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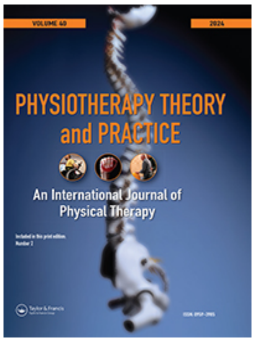

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RESEARCH REPORT

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Plantar intrinsic foot muscle activation during functional exercises compared to isolated foot exercises in younger adults

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ABSTRACT

Background: Training the plantar intrinsic foot muscles (PIFMs) has the potential to benefit patients with lower extremity musculoskeletal conditions as well as the aged population. Isolated foot exercises, often standard in clinical practice, are difficult to perform, whereas functional exercises are much easier to accomplish. However, it is unclear whether functional exercises are comparable to isolated foot exercises in activating the PIFMs.
Objective: This study aims to compare the activation of PIFMs between functional exercises versus isolated foot exercises.
Methods: Using surface electromyography (EMG), muscle activation of three PIFMs was measured in four functional exercises (i.e. normal/unstable toe stance, toe walking, and hopping) versus a muscle-specific isolated foot exercise in 29 younger adults, resulting in 12 comparisons.
Results: Functional exercises showed larger mean EMG amplitudes than the isolated foot exercises in 25% of the 12 comparisons, while there was no difference in the remaining 75%.
Conclusion: Functional exercises provoked comparable or even more activation of the PIFMs than isolated foot exercises. Given that functional exercises are easier to perform, this finding indicates the need to further investigate the effectiveness of functional exercises in physical therapy to improve muscle function and functional task performance in populations that suffer from PIFM weakness or dysfunction.

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Physical therapy; functional training; foot exercises; electromyography; intrinsic foot muscles

Introduction

Changes in plantar intrinsic foot muscle (PIFM) morphology or dysfunction are associated with aging (Mickle, Angin, Crofts, and Nester, 2016) as well as with several lower extremity conditions: plantar fasciitis (Chang, Kent-Braun, and Hamill, 2012); Achilles tendinopathy (Romero-Morales et al., 2019); chronic ankle instability (Feger et al., 2016); hallux valgus (Arinci, Genç, Erdem, and Yorgancioglu, 2003; Stewart, Ellis, Heath, and Rome, 2013); symptomatic pronated feet (Zhang et al., 2019); and diabetic neuropathy (Henderson et al., 2020). Active contraction of these PIFMs is related to controlling the medial longitudinal foot arch when loaded (Kelly et al., 2014) or balancing (Ferrari, Cooper, Reeves, and Hodson-Tole, 2020; Kelly, Kuitunen, Racinais, and Cresswell, 2012) as well as to stiffening the foot during push off (Farris, Birch, and Kelly, 2020). Training the PIFMs to improve these functions could benefit younger and older adults. However, the involvement of these specific muscles in foot exercises is yet understudied. Therefore, and to get a better understanding of the effectiveness of certain exercises to train the PIFMs, the evaluation of muscle activation is needed.

Rehabilitation and prevention of PIFM-related conditions, or its secondary implications, generally involve prescription of exercises to strengthen the PIFMs or to improve their function (Lee and Choi, 2019; Tudpor and Traithip, 2019). Due to the overlap in osteokinematic function between extrinsic and intrinsic foot muscles (Kurihara et al., 2014), isolated foot exercises that involve toe flexion (i.e. traditional foot exercises such as towel-curl and marble pick-up) allow the extrinsic foot muscles to compensate for intrinsic foot muscle weakness or dysfunction. In an attempt to exclude extrinsic

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foot muscle's contribution, isolated foot exercises (e.g. short foot exercise and toe spread-out exercise) have been designed that specifically target the PIFMs in isolation. Studies that investigated the effects of these exercises demonstrated increased toe flexor strength (Day and Hahn, 2019; Matsumoto, Fujita, and Osaka, 2019) but without structural changes of the PIFMs being observed (Matsumoto, Fujita, and Osaka, 2019). Regarding biomechanical parameters divergent results have been reported for the effect on foot function and balance control during gait (Willemse et al., 2022). The absence of structural adaptations and functional training results may be ascribed to constraints that are inherent to PIFM training, such as the difficulty to perform PIFM exercises and the dissimilarity with daily or sports activities. This is a clear argument to consider exercises that are more functional in nature.

Whereas functional exercises are based on automated motor control, the performance of PIFM exercises requires a certain level of voluntary fine motor control. Even after training, this skill is insufficiently developed in a considerable subset of individuals (Fraser and Hertel, 2019; Kim, Kwon, Kim, and Jung, 2013) which inhibits the ability to correctly contract selected muscles, hampering the effectiveness of the exercises. In addition, the perceived difficulty is likely to impede exercise adherence (Escolar-Reina et al., 2010). In contrast, the more traditional isolated foot exercises (e.g. towel-curl and marble pick-up) are easier to accomplish and also target the PIFMs (Lynn, Padilla, and Tsang, 2012). However, as these exercises are characterized by a toe flexion movement, it is unclear to what extent these concentric exercises are effective in activating the PIFMs in addition to the extrinsic toe flexor muscles, known as the primary toe movers (McKeon, Hertel, Bramble, and Davis, 2015).

