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original research

Intrinsic Foot Muscle Activation During Specific Exercises: A T2 Time Magnetic Resonance Imaging Study

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Context: The intrinsic foot muscles maintain the medial longitudinal arch and aid in force distribution and postural control during gait. Impaired intrinsic foot-muscle function has been linked to various foot conditions. Several rehabilitative exercises have been proposed to improve it; however, literature that identifies which individual muscles are activated during specific intrinsic foot-muscle exercises is lacking.

Objective: To describe changes in activation of the intrinsic plantar foot muscles after 4 exercises as measured with T2 magnetic resonance imaging (MRI).

Design: Descriptive laboratory study.

Setting: Research laboratory.

Patients or Other Participants: Eight healthy National Collegiate Athletic Association Division I collegiate cross-country and track athletes (5 men and 3 women: age = 20 ± 0.93 years, height = 180.98 ± 10.84 cm, mass = 70.91 ± 7.82 kg).

Intervention(s): Participants underwent T2 MRI before and after each exercise. They completed 1 set of 40 repetitions of each exercise (short-foot exercise, toes spread out, first-toe extension, second- to fifth-toes extension).

Main Outcome Measure(s): Percentage increases in muscle activation of the abductor hallucis, flexor digitorum brevis, abductor digiti minimi, quadratus plantae, flexor digiti minimi, adductor hallucis oblique, flexor hallucis brevis, and interossei and lumbricals (analyzed together) after each exercise were assessed using T2 MRI.

Results: All muscles showed increased activation after all exercises. The mean percentage increase in activation ranged from 16.7% to 34.9% for the short-foot exercise, 17.3% to 35.2% for toes spread out, 13.1% to 18.1% for first-toe extension, and 8.9% to 22.5% for second- to fifth-toes extension. All increases in activation had associated 95% confidence intervals that did not cross zero.

Conclusions: Each of the 4 exercises was associated with increased activation in all of the plantar intrinsic foot muscles evaluated. These results may have clinical implications for the prescription of specific exercises to target individual intrinsic foot muscles.

Key Words: short-foot exercise, muscle functional magnetic resonance imaging, toes spread out, medial longitudinal arch

Key Points

- Clinicians can prescribe the short-foot exercise, toes-spread-out exercise, first-toe–extension exercise, and second- to fifth-toes–extension exercise to activate the intrinsic foot muscles.
- These exercises can result in a 9% to 35% increase in intrinsic foot-muscle activity.

The foot is an intricate structure consisting of a complex network of bones, ligaments, and muscles that work synchronously to maintain its shape and allow movements such as walking and running. The extrinsic foot muscles primarily provide osteokinematic movements,[1,2] whereas the intrinsic foot muscles maintain the medial longitudinal arch,[3–6] control the degree and velocity of arch deformation,[7] and aid in postural control during stance and gait.[8–11] Several conditions, such as plantar fasciopathy,[1,3,6] hallux valgus,[12–14] and pes planus,[1,12,15,16] are associated with weakened or atrophied intrinsic foot muscles. Rehabilitation and strengthening of these muscles are used to treat these conditions,[1,2,17] and prophylactic exercises targeting the intrinsic foot muscles may aid in injury prevention. Unfortunately, literature describing the individual activation levels for most of the intrinsic foot muscles during specific exercises is lacking. Surface electromyography[4,6,13,18] (sEMG) has been used to describe activation of the abductor hallucis, flexor digitorum brevis, and quadratus plantae, but the small sizes and close proximity of these muscles increase the risk for crosstalk from adjacent and underlying muscles.[19] Intramuscular EMG with fine-wire electrodes has been used to observe activation and minimize crosstalk of the abductor hallucis, flexor digitorum brevis, and quadratus plantae during gait.[9] However, it is difficult to confirm into which muscle an electrode has been inserted, and thus, researchers often use ultrasonography[5,9] to ensure fine-wire placement. The smaller number of muscles analyzed during these studies may not represent the foot core system[2] as a functional unit.

