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Relationship between intrinsic foot muscle activity and dynamic balance performance during Y-Balance Test

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ABSTRACT

Objective: Intrinsic foot muscles contribute to the maintenance of the foot arch, distribution of plantar loads, and postural control. However, the specific roles of individual intrinsic foot muscles in dynamic balance tasks remain unclear. Therefore, this study aimed to investigate whether the intrinsic foot muscle activity influences dynamic balance performance during the Y-Balance Test.

Methods: Nineteen healthy adults (6 men and 13 women) participated in this study. Surface electromyography was used to record the activity of the abductor hallucis (AH), dorsal interosseous (DI), and abductor digiti minimi (ADM). The participants performed the YBT in three directions: anterior, posteromedial, and posterolateral. The trial with the greatest reach distance in each direction was analyzed. Muscle activity was quantified using integrated electromyography (IEMG) and was normalized to the IEMG obtained during single-leg standing. Two-way repeated-measures analysis of variance was conducted to examine the effects of the reach direction and muscle activity. Correlation analyses were subsequently performed to investigate the relationship between reach distance and muscle activity.

Results: A significant interaction was found between the reach direction and muscle activity. AH activity was significantly greater during anterior reach than during posteromedial or posterolateral reach. During the posterolateral reach, ADM activity was significantly greater than that of the AH. Correlation analyses revealed a positive correlation between the AH and DI activity in the anterior and posterolateral reaches. Furthermore, a significant positive correlation was observed between ADM activity and the normalized reach distance in the posterolateral direction.

Conclusions: Intrinsic foot muscle activity differed according to the reach direction during the YBT. In addition, the activity of specific intrinsic foot muscles, particularly the ADM, may contribute to dynamic balance depending on the direction of movement.

Keywords: intrinsic foot muscles; surface electromyography; Y-Balance Test; dynamic balance

INTRODUCTION

The intrinsic foot muscles (IFMs) are a group of muscles that originate from and are inserted within the foot. These muscles contribute to maintaining the medial longitudinal arch, regulating plantar soft tissue stiffness during gait, and facilitating efficient function of the extrinsic foot muscles.[1-6] The IFMs are organized into four anatomical layers and consist of 12 muscles.[7,8] The firing frequency of muscle spindles differs among individual IFMs according to toe movement, suggesting that each muscle may have distinct functional roles.[9]

Postural control is among the primary functions of the IFMs. IFM activity increases with the difficulty of static balance tasks increases, and IFM activity is associated with center of pressure (COP) displacement.[10,11] Furthermore, although COP variability increases with greater postural challenges, fluctuations in IFM activity remain relatively small, suggesting that IFMs may contribute more to foot stabilization than to direct balance control.[12] IFMs contribute to postural stability during static standing. In addition, these muscles actively support the medial longitudinal arch and regulate arch deformation under load, while also contributing to the control of foot stiffness during dynamic weight-bearing activities such as walking and running.[5,13] During dynamic balance tasks, the COP continuously shifts within the base of support, requiring the maintenance of foot stability while controlling body posture. Therefore, appropriate activation of IFMs is considered essential

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for stabilizing the foot and facilitating efficient force transmission. Consequently, evaluating IFM activity during dynamic balance tasks may provide a better understanding of the functional role of these muscles in dynamic postural control.[12]

The Y-Balance Test (YBT) is a widely used and reliable tool for assessing neuromuscular control and dynamic balance.[14] Individuals with a higher medial longitudinal arch generally exhibit greater reach distances during the YBT.[15] The abductor hallucis (AH), a major IFM, contributes to the medial longitudinal arch support and prevents excessive navicular drops.[2] Therefore, IFM activity may influence YBT performance. Additionally, individuals with flatfoot deformity and AH atrophy demonstrate reduced H-reflex excitability and increased COP displacement during single-leg standing.[16] Thus, individual IFMs may play distinct functional roles in balancing.

Although IFMs may influence dynamic balance, the relationship between the activity of individual IFMs and YBT performance remains unclear. Surface electromyography provides an objective and non-invasive method for quantifying muscle activity during functional tasks. Therefore, this study aimed to investigate the influence of the activity of individual IFMs on YBT performance using surface electromyography.

