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# A comparison of abductor hallucis muscle activation and medial longitudinal arch angle during nine different foot exercises

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ABSTRACT

*Background:* Intrinsic foot muscles are known to support the medial longitudinal arch (MLA) and stabilize the foot, and they are activated with weight bearing and increased postural demand. Various types of intrinsic foot muscle training have been reported, but one of the most useful of these, the short foot exercise, is challenging to perform effectively and requires practice, making it difficult to implement in ordinary clinical settings.
*Research question:* What are the differences in abductor hallucis longus (ABH) muscle activity and MLA angle during intrinsic foot muscle exercises that employ weight bearing and balancing conditions when they are performed with minimal practice?
*Methods:* Sixteen healthy volunteers performed nine different intrinsic foot muscle exercises, practiced once or twice. The exercises consisted of toe curl, short foot without pushing, short foot with pushing and toe spread exercises in sitting and standing positions, and single leg swing in a standing position. Each exercise was performed three times for five seconds. The activities of the ABH muscles were measured using surface electromyographic (EMG) sensors and the MLA angles during the exercises were captured using an optical motion tracking system. The integrals of the ABH EMG signals were calculated.
*Results:* Differences in the integral and maximum of the ABH EMG signal were found between the exercises ($p < 0.001$). Post-hoc pair-wise analysis revealed that the EMG activity was larger during the swing exercise than in exercises other than toe spread, both in sitting and standing positions, and short foot exercise with pushing while standing. The minimum MLA angle during each exercise was smaller for the toe spread exercise in a sitting position than other exercises ($p < 0.023$).
*Significance:* A single leg swing exercise may be effective for self-exercise of intrinsic foot muscles, particularly when intensive supervised physiotherapy is not possible.

## 1. Introduction

Intrinsic foot muscles are the muscles that both originate and insert on the foot. They are known to support the medial longitudinal arch (MLA) [1–3] and stabilise the foot [4]. Injury to or dysfunction of the plantar intrinsic foot muscles can produce foot deformity, pain, and disability [5]. Associations have been reported between impaired intrinsic foot muscles and plantar fasciitis [6], pes planus [2,3,7] and painful hallux valgus [8]. Therefore, exercises for strengthening the intrinsic foot muscles have been prescribed in rehabilitation and sports medicine to prevent or treat these foot injuries [9–13]. The effect of these exercises has been reported to correct static foot alignment and foot kinematics during gait in people with pes planus [14,15]. It was also reported in the healthy individuals that one exercise for strengthening the intrinsic foot muscles reduced arch collapse and improve balance ability [16].

There are several exercises to strengthen intrinsic foot muscles, including toe curl exercises, short-foot exercises, unilateral balance activities and toe spread exercises [17–19]. The toe curl exercise (Fig. 1a), which is also called a towel curl, is traditionally the most common exercise [4]. The short-foot exercise (Fig. 1b), which is performed by pulling the metatarsal heads toward the heel without curling the toes,

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has been recommended more recently, since it has been reported that the electromyographic (EMG) activity of the abductor hallucis (ABH) muscle was higher during short foot exercises than toe curl exercises [19]. However, the short-foot exercise is difficult to perform for people who are not used to using their intrinsic foot muscles [17,19]. Previous studies of short-foot exercises gave supervised practice times of between 1 hour and 2 weeks [12,16,19], which is too much time to make this practical in ordinary clinical settings. Alternatively, one study used EMG-based biofeedback to guide participants [17], which is too costly to make this approach ubiquitous in everyday clinical practice.

Weight bearing and balancing activates the intrinsic foot muscle; ABH muscle activation has been shown to be greater when standing than in sitting and performing the toe-spreading exercise [18], and greater during single leg stance compared to double leg stance [20]. However, information regarding the effect of weight bearing and balancing tasks on intrinsic foot muscle activation compared to other well-known intrinsic foot muscle exercises, such as toe curl and short foot exercises, is limited.

The primary purpose of this study was to compare the effectiveness of different intrinsic foot muscle exercises in sitting and standing positions and a balancing task, all with minimum practice, such that they could be explained to individuals sufficiently for them to be able to do the exercise independently within one clinic visit, on the EMG activation of ABH. The secondary objective was to analyse the MLA angle during each exercise.