Functional exercises as opposed to isolated foot exercises (i.e. both traditional and PIFM exercises) are habitual movements and challenge the PIFMs the way these muscles act in usual daily activities or sports activities. For instance, tasks in daily life are accomplished by a high level of coordinated neuromuscular control, which is reflected in functional exercises. Moreover, these tasks are often performed weight bearing, whereas isolated foot exercises usually are not. Specifically, for the PIFMs, these muscles behave eccentrically and concentrically in an alternated fashion during walking (Kelly, Lichtwark, and Cresswell, 2015) as opposed to the primarily concentric contractions during isolated foot exercises. In addition, although PIFMs are believed to contribute to balance by producing grip force (de Win et al., 2002; Menz, Morris, and Lord, 2005) isolated foot exercises barely challenge the postural system. These discrepancies between how the PIFMs act in these foot exercises compared to daily life activities can be defeated by increasing the functionality of the training and increasing the postural demand. Indeed, single-leg stance and toe walking intensified the activation levels of the PIFMs compared to double-leg stance and regular walking, respectively (Kelly, Kuitunen, Racinais, and Cresswell, 2012; Zelik, La, Ivanenko, and Lacquaniti, 2015). Exercises that bring the center of pressure maximally distal to the metatarsophalangeal (MTP) joints might also be effective in increasing PIFM activation. This is because these muscles, spanning the MTP joints, are then maximally forced to produce a toe flexion moment to resist the external moment generated by the ground reaction force and its larger moment arm. Likewise, tasks that require the body's center of mass to be raised or accelerated are potentially effective as these conditions challenge the PIFMs in the role they have in functional activities (Farris, Kelly, Cresswell, and Lichtwark, 2019; Riddick, Farris, and Kelly, 2019).

In order to better design exercise interventions that effectively target the PIFMs, insight into the activation of PIFMs in functional exercises compared to isolated foot exercises is needed. Although some efforts have been made to examine PIFM activation across various foot exercises (Goo, Heo, and An, 2014; Gooding, Feger, Hart, and Hertel, 2016; Heo, Koo, and Yoo, 2011; Jung et al., 2011; Kim, Kwon, Kim, and Jung, 2013; Park and Hwang, 2020) no studies exist that compared the effects of isolated foot exercises with functional exercises. Considering the potential of functional exercises in activating the PIFMs and the limited scope of the existing literature, the current study primarily aims to compare the mean muscle activation of PIFMs across functional and isolated foot exercises. In addition, we examined if several repetitions of dynamic functional exercises are needed to approximate the isolated foot exercises in terms of muscle activation integrated over time, because of the shorter bursts of muscle activation in these dynamic activities. As a secondary aim, we determined the effect of two variations of foot exercises on the activation of the PIFMs. To this end, we examined if PIFM activation increases when the exercise is isometric compared to concentric and when the center of pressure is brought more distally to the MTP joints.

Methods

Design

To compare PIFM activation across exercises performed within the same laboratory session, a crossover experimental design was used. Surface electromyography (sEMG) with ultrasound-guided placement of the electrodes was used to evaluate the immediate effect on muscle activation.

Participants

Participants were recruited by convenience sampling among students and staff members of the Fontys University of Applied Sciences, Eindhoven, the Netherlands (hereafter referred to as Fontys). Individuals were eligible when aged between 18 and 40 years, to ensure that the nervous system and motor unit characteristics are not affected by aging (Campbell, McComas, and Petito, 1973; Lexell and Downham, 1992; Thomlinson and Irving, 1977). Individuals who reported to have current lower extremity musculoskeletal symptoms, neurological or neuromuscular conditions, severe foot deformities (i.e. clubfoot or deformities that hinder daily life activities), or those with a history of trauma or surgical treatment of the lower extremity were excluded from participation. To avoid interference with the EMG equipment, individuals with implanted electronic devices, irritated skin, or with allergies to silver were also excluded. After given verbal and written information, each participant provided written informed consent to participate in the study. The study population consisted of 29 participants (21 women, 8 men) with a mean age of 23.3 (sd: 3.8) years. The Institutional Ethics Committee of Fontys confirmed that the protocol is in accordance with the European Code of Conduct for Research Integrity (Registration Number: 85willemse30082022).

Experimental procedures

All measurements were taken from the limb the participant chose most often as the supporting limb (i.e. dominant stance limb), when asked three times to stand on one leg. To assess foot arch morphology and mobility, the foot was scanned with a 3D scanner (Tiger, Materialise, Leuven, Belgium) in a sitting position (i.e. ~10% weight bearing) and in single-leg stance while lightly holding a bar to remain balanced (i.e.~90% weight bearing) (Williams and McClay, 2000). The knee was kept aligned with the ankle joint. From these scans, the arch height index (AHI), a measure for foot posture, and the relative arch deformation (RAD), reflecting arch mobility, were estimated (Williams and McClay, 2000). The AHI was calculated for both loading conditions as the ratio of the dorsum height at 50% of the total foot length to the truncated foot length (i.e. total foot length minus the toes) (McPoil et al., 2008). The RAD was calculated as the difference in dorsum height between both weight bearing conditions, divided by the dorsum height in the 90% loaded condition and normalized to body weight (BW) by multiplying with 10^4/BW (Williams and McClay, 2000). For each foot arch variable, the mean of three trials was taken as the final value to describe the study population in terms of foot arch characteristics. This data analysis was done using a custom-made Matlab R2020b script (MathWorks, Natick, MA, USA). The manual assessment of these foot arch variables previously showed good intra-tester en inter-tester reliability (ICC >0.8) and fair validity with radiographic measurements (ICC >0.7) (Williams and McClay, 2000).