METHODS

Participants. Nineteen healthy adults (6 men and 13 women) participated in this study. The mean age, height, and body mass of the participants were 21.6 ± 1.1 years, 163.8 ± 9.2 cm, and 57.8 ± 7.6 kg, respectively.

The required sample size was calculated using G*Power (version 3.1.9.7) for a repeated-measures analysis of variance (ANOVA) with within factors. The analysis assumed an effect size of 0.40, an alpha level of 0.05, a statistical power of 0.95, Number of groups of 3, Number of measurements of 3, a correlation among repeated measures of 0, and a nonsphericity correction (ε) of 0.50. Following the procedure described by Tsushima, the total sample size estimated by G*Power (57) was divided by the number of repeated measurements (3), resulting in a minimum required sample size of 19 participants.[17] Based on the pilot data obtained from six participants, the estimated partial eta squared (ηp^2) was 0.473. Considering the small sample size of the pilot study and potential overestimation of the effect size, a conservative effect size was used for the a priori power analysis.

The eligibility criteria included a Foot Posture Index-6 score between 0 and 5 and a Navicular Drop Test value of <1 cm, indicating normal foot posture.[18,19]

The study protocol was approved by the Ethics Committee of the Yamagata Prefectural University of Health Sciences (approval no. 2306-08). All participants received verbal and written explanations of the study procedures and provided written informed consent prior to participation.

Electromyographic measurement. Muscle activity was recorded from AH, dorsal interosseous (DI), and abductor digiti minimi (ADM). The electrode placement sites were as follows: the midpoint between the navicular tuberosity and medial calcaneal tubercle for AH; midpoint of the second metatarsal between the first and second metatarsal heads for DI; and the area anterior to the base of the fifth metatarsal for ADM.[20]

The muscles were identified using ultrasonography prior to electrode placement. After the skin was treated with alcohol, the electrodes were positioned parallel to the muscle fiber orientation.

Electromyographic signals were recorded using a Trigno Wireless EMG System (Delsys Inc., Natick, MA, USA) equipped with Trigno Quattro Mini sensors at an interelectrode distance of 10 mm. Data were acquired using Nexus 2 software. Signals were sampled at 1,000 Hz and filtered using a bandpass filter of 20–450 Hz. The EMG signals were full-wave rectified, and integrated electromyography (IEMG) values were calculated. Because obtaining maximal voluntary contractions of the intrinsic foot muscles is difficult,[21] muscle activity recorded during single-leg standing has been used as a normalization reference that reflects the coordinated function of the lower extremity musculature during closed kinetic chain (CKC) tasks.[22,23] Therefore, the IEMG value obtained during the middle 5s of a 10-s single-leg standing task, excluding the first and last 2.5s, was used as a normalization reference. Muscle activity during the experimental tasks was normalized to this value and expressed as %IEMG for comparison.

YBT. The participants performed the YBT while standing on their dominant leg. The dominant leg was defined as the preferred leg for kicking a ball. Previous studies have reported asymmetries in postural control during a single-leg stance between the dominant and nondominant legs.[24] Therefore, in the present study, the preferred kicking leg was consistently used to define leg dominance. The reach movements were executed in three directions: anterior, posteromedial, and posterolateral (Fig.1). Three trials were performed in each direction, and the trial with the greatest reach distance was selected for analysis.

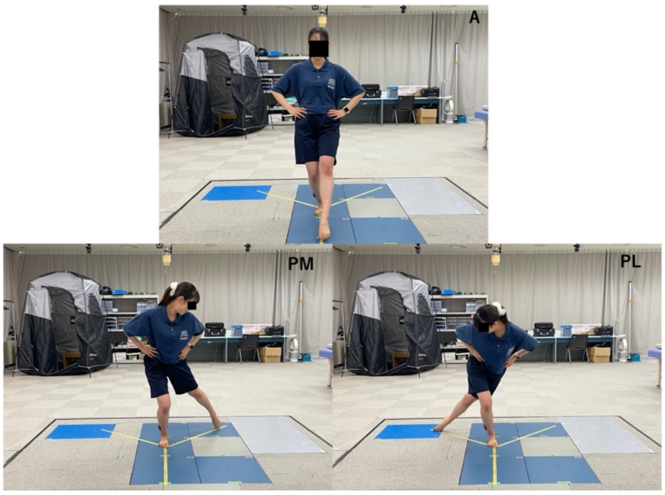

Figure 1. Y-Balance Test Procedure
Participants performed the Y-Balance Test in the anterior (A), posteromedial (PM), and posterolateral (PL) directions while standing on their dominant legs.