## 2. Methods

### 2.1. Participants

Sixteen asymptomatic volunteers (31 ± 6 years old, 12 males and 4 females) participated in this study. Fifteen were right footed and one was left footed by the Waterloo Footedness Questionnaire [21]. The exclusion criteria included any foot injury within the prior 12 months, any surgical intervention on the foot, any known allergy to adhesive or skin lotion, any medical disorders that precluded a person from performing the exercises, and pregnancy. This study was approved by the Imperial College Research Ethics Committee and written informed consent was obtained from all participants.

### 2.2. Instrumentation

Wireless surface EMG sensors (Delsys Trigno, Natick, MA, USA) were used to monitor the activities of the ABH muscles, with sensors connected to a single-channel EMG amplifier. An eight-camera optical motion tracking system (Qualisys, Gothenburg, Sweden) was used to collect the kinematic data of the feet. The infra-red cameras captured the three-dimensional trajectories of reflective markers at an acquisition rate of 150 Hz.

### 2.3. Procedures

The muscle bellies of the ABH were palpated, and the EMG electrodes were placed on the skin directly above, which was approximately 1–2 cm posterior to the navicular tuberosity (Fig. 2). To track the foot motion and measure the MLA angle, six reflective markers were attached to the skin overlying the anatomic points: navicular tuberosity (NAV), medial aspect of the first metatarsal head (1MH), medial aspect of the first interphalangeal joint (1IJ), lateral aspect of the fifth metatarsal head (5MH), distal end of the calcaneus (DCA), and medial side of the calcaneus (MCA) (Fig. 2). The MCA marker was placed 30 (women) or 40 (men) mm from the most posterior part of the calcaneus and 30 (women) or 35 (men) from the floor [17,19].

Participants performed nine different foot exercises, including one balancing task (Fig. 1): toe curl, short foot without pushing, short foot with pushing and toe spread exercises in sitting and standing positions, and single leg swing in a standing position. Before doing each exercise, verbal instruction and a demonstration were provided, and participants practiced each exercise once or twice for familiarization. Participants were asked to hold each exercise position for five seconds with