We collected activation data of four muscles with sEMG equipment (Trigno (Quattro sensor), Delsys Inc., Natick, MA, USA). Three superficial PIFMs were selected with closest proximity to the medial longitudinal arch: 1) m. abductor hallucis (AbH); 2) m. flexor digitorum brevis (FDB); and 3) m. flexor hallucis brevis (FHB). In addition, to answer one of the secondary research questions, m. flexor hallucis longus (FHL) was selected to represent the extrinsic toe flexor muscles because of its accessible muscle belly.

The electrode position for AbH and FHL was at the location of the muscle belly, which was identified by using ultrasound (Branthwaite, Aitkins, Lindley, and Chockalingam, 2019) (Lumify, Philips Healthcare Inc., Bothell, WA, USA), because of the inter-individual variation in alignment of these muscles observed in our previous ultrasound study (Willemse, Wouters, Pisters, and Vanwanseele, 2022). According to our scan protocol (Willemse, Wouters, Pisters, and Vanwanseele, 2022), the electrode position for AbH on its muscle belly was located by scanning the muscle in the longitudinal direction from the origin on the medial process of the calcaneal tuberosity toward just inferior to the navicular tuberosity. The electrode position for the FHL was just distal to the soleus insertion onto the Achilles tendon (Oku et al., 2021; Péter et al., 2015). This reference point was imaged by first scanning the FHL from the medial side in the transverse plane just superior to the medial malleolus, then rotating the probe 90 degrees and, if necessary, sliding the probe in longitudinal direction. The electrode position for FHB and FDB was based on palpating anatomical bony landmarks (Branthwaite, Aitkins, Lindley, and Chockalingam, 2019). For FHB, the electrode position was on the plantar side of the foot, midway the first metatarsal shaft (Branthwaite, Aitkins, Lindley, and Chockalingam, 2019), indicated by a line drawn between the medial process of the calcaneal tuberosity and the first MTP joint (Figure 1). The electrode position for FDB was the intersect between the line drawn from the medial process of the calcaneal tuberosity to the second ray and the line traced from

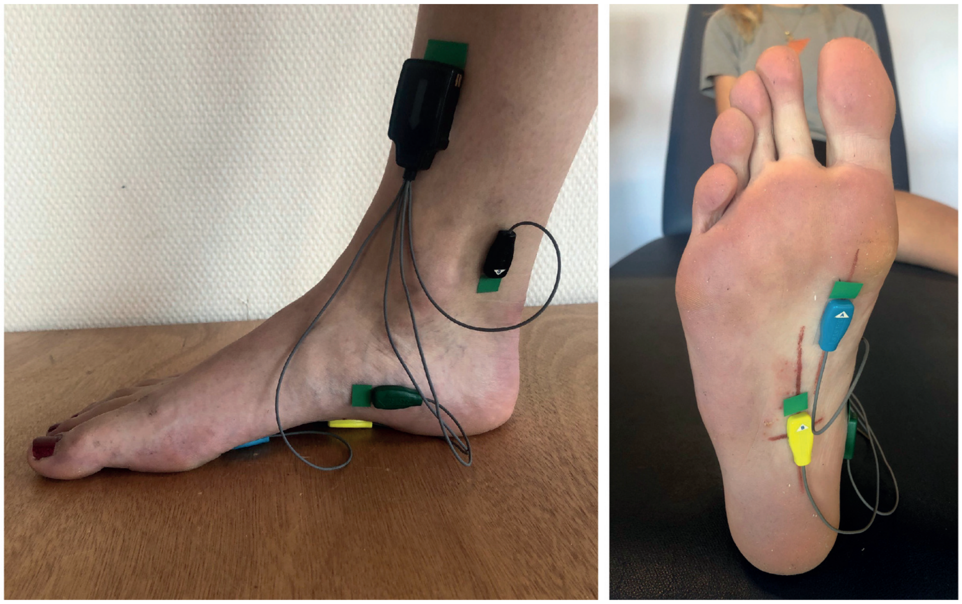

Figure 1. Electromyography electrode positions. The left picture shows the electrode positions for the (from proximal to distal) flexor hallucis longus, abductor hallucis, flexor digitorum brevis and flexor hallucis brevis. The right picture shows the electrode positions for flexor digitorum brevis (proximal electrode) and flexor hallucis brevis (distal electrode).

the navicular tuberosity perpendicular to the long axis of the foot (Branthwaite, Aitkins, Lindley, and Chockalingam, 2019) (Figure 1).

