinal reflex in FF individuals was not robust enough to counterbalance the larger postural sway.

4.3. Inhibition of AbH H-reflex with increased postural difficulty

In both participant groups, we observed a lower AbH H-reflex under the SLS condition compared to the prone and DLS conditions. This decreased H-reflex related to weight bearing is consistent with previous studies showing significant downward modulation of the

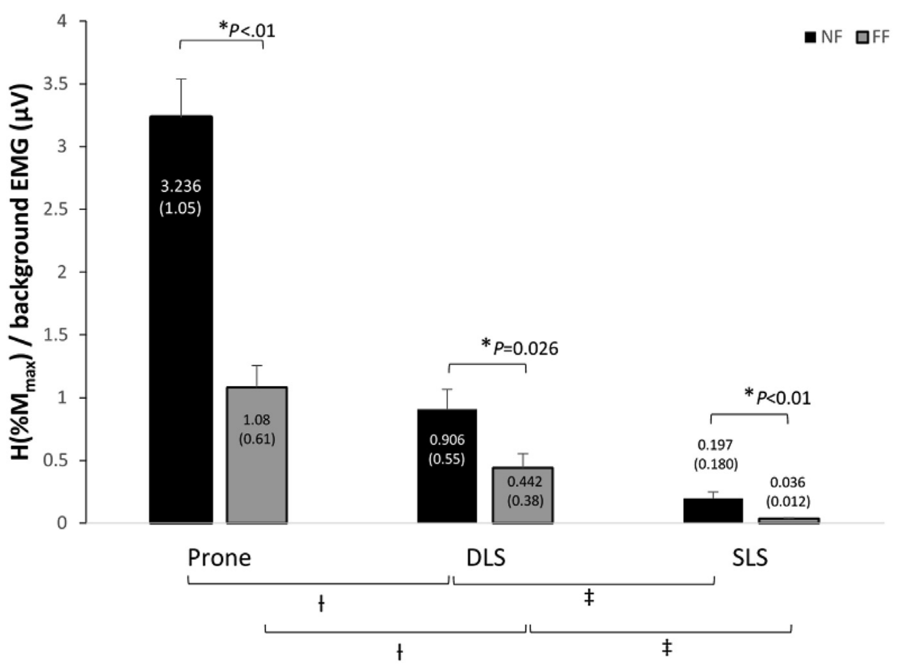

Fig. 3. Differences in the abductor hallucis H-reflex under different postural conditions. Data are presented as the mean (standard error). Abbreviations: FF, flexible flatfoot; NF, normal foot; DLS, double-leg stance; SLS, single-leg stance.
*Statistically significant difference between groups (P < .05).
ǂStatistically significant weight-bearing effect within groups (P < .01).
‡Statistically significant postural-difficulty effect within groups (P < .01).

Table 2
M_{max} and M_{sti} for the three postural conditions.

	Prone	DLS	SLS	Statistics
M_{max} (mV)	NF: 18.44 ± 1.14	NF: 18.44 ± 0.83	NF: 18.83 ± 2.11	Group effect: *P* = .24
	FF: 18.73 ± 0.24	FF: 18.75 ± 0.16	FF: 18.42 ± 1.53	Postural difficulty effect: *P* = .44
M_{sti} (% M_{max})	NF: 50.89 ± 1.90	NF: 50.76 ± 1.68	NF: 50.87 ± 2.23	Group effect: *P* = .72
	FF: 50.96 ± 1.29	FF: 51.65 ± 1.58	FF: 51.20 ± 2.35	Postural difficulty effect: *P* = .50

Data are presented as mean ± standard deviation. Abbreviations: M_{max}, maximum M wave; M_{sti}, stimulus M wave; DLS, double-limb stance; SLS, single-limb stance.

Table 3
Abductor hallucis EMG (%MVIC) under different postural conditions.