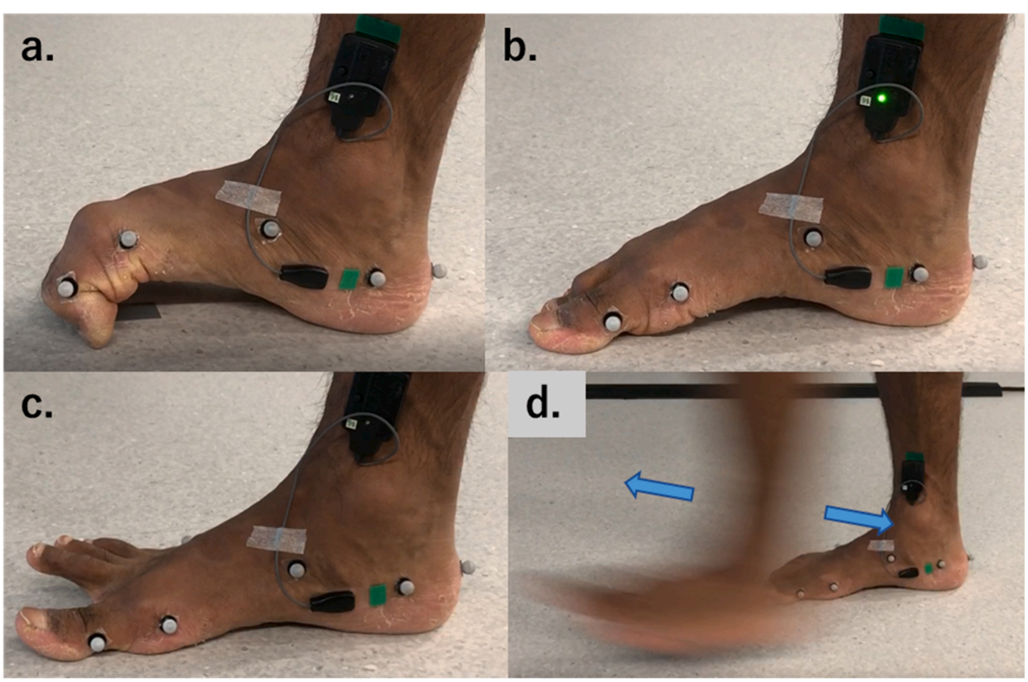


**Fig. 1.** a. Toe curl exercise: Participants curled their toes as much as possible, b. Short foot exercise: Participants shortened their foot in the anteroposterior direction and actively attempted to bring the head of their first metatarsal toward their heel, without toe flexion. This was performed with and without attempting to push the toes onto the floor. c. Toe spread exercise: Participants actively spread their toes as much as possible. d. Stand swing: Participants stood on one leg (measured leg) and swung the other leg in antero-posterior directions as much as possible, while maintaining their balance. Toe curl, short foot and toe spread exercises were done in both sitting and standing positions.

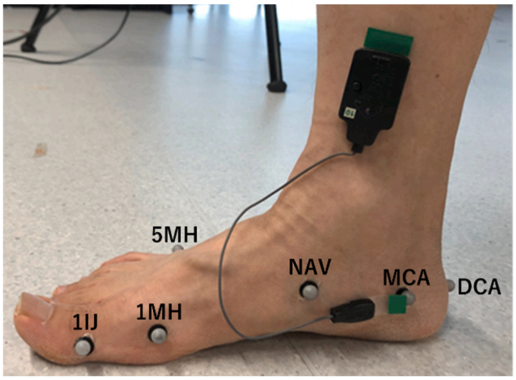


**Fig. 2.** Retro-reflective marker and surface EMG sensor placement on the foot, shown in a neutral posture. Markers were placed on the navicular tuberosity (NAV), medial aspect of the first metatarsal head (1MH), medial aspect of the first interphalangeal joint (1IJ), lateral aspect of the fifth metatarsal head (5MH), distal end of the calcaneus (DCA), and medial side of the calcaneus (MCA).

maximum effort. Each exercise was performed three times with 20 second intervals between trials. The order of the exercises was randomized. Lastly, maximum voluntary contraction (MVC) was measured by manual muscle testing of isometric maximum abduction and maximum flexion of the big toe. The larger EMG signal during abduction or flexion was defined as the activity during MVC.

### 2.4. Data processing

The EMG data were processed in MATLAB (MathWorks, Natick, MA, USA) using custom written code. Raw EMG datasets had their DC offset removed, were rectified and were filtered with a second order low-pass filter with a cut-off frequency of 6 Hz. All EMG data were normalised with the MVC. For each exercise, maximum muscle activation and integrated muscle activation of the ABH during the five second exercise were calculated, and the averages of each for the three trials were calculated for use in the statistical analysis.

The MLA angle was defined as the angle between the 1MH, NAV and MCA markers in a plane perpendicular to the plantar plane of the foot bisecting markers on the 1MH, 5MH and DCA. The perpendicular plane incorporated the 1MH and MCA markers [17]. The MLA angle during each trial was calculated in MATLAB and the minimum MLA angle was extracted.

### 2.5. Statistical analysis

Shapiro-Wilk tests were performed; EMG data were not normally distributed, but the minimum MLA angles were normally distributed. A Wilcoxon signed-rank test was used to determine whether there were any differences in the EMG data between the dominant and the non-dominant sides. No significant difference between the dominant and the non-dominant side was observed in any exercise; thus, the averages of the dominant and the non-dominant sides were used for the subsequent analyses. A Friedman test was conducted to examine the difference between integral and maximum ABH EMG activity levels between the exercises. The Dunn–Bonferroni test was used for post-hoc pairwise analyses. Regarding the minimum MLA angles, a paired t-test was used to determine whether there were any differences in the minimum MLA angles between the dominant and the non-dominant sides. A significant difference between the dominant and the non-dominant sides was observed in some exercises; thus, the dominant and the non-dominant sides were analysed separately. Repeated measure ANOVA was conducted to examine the difference in minimum MLA angles between the exercises. The Tukey test was used for post-hoc analysis. All statistical tests were conducted using SPSS 29.0 for Windows (SPSS Inc, Chicago, IL, USA). Significance was defined as $p < 0.05$.