Muscle functional magnetic resonance imaging (MRI) has been used to quantify changes in T2 signal intensity on the basis of hemodynamic, metabolic, and mechanical changes that are directly related to neuromuscular activation of muscle tissue.[20–22] The use of T2 MRI allows for a noninvasive assessment of individual muscle activation. To

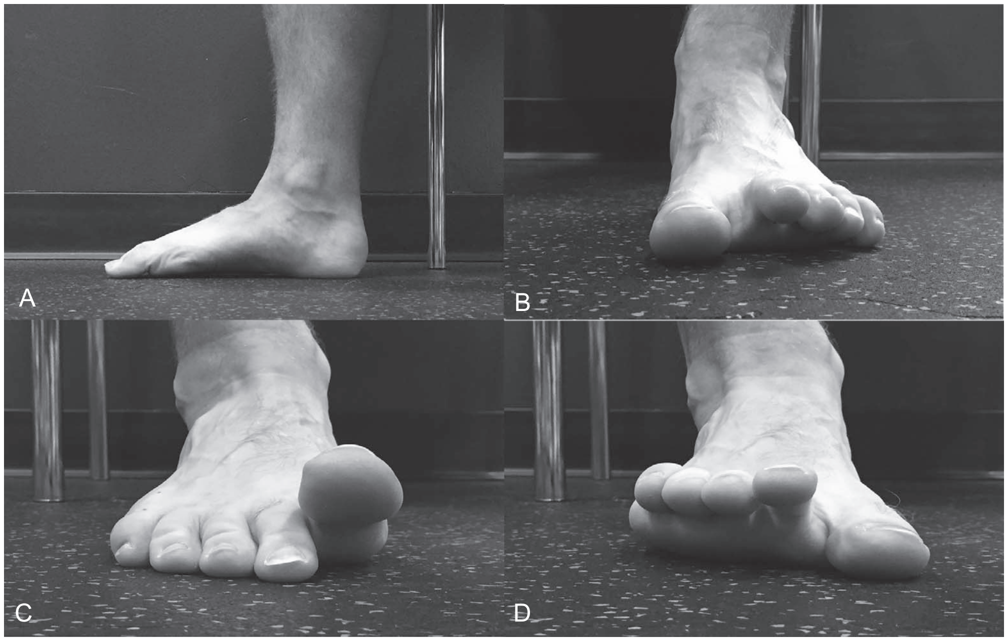

Figure 1. Intrinsic foot muscle exercises: A, short-foot exercise; B, toes-spread-out exercise, C, first-toe extension; and D, second- to fifth-toe extension.

our knowledge, this technique has not been used previously to assess activation patterns of the intrinsic foot muscles. Several exercises that are currently prescribed for the rehabilitation of acute and chronic foot and lower extremity conditions are thought to improve intrinsic foot-muscle function.[2,17] However, limited evidence describes specifically which intrinsic foot muscles are targeted by different exercises. Using a technique that can provide a more comprehensive analysis of muscle activity within the intrinsic foot muscles is crucial for determining which muscles are contracting during specific exercises. Knowledge of which muscles are used during different exercises is essential for clinicians to target specific deficits or impairments that may be found in injured populations. Therefore, the purpose of our study was to quantify intrinsic plantar foot muscle activation as measured by T2 MRI after 4 specific exercises.

METHODS

We performed a descriptive laboratory study using a crossover study design. The independent variable was time (pre-exercise and postexercise). Four exercises were analyzed: short-foot exercise, toes spread out, first-toe extension, and second- to fifth-toes extension (Figure 1). Our dependent variable was T2 time, which is presented as the percentage increase in activation (relative to baseline levels of activation) after each of the 4 exercises, recorded individually for these intrinsic plantar foot muscles: abductor hallucis, flexor digitorum brevis, abductor digiti minimi, quadratus plantae, flexor digiti minimi, adductor hallucis oblique, flexor hallucis brevis, and interossei and lumbricals.