The skin at the identified electrode positions was prepared for optimal conduction of the electrical signal from the muscles to the electrodes. To this end, hair was removed and the skin rubbed with a hypoallergic abrasive paste aimed to clean the skin and to remove any impeding dead skin cells. The granular residue of the paste was removed by dabbing the skin with medical tape. The electrodes were attached to the skin with double-sided adhesives and oriented parallel to the longitudinal direction of the muscle fibers. The sensor head (i.e. reference electrode) was placed on the medial aspect of the tibia (Figure 1).

Figure 2 shows the exercises of the experimental protocol. The series of exercises started with the reference exercise that was used to normalize the EMG amplitude for the experimental exercises. For the reference exercise, the participant was instructed to place the ball of the foot against the edge of a step, maintaining the plantar side of the foot parallel to the step surface, while holding a vertical post to stay balanced. Pilot testing showed that this exercise provokes higher levels of activation for all four muscles simultaneously compared to the muscle-specific reference exercises proposed by Kendall (2010). The protocol further consisted of five static isolated foot exercises (i.e. four PIFM exercises and one traditional foot exercise) and four functional exercises (i.e. two static and two dynamic). The PIFM exercises consisted of "hallux grip" and "lesser toe grip," "toe spread-out" and "short foot." The traditional isolated foot exercise was the "toe-curl" as this is characterized by an extensive toe flexion motion (i.e. concentric exercise). The static functional exercises were "single-leg toe stance," with and without forward lean on a firm surface, and single leg toe stance on a compliant surface (green-level balance pad; Theraband, Akron, OH, USA). The dynamic functional exercises consisted of "toe walking" and "hopping" in place. Due to the increasing risk of sensor detachment with exercise type (i.e. static foot exercise, static functional exercise, and dynamic functional exercise), the order of exercise type was fixed, but to avoid as much as possible systematic error, the exercise order within the exercise types was random.

After the researcher had given verbal instruction about the exercise (Figure 2), the participant was allowed to practice the exercise once. Then, for each static exercise, three trials with approximately a 5-second contraction were performed with a 20-second rest period between the trials. The rest period between the exercises was 1 minute. The researcher verbally encouraged the participant to achieve maximal effort during the exercises. For the dynamic exercises, three consecutive repetitions were performed within one recording. Each recording ended with relaxed muscle status. The researcher rated the motor performance for each exercise on a 3-point scale (i.e. 0 = does not initiate movement or starting position cannot be

Figure 2. Exercises that were included in the protocol with the instructions verbally provided to the participants. For each isolated exercises, it is indicated which muscle (group) is targeted by the exercise. Note: * indicates the muscle-specific isolated foot exercise that was used for the comparison with functional exercises (i.e. the isolated foot exercise that provoked the largest mean EMG amplitude for the corresponding muscle). PIFMs: plantar intrinsic foot muscles.

maintained; 1 = completes the exercise partially or with compensations, slowness, or obvious clumsiness; and 2 = completes the exercise with a standard pattern) modified from Fraser and Hertel (2019). Trials with motor performance score <2 were not included in the analysis. This is because ideally the exercise performance is a learned skill in an intervention setting, which is where we aim to do recommendations for. Each participant attained the maximum motor performance score for the functional exercises. The distribution of this score for the isolated foot exercises is shown in Supplementary File 1.

Data acquisition and post-processing

EMG data for trials in which the sensor(s) detached were abandoned for further analysis (Supplementary File 2). The acquired EMG signals (EMGworks acquisition software, Delsys Inc., Natick, MA, USA; 2222 Hz sample rate, bandwidth: 20–450 Hz) were processed in Matlab R2020b (MathWorks, Natick, MA, USA). First, the offset was subtracted from the signal. Then, a 6^{th} order 140 Hz high-pass Butterworth filter was applied to attenuate low-frequency signal power (Potvin and Brown, 2004), and the rectified resulting signal was smoothed to an EMG envelope with a 2^{nd} order 1 Hz low-pass Butterworth filter without phase lag (Potvin and Brown, 2004).

The same onset and termination of the exercise for all muscles together was manually selected from the rectified high-pass filtered signals for each of the trials (Knox et al., 2021) (Supplementary File 3). First, the muscle with the most profound EMG signal was selected. This was the FHL, except for the isolated PIFM exercises (i.e. FHB for hallux grip, FDB for lesser toe grip, and AbH for toe spread-out). Using the EMG signal of that muscle, the onset of the exercise was determined as the moment where the EMG amplitude started to substantially increase and the termination was the point where the EMG amplitude returned to a resting level (Knox et al., 2021).

The EMG envelope for each exercise trial was expressed relative to the reference exercise. Two EMG amplitude parameters were then extracted. To compare the activation level of the muscles across the exercises, the mean amplitude (in %) over the exercise duration was used. However, the difference in exercise duration between static and dynamic exercises is not reflected in this parameter. Because contraction time also determines exercise effectiveness (Ratamess et al., 2009), the EMG amplitude integrated over time (iEMG in %·s) was calculated as well. For static exercises, iEMG was calculated for the middle 3 seconds of the exercise interval (Campy, Coelho, and Pincivero, 2009) to account for the variability in exercise duration. See Supplementary File 3 for a visualization of the extracted parameters. The mean of the EMG amplitude parameters over the three trials was used for further analysis.