## 3. Results

### 3.1. The EMG activity of the ABH

Differences in both the integral and maximum of the ABH EMG signals were observed among exercises ($p < 0.001$). Post-hoc pairwise analyses revealed that the integral of ABH EMG activity was larger for the swing exercise than for exercises ($p \leq 0.022$) other than toe spread, both in sitting and standing positions, and the short foot exercise with and without pushing in standing position (Fig. 3). On the other hand, it was smaller for seated toe curl than for other exercises ($p \leq 0.001$), except for the seated short foot exercise with and without pushing and standing toe curl exercise (Fig. 3). It was smaller for seated short foot and toe curl exercises than toe spread in standing position ($p \leq 0.028$; Fig. 3).

Similar results were observed for the maximum EMG activity during each exercise; it was larger for the swing exercise than for other exercises ($p \leq 0.036$), exceptions being the toe spread exercises and standing short foot exercise with pushing (Fig. 4). It was smaller for seated toe curl than other exercises ($p \leq 0.003$) other than the short foot without pushing exercises, toe curl in standing, and seated short foot with pushing. (Fig. 4). It was smaller for toe curl exercise in sitting and standing position than in toe spread in standing position ($p \leq 0.022$; Fig. 4). The swing exercise resulted in all participants activating their ABH muscles to at least 60 % MVC, with mean outputs surpassing 100 % MVC, whereas other exercises resulted in activations of less than 20 % for multiple participants (Figs. 3 and 4). Participants appeared to fall into categories of those who struggled to activate ABH muscles during short foot exercises and those who were able to activate the muscles during short foot exercises (e.g., Fig. 5).

### 3.2. The MLA morphology

A difference in minimum MLA angles was observed between

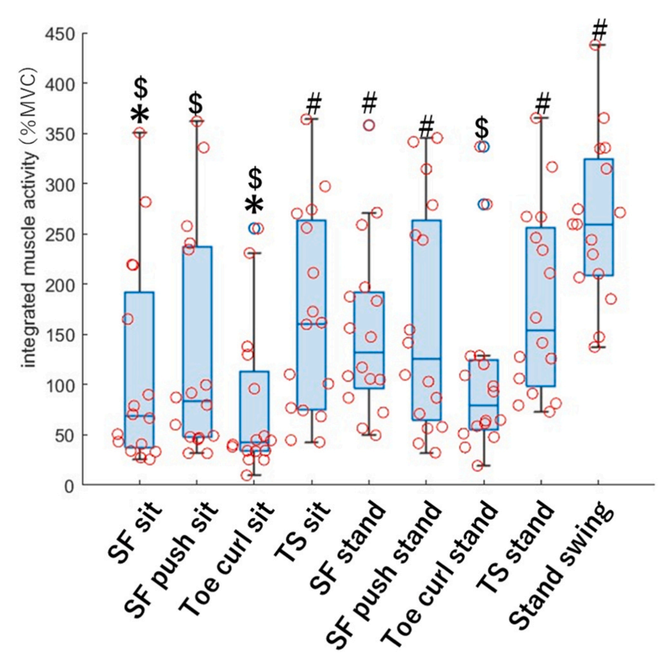


**Fig. 3.** Cumulative muscle activity of abductor hallucis longus (ABH) during five seconds of short foot (SF), toe curl, toe spread (TS), and single leg swing (stand swing) exercises. $: significantly smaller than stand swing exercise ($p \leq 0.022$). #: significantly larger than toe curl exercise in sitting position ($p \leq 0.011$). *: significantly smaller than TS stand exercise ($p \leq 0.028$).