The reach distance was normalized to lower limb length and expressed as a percentage. A reflective marker was attached to the medial aspect of the distal phalanx of the hallux, and marker trajectories were recorded using a three-dimensional optical motion capture system. The analysis interval was defined as the period from when the vertical marker position exceeded the mean + 2 SD of the baseline (1-s resting period prior to movement) until it returned below that value

Participants were allowed multiple practice trials before data collection to ensure familiarity with the tasks. During testing, participants placed their hands on their pelvis and maintained a single-leg stance on their dominant limbs. Trials were repeated if the participant lost balance, touched the floor with the reaching limb, removed their hands from the pelvis, or if lifting of the stance heel was visually observed by the examiner.

Statistical Analysis. All statistical analyses were performed using the SPSS version 25 software (IBM Corp., Armonk, NY, USA).

A two-way repeated-measures ANOVA was conducted with reach direction and muscle as within-subject factors, each consisting of three levels. The assumption of sphericity was evaluated using the Mauchly’s test. When the assumption was violated, Greenhouse–Geisser corrections were applied.

When significant interactions were identified, one-way repeated-measures ANOVA and Bonferroni-adjusted post-hoc comparisons were performed.

As a secondary analysis, Pearson's correlation coefficients were calculated to examine the relationship between intrinsic foot muscle activity and normalized reach distance. Statistical significance was set at $p < 0.05$.

RESULTS

Two-way repeated-measures ANOVA revealed no significant main effect of reach direction ($F(2, 36) = 1.932$, $p = 0.160$, $\eta p^2 = 0.097$). Similarly, no significant main effect of muscle type was observed ($F(1.401, 25.215) = 0.795$, $p = 0.421$, $\eta p^2 = 0.042$). However, there was a significant interaction between reach direction and muscle ($F(1.795, 32.306) = 7.865$, $p = 0.002$, $\eta p^2 = 0.304$).

Subsequent post-hoc analyses demonstrated that AH activity was significantly greater during anterior reach than during the posteromedial and posterolateral reaches. Furthermore, during posterolateral reach, ADM activity was significantly greater than AH activity (Table 1).

Table 1 Muscle activity of each muscle in the lower limb reaching direction

	A	PM	PL
AH	242.6±104.5 *,†	158.1±77.4	146.2±119.2
DI	267.9±154.6	197.3±98.9	177.3±96.5
ADM	196.3±130.9	168.7±119.2	230.9±200.0 ‡

*p＜0.01 vs. PM. †p＜0.01 vs. LM. ‡p＜0.01 vs. A AH.

A, anterior; PM, posteromedial; PL, posterolateral; AH, abductor hallucis; DI, dorsal interosseous; ADM, abductor digiti minimi.

Correlation analyses revealed significant positive associations between AH and DI activity in both the anterior and posterolateral reaches. Additionally, ADM activity positively correlated with the normalized reach distance in the posterolateral direction (Table 2).

Table 2 Correlations between muscle activity and lower limb reach distances

A

	DI	ADM	Reach distances
AH	0.49 *	−0.06	0.1
DI		−0.27	0.25
ADM			−0.34

PM

	DI	ADM	Reach distances
AH	0.45	0.32	−0.01
DI		0.27	−0.24
ADM			−0.03

PL

	DI	ADM	Reach distances
AH	0.63 *	−0.23	0.04
DI		0.27	−0.01
ADM			0.53 *

A, anterior; PM, posteromedial; PL, posterolateral; AH, abductor hallucis; DI, dorsal interosseous; ADM, abductor digiti minimi.

DISCUSSION

IFMs may contribute to posture control and regulation of foot stiffness. Although previous studies have demonstrated the importance of the IFMs in static balance tasks, their role in dynamic balance remains unclear. Therefore, this study investigated the activity of individual IFMs during the YBT, a widely used assessment of dynamic balance and neuromuscular control.