For the comparison with the functional exercises, one muscle-specific isolated foot exercise was selected. This was the exercise that provoked the largest mean EMG amplitude for that specific PIFM. The muscle-specific isolated foot exercise was the hallux grip for the FHB, toe curl for the FDB, and toe spread-out for the AbH (Figure 2). Supplementary File 4 shows the mean EMG amplitude across all exercises in descending order of the median value.

The mean EMG amplitude and the IEMG were compared between the muscle-specific isolated foot exercise and the four functional exercises (i.e. toe stance, toe stance on a compliant surface, toe walking, and hopping). The iEMG was only compared for dynamic functional exercises (i.e. toe walking and hopping) because the duration of the static functional exercises is invariant to the muscle-specific isolated foot exercise for this comparison.

Statistical analysis

SPSS 28.0 (IBM, Chicago, IL, USA) was used to analyze the data statistically. Since normal distribution was not satisfied in the majority of the dependent variables, Wilcoxon signed rank tests ($\alpha = 0.05$, one-tailed) were performed for each of the three PIFMs to statistically test the difference in the mean EMG amplitude as well as in the iEMG between the isolated foot exercises and the functional exercises. The p-values were corrected for multiple testing (18 comparisons) using the Holm-Bonferroni approach. In case of differences in iEMG between the muscle-specific isolated foot exercise and functional exercises, it was also deduced from this parameter how many exercise repetitions were needed for comparable iEMG.

To compare the muscle activation between concentric and isometric foot exercises, the mean EMG amplitude was compared between the toe curl exercise (i.e. a concentric exercise) and the toe grip exercise (i.e. an isometric exercise; hallux grip for FHB, AbH, and FHL; lesser toe grip for FDB). To test if PIFM activation increases when body weight is brought more anteriorly to the MTP joints, normal single-leg toe stance was compared with single-leg toe stance with a forward lean. For each of these secondary questions, a Wilcoxon signed rank test ($\alpha = 0.05$, one-tailed) was performed for each muscle (4 for toe curl vs toe grip; 3 for toe stance vs. toe stance with forward lean). The *p*-values were corrected for multiple testing using the Holm-Bonferroni approach.

Results

Table 1 shows the demographics of the study population. The study population consisted of 29 participants (21 females and 8 males) with a mean age of 23.3 (sd: 3.8) years.

Figure 3 illustrates the median within-subject differences in the EMG amplitude parameters between the muscle-specific isolated foot exercise and each of the functional exercises. Table 2 presents the absolute group's EMG amplitude parameters for each of the investigated exercises. Of the 12 comparisons, 3 showed a significantly greater mean EMG amplitude for the functional exercises and 9 comparisons showed similar activation between the muscle-specific isolated foot exercise and each of the functional exercises. During hopping, FHB and AbH exhibited a significantly larger mean EMG amplitude than during the muscle-specific isolated foot exercise (FHB – median difference: 48%, IQR: 4% to 80%, $p < .05$; AbH – median difference: 108%, IQR: 79% to 153%, $p < .05$). In addition, toe stance on a compliant surface showed a larger mean EMG amplitude for FHB compared to the muscle-specific isolated foot exercise (median difference: 29%, IQR: −9% to 54%, $p < .05$).

The magnitude of iEMG was significantly greater for the muscle-specific isolated foot exercise than the functional exercises for 5 of the 6 comparisons and similar for 1 comparison. During toe walking, iEMG was 2.8 times smaller than during the muscle-specific isolated foot exercise for FHB (median difference: −103%·s, IQR: −215 to −66%·s, $p < .05$) and 2.9 times smaller for FDB (median difference: −99%·s, IQR: −248 to −30%·s, $p < .05$). In addition, iEMG for hopping was 9.1 times smaller for FHB (median difference: −157%·s, IQR: −255 to −111%·s, $p < .05$); 7.7 times smaller for FDB (median difference: −160%·s, IQR: −424 to −47%·s, $p < .05$); and 2.4 times smaller for AbH (median difference: −33%·s, IQR: −327 to −15%·s $p < .05$). For AbH, iEMG did not vary significantly across toe walking and AbH's specific isolated foot exercise.

Isometric exercises resulted in significantly larger mean EMG amplitude compared to concentric exercises for FHB (median: −14%, IQR: −33 to −5%, $p < .05$) and AbH (median: −8%, IQR: −72 to −4%, $p < .05$), whereas the opposite was shown for FDB (median: 23%, IQR: −13% to 84%, $p < .05$) and FHL (median: 48%, IQR: 24% to 86%, $p < .05$).

The mean EMG amplitude obtained during toe stance with forward lean did not differ significantly from normal toe stance for each PIFM (median: 11%, IQR: −2% to 17%, $p = .05$ (FHB); median: 6%, IQR: −1% to 15%, $p = .05$ (FDB); median: 5%, IQR: −13% to 17%, $p = .22$ (AbH)).