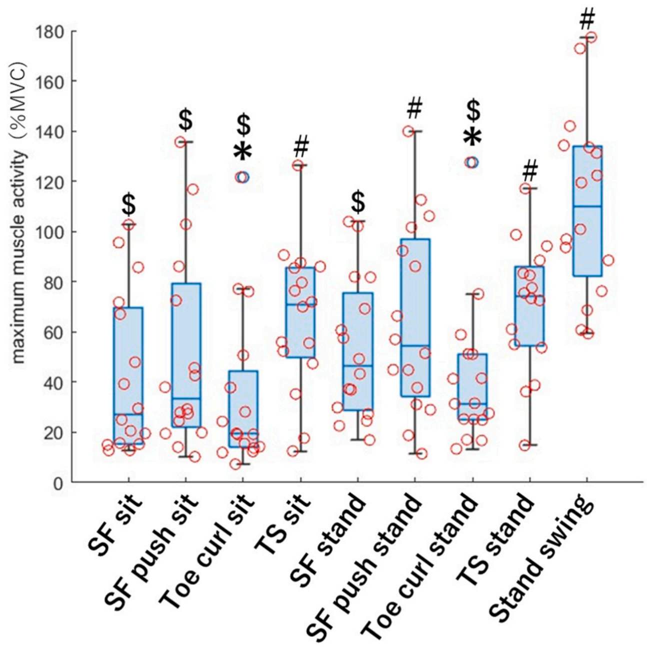


**Fig. 4.** Maximum muscle activity of abductor hallucis longus (ABH) during short foot (SF), toe curl, toe spread (TS), and single leg swing (stand swing) exercises. $: significantly smaller than stand swing exercise ($p \leq 0.036$). #: significantly larger than toe curl exercise in sitting position ($p \leq 0.003$). *: significantly smaller than TS stand exercise ($p \leq 0.022$).

exercises for both dominant and non-dominant sides ($p < 0.001$, F=21.47 and $p<0.001$, F=13.28, respectively). The minimum MLA angle (Table 1) was smaller during the toe spread exercise in a sitting position than during other exercises for both dominant and non-dominant sides ($p \leq 0.23$). During each exercise, the minimum MLA angle was larger in a standing position than in a seated position, other than for the short foot exercise and toe curl exercise on the non-dominant side. Results of further statistical comparisons may be found in the supplementary material.

## 4. Discussion

This study has found that a standing single-leg swing exercise could activate the ABH muscle to a greater amount compared to other intrinsic foot muscle exercises, even for people who struggled to activate the ABH muscle during short foot exercises, without requiring large amounts of time to learn and practice the exercise. This indicates that the swing exercise may be useful for patients for whom intensive, supervised physiotherapy is not an option and, therefore, they need to perform a self-exercise regimen of their intrinsic foot muscles.

Several studies have previously investigated the difference in ABH muscle activation between various intrinsic foot muscle exercises. Prior research studies have demonstrated that the muscle activation of the ABH is greater in short-foot exercises than in toe curl exercises [19]. The current study found no significant differences between muscle activations during the short foot exercise and the toe-curl exercise in either sitting or standing positions (Figs. 3 and 4). This may have been influenced by the limited number of participants, but the results also showed a wide range of ABH muscle activations during the short foot exercises, with some participants having maximum ABH muscle activity approaching 100 % MVC, while many others had maximum ABH muscle activity with less than 20 % MVC. This means that some people were able to activate ABH using the short foot exercise, but others were not. The practice time for each foot intrinsic muscle exercise in the present study was shorter than in previous studies that reported good ABH muscle activity with short foot exercises [16,19]. This may have resulted in more people not successfully activating their ABH using this approach. The current study also showed that the time-integrated ABH activation during the seated toe curl exercise was smaller than during the seated toe spread exercise and all the exercises in standing position, other than toe curl. This is consistent with previous understanding that toe curl is not very effective as an intrinsic foot muscle exercise [19,22].

Increasing postural demand as well as weight bearing has been shown to have an effect on activating ABH muscles. ABH activation during the toe-spreading exercise has been found to be greater when standing than in sitting [18]. EMG signals of ABH during standing, squatting and heel raise were found to be greater during single-limb positions than during double limb positions [20]. In addition, mean ABH EMG amplitude was greater in single leg stance than in double leg stance, with EMG amplitude waveforms correlated to of pressure [23]. Another study showed that functional exercises such as toe stance, toe walking, and hopping provoked comparable or more activation of the plantar intrinsic foot muscles than isolated foot exercises and suggested the usefulness of the functional exercises. However, the functional exercises in that study were in a heel-raised position which is less applicable to people with foot symptoms [24]. Our study has shown that a simple standing single leg swing exercise achieved good ABH activation and all participants could activate their ABH muscles to at least 60 % MVC, which was higher than during other intrinsic foot muscle exercises. As the swing exercise was performed while balancing on one leg, high weight bearing and postural demands may have resulted in the high ABH activation. The important message is that the swing exercise produced high ABH activation without any instructions for foot movement, which suggests that adding elements of weight bearing and postural demands may enable greater training of the ABH, even when there is not much time for training and practice.