The primary finding of this study was that IFM activation patterns differed according to the reach direction. Specifically, AH activity was highest during the anterior reach. The primary actions of the AH are abduction and flexion of the hallux at the metatarsophalangeal joint.[7] During anterior reaching, the body's COP shifts anteriorly, thereby increasing the demand for forefoot stabilization. Under these conditions, AH activation may facilitate hallux loading and maintenance of the medial longitudinal arch, thereby enhancing the stability of the stance foot during the reaching tasks.

A significant positive correlation was also observed between AH and DI activity during the anterior reach. The DI responds to movements involving toe abduction, and increased spindle discharge has been observed during hallux and second toe abductions.[9] Therefore, the coordinated activation of the AH and DI observed in the present study may reflect a synergistic mechanism for stabilizing the forefoot and controlling toe position during dynamic balance tasks. Multiple IFMs may act in concert rather than independently to maintain postural stability during anterior reaching.

Another important finding was increased ADM activation during posterolateral reach. Previous studies have demonstrated that sensory input and muscle spindle discharge from the ADM increase in response to the loading of the lateral aspect of the foot.[9]During posterolateral reach, the COP was likely to be displaced laterally, resulting in greater loading of the lateral column of the foot. Consequently, the ADM may be preferentially recruited to enhance lateral foot stability and maintain balance under these conditions.

Furthermore, ADM activity was positively associated with posterolateral reach distance. Given that the ADM abducts the fifth toe, greater activation of this muscle may increase the functional base of support during posterolateral reaching. This association suggests that ADM activation may contribute to the maintenance of lateral foot stability during this task. This may facilitate the maintenance of the body's center of mass within the limits of stability, thereby allowing participants to achieve greater reach distances. Recent evidence suggests that the ADM contributes to frontal-plane postural control and responds to vestibular perturbations during balance tasks.[25]

The present findings are consistent with these observations and suggest that the ADM may contribute to dynamic balance, particularly during tasks involving lateral displacement of the body's center of mass.

The relatively large interindividual variability in muscle activity may be partly attributable to the normalization procedure. Because obtaining maximal voluntary contractions (MVC) from the intrinsic foot muscles is difficult, muscle activity was normalized to that recorded during single-leg standing, as previously described.[22,23] However, non-MVC normalization methods may be influenced by inter-individual differences in muscle activation patterns and postural control strategies.[26] Consequently, the normalization procedure may have contributed to the variability observed in the present this study.

The lack of significant differences in muscle activity in some reach directions may be explained by the primary role of the intrinsic foot muscles in stabilizing the foot during balance tasks, which results in relatively small changes in muscle activation.[12] Furthermore, the relatively large interindividual variability in muscle activation patterns may have reduced the statistical power to detect significant differences.

This study had some limitations. First, because the IFMs are small and anatomically adjacent muscles, the possibility of electromyographic crosstalk cannot be completely excluded, despite careful electrode placement. Second, although YBT reach distance is commonly used as an indicator of dynamic balance performance, it is influenced by multiple factors, including lower-extremity strength, joint mobility, flexibility, and movement coordination.[27] Therefore, the relationship between the IFM activity and reach distance should be interpreted with caution. Third, this study did not directly assess COP displacement or lower-limb kinematics during the YBT. Therefore, the mechanisms underlying observed muscle activation patterns remain unclear. Fourth, the study population included a disproportionate number of female participants, which may limit the generalizability of our findings to other populations. Finally, because this study used a cross-sectional design, causal relationships between IFM activity and dynamic balance performance could not be established. Future intervention studies targeting specific IFMs are warranted to determine whether enhancing IFM function can improve dynamic balance performance.

CONCLUSION

The activation patterns of the IFMs differed according to the reach direction during the YBT. AH activity was greater during anterior reaching, whereas ADM activity was greater during posterolateral reaching. In addition, ADM activity was positively associated with posterolateral reach distance. These findings suggest that individual IFMs may have direction-specific functional roles during dynamic balance tasks, with the ADM potentially contributing to dynamic balance during posterolateral reaching.

AUTHOR CONTRIBUTIONS

Y.M. conceived and designed the study, collected and analyzed the data, and drafted the manuscript. T.N. critically revised the manuscript. K.S. supervised the study and critically revised the manuscript. All authors have read and approved the final version of the manuscript.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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