Discussion

The main aim of this study was to provide better insights into the activation of PIFMs during functional exercises compared to isolated foot exercises. We demonstrated that functional exercises provoked comparable or even more activation of PIFMs than isolated foot exercises. Despite the shorter duration of the dynamic functional exercises, performing a few repetitions of these exercises resulted in iEMG of which the magnitude was similar to the muscle-specific isolated foot exercise. Furthermore, isometric exercises were associated with larger PIFM activation compared to concentric exercises, while forward leaning during the toe stance did not affect PIFM activation.

Some functional exercises were more effective in activating the PIFMs than the muscle-specific isolated foot exercise, while others were equally effective. As all functional exercises were performed in a toe stance position, this position seems to activate the PIFMs substantially. Toe stance requires the calf muscles to generate ankle plantar flexor force, which needs to be transmitted to the ground distal to the MTP joints. Therefore, the foot must serve as a rigid lever and the MTP joints must stiffen to resist the external toe extension moment generated by the ground reaction force.

Table 1. Demographics of the study population ($n = 29$).

Variable	Mean ± sd; frequency (%)
Gender (F/M)	21 (72%)/8 (28%)
Age (years)	23.3 ± 3.8
Body length (cm)	174 ± 11
BMI (kg/m^2)	23.3 ± 3.1
Dominant stance limb (L/R)	9 (31%)/20 (69%)
Arch Height Index, unloaded	0.38 ± 0.03
Arch Height Index, loaded	0.36 ± 0.03
Relative Arch Deformation (N^{-1})	7.8 ± 3.1

Note: F: female, M: male, BMI: body mass index, L: left, R: right, sd: standard deviation.