Previous studies have reported that ABH is one of the muscles that maintains the MLA. It was found that navicular drop increased following a decrease of ABH muscle activity brought on by a tibial nerve block [3] or a fatiguing task [2], and electrical stimulation of the ABH counteracted MLA compression under a load [1]. Conversely, it has been reported that MLA morphology during short foot exercises did not change significantly, even when EMG activity of the ABH was observed to increase [17]. Following on from this, the suggestion was that estimating the change in ABH activity by the change of MLA morphology would be misleading [17]. This was consistent in the current study; exercises with high EMG activation of ABH did not necessarily show smaller MLA angles. The single leg swing exercise did not show the smallest MLA and the minimum MLA angle was smaller during standing than during sitting in most exercises; however, ABH activations were not greater during sitting than during standing. This suggests that estimating the activation of ABH from MLA angle would be difficult.

## 5. Strengths and limitations

The strength of this study is that it investigated the effect of a balancing task on the activation of intrinsic foot muscle, for which the existing clinical rehabilitation exercises are difficult to learn, and often require extensive time to perform correctly. There were several limitations in this study. Although there are many intrinsic foot muscles, and intrinsic foot muscle exercises aim to activate multiple muscles [4], only the activation of ABH was measured due to the difficulty of acquiring data from surface EMG sensors on the plantar surface of the foot during exercises in a standing position. In addition, the single leg swing exercise is not an isolated foot exercise, but rather a whole-body exercise; however, the effect of the exercise on muscles other than intrinsic foot muscles, such as extrinsic foot muscles and gluteus muscles, was not investigated.