	Prone	DLS	SLS
NF	3.30 ± 0.60	6.39 ± 2.24	74.44 ± 38.60[a,b]
FF	2.54 ± 0.28	4.26 ± 4.74	130.31 ± 26.87[b]

Data are presented as the mean (standard error). Abbreviations: FF, flexible flatfoot; NF, normal foot; DLS, double-leg stance; SLS, single-leg stance.
[a] Statistically significant difference between groups (P<.01).
[b] Statistically significant from Prone and DLS conditions within groups (P<.01).

soleus H-reflex when changing from non-weight-bearing conditions to weight-bearing postural conditions (supine, sitting, and standing)(Trimble & Koceja, 2001; Chalmers & Knutzen, 2002). The decreased H-reflex also supported the hypothesis that presynaptic inhibition increases with rising postural complexity(Stein & Capaday, 1988). Our results showed a greater decrease in the AbH muscle H-reflex under SLS conditions compared to DLS conditions. Stein et al. previously reported that downward modulation of the H-reflex occurred under unstable stance conditions or with a reduced base of support due to presynaptic inhibition of Ia afferent inputs being sent by supraspinal structures(Stein & Capaday, 1988). When facing higher postural equilibrium demands, such as in a unilateral or tandem stance, regulation of stance stability may favor central control(Huang et al., 2009). Similarly, Llewellyn et al. reported inhibitory gating of the soleus H-reflex during walking and tandem stance(Llewellyn, Yang, & Prochazka, 1990).

4.4. Study limitations

The present study had several limitations. First, we recruited participants of 18–45 years of age to avoid the effects of aging or deterioration. This makes it difficult to extrapolate our results to other age populations. Second, we acquired the same amplitudes for the tested H-reflex among different postural conditions, assuming that the relative Ia afferents and motor axon thresholds remained constant. It was not practical to acquire H-M recruitment curves for all participants due to the possibility of fatigue effects caused by the numerous stimuli in this study. Third, the retrospective study design makes it difficult to identify the causative mechanism. Finally, postural control ability results from both spinal and supraspinal interactions. Further studies are needed to more comprehensively investigated interactions at the supraspinal level to identify possible influences or changes in individuals with flexible flatfoot.

5. Conclusions

Individuals with flexible flatfoot may exhibit neuromuscular

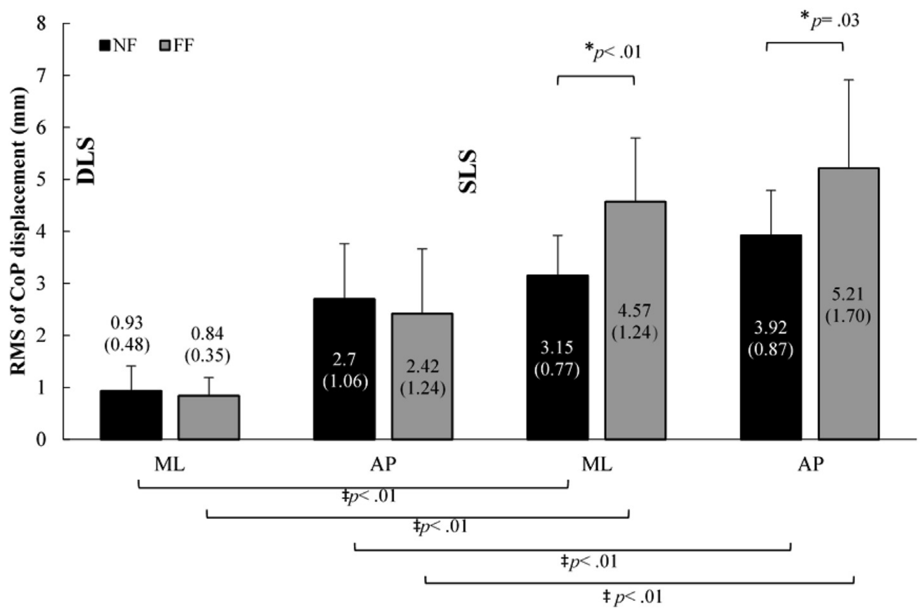

Fig. 4. Differences in CoP displacement during two standing postural conditions. Data are presented as mean (standard error). Abbreviations: FF, flexible flatfoot; NF, normal foot; ML, medio-lateral; AP, anterior-posterior; DLS, double-leg stance; SLS, single-leg stance.

adaptations, such as decreasing H-reflex and increasing EMG, and decreasing postural stability. The reduced AbH muscle reflex observed in participants with flexible flatfoot may indicate reflex adaptations due to a persistently lower medial longitudinal arch. Moreover, increased postural difficulty was associated with greater postural instability in individuals with FF. Compared to those with NF alignments, participants with FF exhibited greater use of active muscle contractions to maintain their postural stability rather than stretch reflexes of the AbH muscle.

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