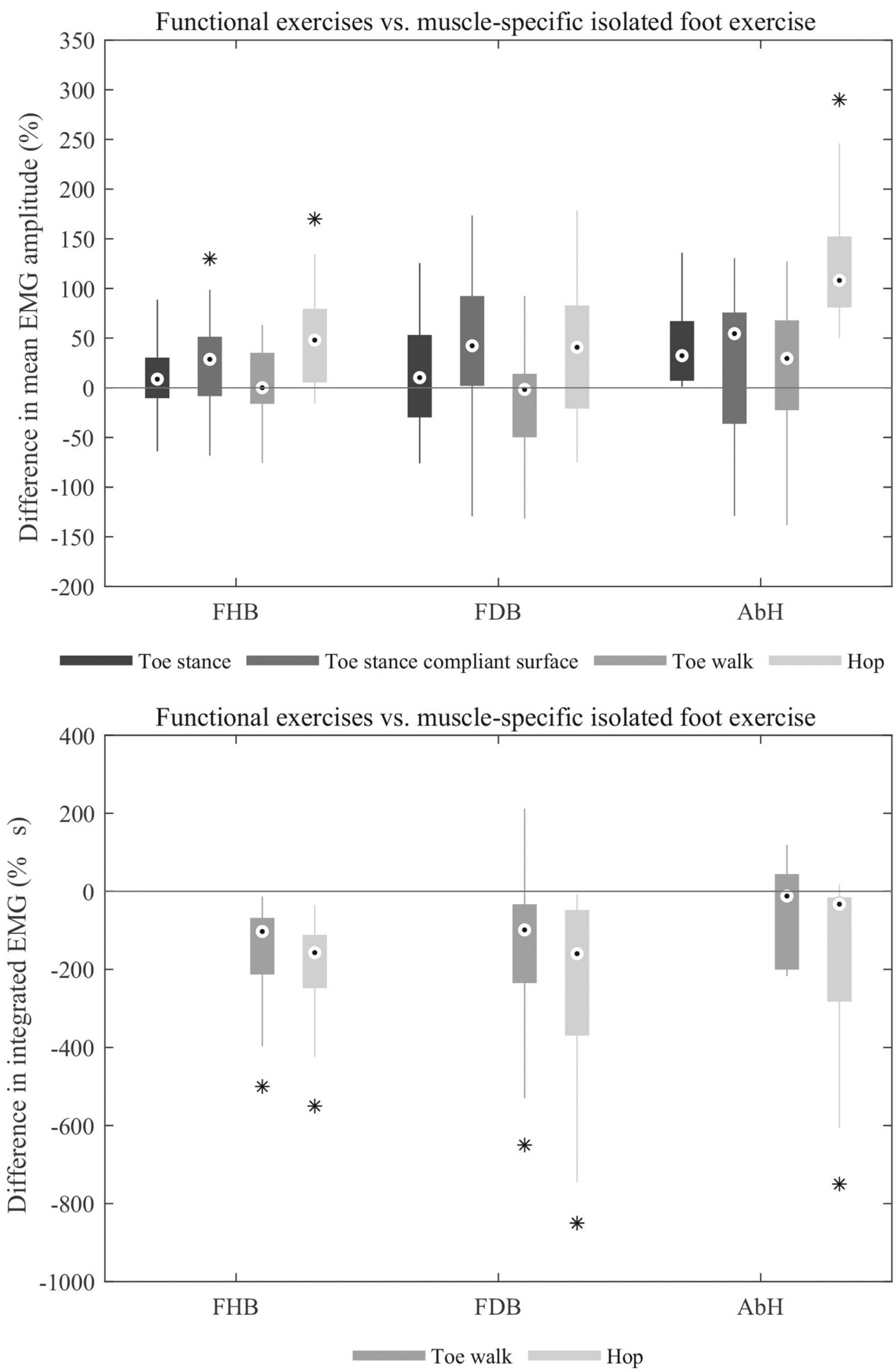

Figure 3. Median and interquartile range for the within-subject difference in mean EMG amplitude (upper graph) and EMG integrated over time (lower graph) between the muscle-specific isolated foot exercise and each of the functional exercises. Outliers are not shown to optimize visualization. Note: * significant difference between the functional exercise and the muscle-specific isolated foot exercise ($p < 0.05$).

Table 2. Median (Mdn) and interquartile ranges (IQR) for the mean electromyography (EMG) amplitude and the EMG amplitude integrated over time (iEMG) during the muscle-specific isolated foot exercise and functional exercises.

	Muscle-specific isolated foot exercise		Toe stance		Toe stance compliant surface		Toe walk		Hop	
	Mdn	IQR	Mdn	IQR	Mdn	IQR	Mdn	IQR	Mdn	IQR
EMG mean (%)										
Flexor hallucis brevis	56	46–92	74	44–96	92	69–121	64	49–82	109	77–145
Flexor digitorum brevis	60	35–119	77	54–109	111	86–164	59	40–79	114	73–209
Abductor hallucis	32	16–123	83	55–118	100	72–149	69	46–126	170	97–281
iEMG (%·s)										
Flexor hallucis brevis	173	141–296	n/a	n/a	n/a	n/a	64	48–82	21	15–34
Flexor digitorum brevis	189	95–329	n/a	n/a	n/a	n/a	55	42–83	25	15–43
Abductor hallucis	77	48–378	n/a	n/a	n/a	n/a	65	36–142	35	23–62

Note: The muscle-specific isolated foot exercises were hallux grip for the flexor hallucis brevis, toe curl for the flexor digitorum brevis and toe spread-out for the abductor hallucis. Mdn: median, IQR: interquartile range, EMG: electromyography, iEMG: electromyography amplitude integrated over time, n/a: not applicable.

This functional interplay between the ankle and the foot may be facilitated by a shared excitatory drive between the ankle plantar flexors and the PIFMs (Kelly, Farris, Cresswell, and Lichtwark, 2019). Toe stance position predisposes the body to an unstable posture. This increased postural challenge may also contribute to the high PIFM activation levels during the functional exercises. Previous studies already demonstrated the active contribution of the PIFMs to foot stiffening (Farris, Kelly, Cresswell, and Lichtwark, 2019; Ferrari, Cooper, Reeves, and Hodson-Tole, 2020) and to remaining balanced (Kelly, Kuitunen, Racinais, and Cresswell, 2012; Ridge et al., 2022), which is in agreement with the current provoked PIFM activation levels during the functional exercises.

The magnitude of iEMG, which takes into account the duration of muscle activation, was in most comparisons smaller for the functional exercises than the muscle-specific isolated foot exercises. However, only 1 to 3 steps of toe walking and 3 to 9 hops are needed to approximate the iEMG of a 3-second muscle-specific isolated foot exercise (i.e. the iEMG was at most 2.9 (toe walking) and 9.1 (hopping) times smaller compared to the muscle-specific foot exercise) without being more time-consuming. Muscular adaptation is not only determined by muscle activation level (i.e. mean EMG amplitude) but also by the time that a muscle is activated (Ratamess et al., 2009) which is reflected by the iEMG. Therefore, our results for the iEMG, in addition to the results for the mean EMG amplitude, indicate that functional exercises, especially the less strenuous toe stance and toe walking, can be included in a therapeutic exercise program just as well as isolated foot exercises to activate the PIFMs.

Isometric exercises seem more appropriate to train the PIFMs as higher muscle activation was demonstrated during these exercises compared to concentric exercises. In several studies (Chatzistergos et al., 2020; Menz, Zammit, Munteanu, and Scott, 2006; Mickle, Caputi, Potter, and Steele, 2016) isometric grip testing of the toes is the designated instrument to test PIFM function, which concords with our findings. In contrast, the wide use of concentric exercises (e.g. the towel-curl exercise) in clinical practice to target the PIFMs disagrees with our results. Concentric isolated foot exercises, however, seem to be suitable to train the extrinsic toe flexors as indicated by the higher activation of FHL during this type of exercise. Nevertheless, although isometric exercising involved the PIFMs more than concentric exercising did, it still not performed better than the functional exercises.