## 6. Conclusion

The present study demonstrates that the ABH muscle is significantly

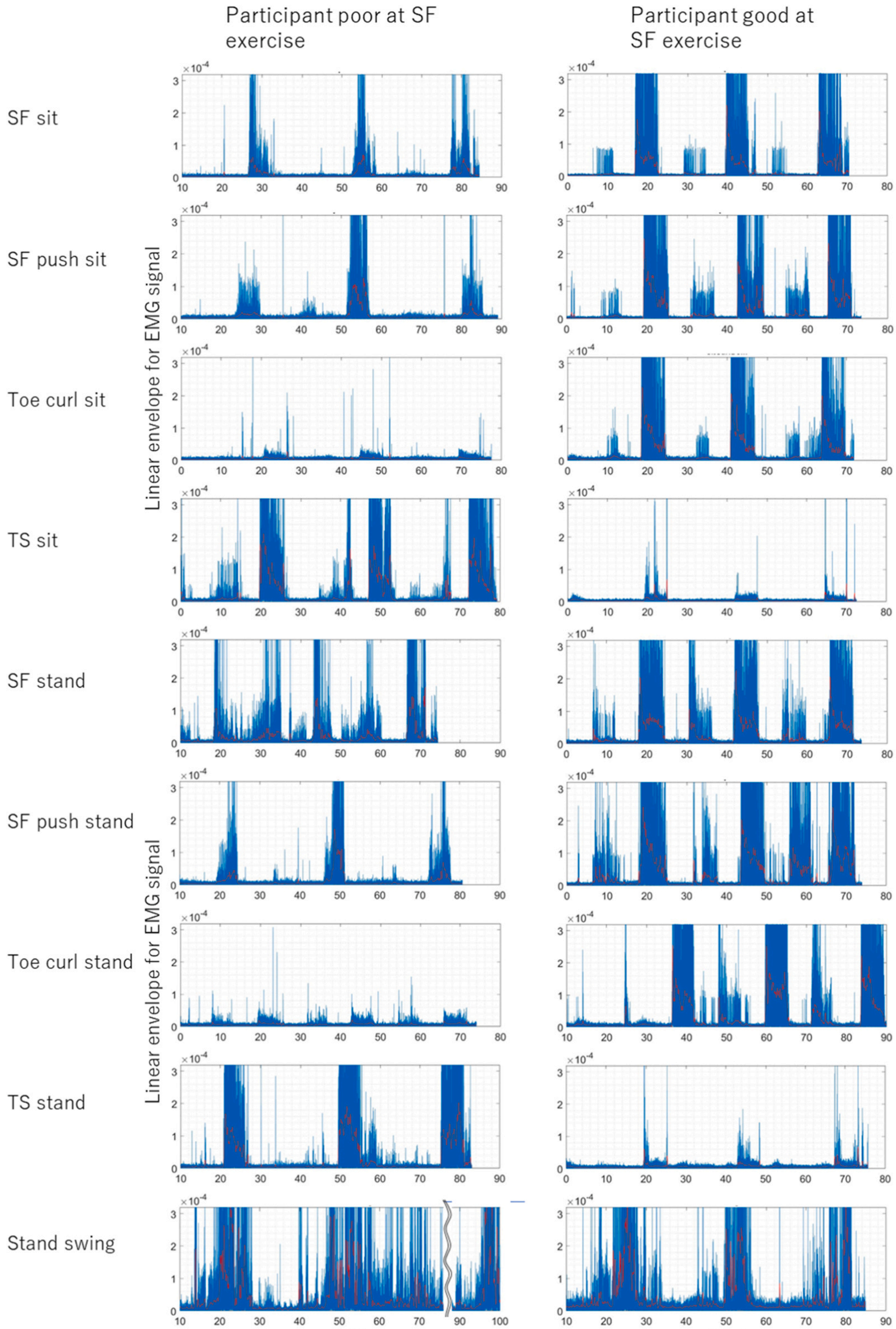


**Fig. 5.** EMG signals collected from a dominant foot of a participant who struggled to activate the abductor hallucis longus (ABH) muscle (left column) and from a dominant foot of a participant who was able to activate the ABH muscle (right column) during short foot (SF) exercises. Note that the opposite activation trend was shown during toe spread (TS) activities, while both participants succeed in activating the ABH muscle during the single leg swing (stand swing) activity. Ten seconds of rest time during the stand swing exercise was removed from the plot for the participant who was poor at SF exercises to enable EMG signals to be plotted for the same amount of time in each case.

**Table 1**
Minimum medial longitudinal arch angles (mean ±one standard deviation) during each exercise. They are the average of minimum medial longitudinal arch angle during each exercise. SF, short foot; TS, toe spread.

| | Sit | | | | |
|---|---|---|---|---|---|
| | SF | SF push | Curl | TS | |
| Dominant | 149.1 ±7.5 | 148.9 ±8.1 | 151.6 ±8.1 | 145.4 ±6.4 | |
| Non-dominant | 147.0 ±7.4 | 146.2 ±7.6 | 148.6 ±7.9 | 141.9 ±6.7 | |
| | Stand | | | | |
| | SF | SF push | Curl | TS | Swing |
| Dominant | 152.8 ±8.8 | 154.3 ±7.5 | 155.5 ±7.4 | 150.9 ±6.9 | 154.9 ±7.0 |
| Non-dominant | 150.1 ±7.4 | 151.5 ±6.9 | 152±7.4 | 147.8 ±7.0 | 151.2 ±6.4 |

activated during a standing single leg swing exercise, without a lengthy practice time and in participants without experience of intentionally activating this muscle. This suggests that the swing exercise may be effective as a self-exercise of intrinsic foot muscles, particularly when it is difficult for a patient to take time practicing the exercise at clinics or with supervised physiotherapy. Further studies are warranted to investigate the effect of this exercise on other intrinsic foot muscles, as well as other muscles external to the foot.

## CRediT authorship contribution statement

**Mai Katakura:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **James Calder:** Writing – review & editing, Methodology, Conceptualization. **Mercedes Aramayo Gomes Rezende:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Angela Kedgley:** Writing – review & editing, Supervision, Resources, Methodology.

## Declaration of Competing Interest

None.

## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gaitpost.2024.06.008.

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