The finding that PIFM activation during toe stance and toe walking is similar to the isolated foot exercises is promising for physiotherapy practice, because of the many advantages of these functional exercises over isolated foot exercise. First, functional training complies with the principle of specificity of training. This conveys that the functional task targeted by the training will most likely improve when the trained motor pattern is consistent with this task (Carson, 2006). Since the primary role of the PIFMs is to contribute to balance and push off, a positive transfer is unlikely for isolated foot exercises such as spreading the toes. Together with our findings, this seems to indicate that the PIFMs can be well trained by functional exercises that include toe stance. These exercises may lack specificity for the prevention or treatment of pronated feet-related conditions as symptoms typically arise from the foot flat phase but are deemed specific for individuals with PIFM weakness such as older adults (Mickle, Angin, Crofts, and Nester, 2016) or patients with diabetic neuropathy (Henderson et al., 2020). Ultimately, functional exercises should also match the cognitive and environmental nature of the target task, for example, by interacting with objects or other individuals or while performing a concurrent cognitive task (Schmidt and Lee, 2011). Another, related, advantage of functional exercises is that these activate numerous other muscle groups in addition to the PIFMs and therefore additional training results may arise, without being more time-consuming. However, the associated downside is that sufficient plantar flexor strength is required for toe stance, which is diminished in older adults (Anderson and Madigan, 2014). Once this requirement is fulfilled, a physical therapist can integrate functional exercises in therapy according to the person's capabilities related to the postural system or strength. In case of difficulties in maintaining balance, variations can be applied (e.g. using an external support, double-leg) in order to facilitate the execution of the exercises in toe stance position. In some situations, e.g. early in rehabilitation, it may be recommended to perform exercises without full weight bearing. In these cases, isolated foot exercises may be appropriate instead. Functional exercises also have adherence-related benefits over isolated foot exercises. Isolated foot exercises require a selection of foot muscles to be innervated, which composes an unnatural motor pattern. A substantial number of healthy younger individuals proved incapable of executing such exercises (Jung, Yi, Choi, and You, 2020; Kim, Kwon, Kim, and Jung, 2013) even after 2 weeks of daily training (Kim, Kwon, Kim, and Jung, 2013). Although other individuals may be able to develop this motor skill (Fraser and Hertel, 2019) it is reasonable that their learning process was accompanied by frustration and annoyance. These negative feelings may lead to decreased adherence or discontinuing the program. In contrast, the easier performance of functional exercises potentially stimulates exercise adherence from the start (Escolar-Reina et al., 2010). Another aspect promoting adherence is the feasibility of integrating functional exercises, such as toe stance and toe walking, in daily routines, while isolated foot exercises require time that is exclusively dedicated to the execution of the exercises.

This is the first study that compared PIFM activation between isolated foot exercises and functional exercises. Selecting the muscle-specific isolated foot exercise for the comparison that was most effective ensured a sensible comparison. It was, however, remarkable that this was not the short foot exercise for any of the PIFMs, which is the most extensively investigated PIFM exercise (Willemse et al., 2022). Furthermore, by including only the trials for which a normal motor pattern was observed, motor ability could not act as a confounding factor. Nevertheless, several limitations need to be considered. Most importantly, the participants were all asymptomatic younger individuals. Future studies should examine how the results apply to the target population, such as older adults with increased fall risk or patients with diabetic neuropathy. In addition, the functional exercises were all performed in toe stance position and are therefore less applicable to patients suffering with symptoms related to the foot flat phase of gait. Further, EMG data does not allow us to do inferences about longitudinal training effects in terms of adaptations in muscle function or strength. Although this relationship needs validation (Vigotsky et al., 2018) our results encourage the design of an intervention study to evaluate the effect of functional exercises against the effect of isolated foot exercises. Such a study would also be suitable to answer the question if the training stimuli of functional exercises is adequate for PIFM's structural adaptation, as well as functional improvements, to occur. The potential of functional exercises to provoke strength gains similar to isolated exercises is already demonstrated for neck, shoulder, and trunk muscles (Jørgensen et al., 2010). Another limitation is that we used sEMG. By placing the electrodes on the skin, this method is, in contrast to needle EMG, non-invasive and does not obstruct movements or the loading of the foot. In turn, sEMG has the drawback that crosstalk from adjacent or deeper muscles is inevitable. Although this may be expected to be profounder when measuring small muscles, such as foot muscles, previous literature demonstrated that crosstalk for these muscles remains within reasonable boundaries (Zelik, La Scaleia, Ivanenko, and Lacquaniti, 2015). Lastly, we have not objectified the performance of the task (e.g. grip force, toe stance kinematics, balance performance, and walking speed). Although standardization was endeavored by the provided instructions, suboptimal performance cannot be ruled out as a confounder of the findings and should be addressed in future studies. Future studies are also recommended to use additional equipment (e.g. motion capture systems and force instruments) to more reproducibly define the onset and offset of the exercises or a specific phase for the dynamic exercises (e.g. the stance phase in toe walking or the take-off and landing phase of hopping).

Conclusion

The findings of this study demonstrate that functional exercises provoke comparable or even more activation of the PIFMs than the most effective muscle-specific isolated foot exercise. This is a first step toward a more meaningful design of a physical therapy program to treat PIFM weakness or dysfunction, especially considering the additional benefits of functional exercises against isolated foot exercises that promote optimal training effects. However, a longitudinal intervention study is required to demonstrate the occurrence of muscular and functional adaptations in target populations, such as in older adults with increased fall risk.

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