Participants

Eight National Collegiate Athletic Association Division I cross-country and track athletes (5 men and 3 women: age = 20 ± 0.93 years, height = 180.98 ± 10.84 cm, mass = 70.91 ± 7.82 kg) participated. Participants were included if they had prior experience with the exercises assessed in this study and could perform all 4 exercises correctly on both feet. They were excluded if they had any conditions known to adversely affect muscle size or function or if they were restricted from full participation in sport due to injury status at the time of testing. All participants provided informed consent, and the study methods were approved by the Institutional Review Board for Health Sciences Research.

Instruments

Participants were scanned on a 3-Tesla MRI machine (Magnetom Trio; Siemens, Munich, Germany) from the most posterior aspect of the calcaneus through the toes with a large Siemens 4-channel flex coil secured around their feet. Images were acquired using a turbo spin-echo pulse sequence with a repetition time of more than 2.5 seconds and echo times of 11 and 67 milliseconds. We performed a voxel-by-voxel fit using these 2 echo times to estimate T2 time. Slice thickness was 10 mm with a 0-mm interslice gap, and scan time was approximately 7 minutes.

Testing Procedures

Participants sat in a non–weight-bearing position for 10 minutes before the baseline scan to minimize activity of the intrinsic foot muscles. They were transferred from a seated position to the scanner and were positioned supine with their feet first in the scanner. Participants' feet were secured in a standardized position of 0° of ankle dorsiflexion against a footplate and lightly wrapped in a flex coil. The standardized position was selected to ensure consistency across all scans and all participants.

After the baseline scan, participants were returned to a seated position with their feet on the floor. They performed 1 of the 4 exercises with the right foot and a different exercise with the left foot (different pairs of exercises were performed on day 1 and day 2). Exercises were performed in alternating fashion (right foot contraction followed by left foot contraction) to the beat of a metronome while seated. The metronome was set at 20 beats per minute, so that each contraction would be 3 seconds in duration. Participants completed 40 repetitions with each foot and then immediately returned to the scanner for the postexercise scan. We determined the number of repetitions (40) through pilot testing and selected this number to elicit a moderate amount of muscle activation across all 4 exercises in all participants. The order of exercises and the foot (right or left) that performed each exercise were randomized using a Latin square. Participants performed 2 of the exercises (1 with each foot) on day 1 and then returned 48 hours later to complete a new baseline scan, the other 2 exercises, and a postexercise scan.

Exercise Descriptions

Short-Foot Exercise. The short-foot exercise was performed by shortening and raising the medial longitudinal arch by bringing the metatarsal heads toward the calcaneus without flexing the toes or contracting the extrinsic foot muscles.[1]

Toes-Spread-Out Exercise. The toes-spread-out exercise was performed by extending all 5 toes and then simultaneously abducting all 5 toes while also flexing the first and fifth toes to the ground, keeping toes 2 to 4 extended. The middle toes were then relaxed.[13]

First- and Second- to Fifth-Toe–Extension Exercise. First-toe extension was performed by extending the great toe while the second to fifth toes remained on the floor in a neutral position. Second- to fifth-toe extension was performed by extending the second to fifth toes while the great toe remained flat on the floor.[23]

Data Processing

A specialized software package (version 2.011; WinVessel, Michigan State University, East Lansing, MI) was used to process the MRI scans pre-exercise and postexercise. For each muscle, the series of 3 contiguous MRI slices that provided the largest cross-sectional area was used for analysis. Muscles were identified by a single trained researcher who was blinded to whether scans were taken pre-exercise or postexercise and which exercise was associated with each scan. Baseline scans were used to establish a threshold for muscle activation above resting values. To establish a threshold value for signal intensity, 5 individual circular regions of interest were traced within the desired muscle on each of the 3 baseline slices. The mean T2 value and associated standard deviation were calculated from these 5 regions of interest and then used as the lower threshold. Any pixel that exceeded the lower threshold (T2 mean + 1 SD) was considered *active tissue* (Figure 2). This threshold was applied to both the pre-exercise and postexercise scans to identify the change in muscle activation after each exercise was performed. An upper limit for signal intensity was set from 900 to 10 000 so that inactive tissue, such as fat, would be excluded from the total number of pixels within each muscle. A lower limit for signal intensity was applied to all scans for any pixel with a value of 0 to 200, which represented other inactive tissues such as blood vessels. Each muscle was manually outlined and a pixel-by-pixel count was obtained for the total number of pixels within that muscle, within the active range (tissue that exceeded 1 SD above the mean resting T2 value to the upper limit of 900), and within any inactive tissue (T2 values between 0 and 200). The percentage increase in muscle activation after each exercise was calculated using the following equations:

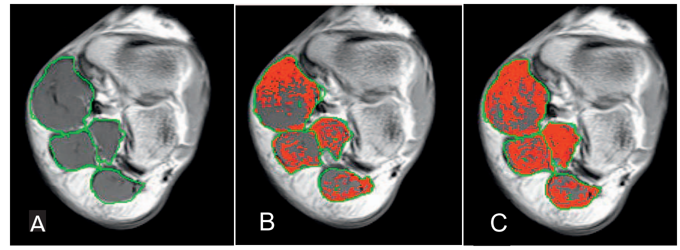

Figure 2. Representative example illustrating A, muscle heads; B, pre-exercise levels of activation, and C, postexercise levels of activation used in the analysis of muscle activation after intrinsic foot-muscle exercises.

$$\frac{\text{Active Pixels}}{(\text{Total Pixels} - \text{Inactive Pixels})} \times 100 = \%\ \text{Active Muscle}$$

$$\begin{aligned}&\%\ \text{Active Muscle Postexercise}\\&\quad - \%\ \text{Active Muscle Pre-exercise}\\&\quad = \%\ \text{Increase in Activation}\end{aligned}$$

This process was followed for each of the 3 largest slices within a muscle, and we used the most active individual slice of each muscle for data analysis. Due to the 10-mm slice thickness and the orientation of the adductor hallucis transverse, we were unable to clearly distinguish this muscle in 3 contiguous slices for each participant and, thus, this muscle was not included in our analysis. In addition, the interossei and lumbricals were not separated by clear fascial borders and, therefore, were treated as a single group in the analysis.

Statistical Analysis

The T2 time for each muscle was measured pre-exercise and postexercise and reported as the percentage increase in muscle activation after each exercise, as demonstrated in the aforementioned equations. Group means and 95% confidence intervals (CIs) were calculated for the percentage increase in activation of each muscle after each exercise. A muscle was considered to be activated above baseline value when the lower limit of the 95% CI did not cross zero. A Pearson correlation coefficient was also calculated to assess possible relationships between pre-exercise levels of activation and the percentage change in activation after the exercises.

RESULTS

Each of the 4 exercises resulted in activation of all of the intrinsic plantar foot muscles by at least 8.9% (range, 8.9% to 35.2%) with associated 95% CIs that did not cross zero (Table).

Short-Foot Exercise

The short-foot exercise resulted in an increase in muscle activation ranging from 16.7% ± 12.1% in the quadratus plantae to 34.9% ± 8.1% in the abductor digiti minimi (Figure 3A).

Table. Increase in Intrinsic Foot-Muscle Activation With 4 Intrinsic Foot Muscle Exercises, Mean % (95% Confidence Interval)

Muscle	Exercise			
	Short Foot	Toes Spread Out	First-Toe Extension	Second- to Fifth-Toe Extension
Abductor hallucis	29.7 (16.8, 42.6)	18.9 (7.4, 30.5)	16.9 (8.3, 25.5)	16.5 (5.8, 27.2)
Flexor digitorum brevis	24.8 (11.8, 37.9)	27.0 (18.3, 35.7)	18.1 (9.5, 26.7)	15.1 (5.4, 24.7)
Abductor digiti minimi	34.9 (26.7, 43.0)	35.2 (23.6, 46.9)	14.1 (3.9, 24.2)	22.5 (10.0, 35.1)
Quadratus plantae	19.0 (12.0, 26.0)	25.4 (12.6, 38.2)	13.9 (5.8, 21.9)	17.0 (4.7, 29.3)
Flexor digiti minimi	23.4 (4.0, 42.9)	30.2 (9.7, 50.6)	16.3 (6.5, 26.1)	10.3 (4.9, 15.7)
Adductor hallucis oblique	22.4 (4.5, 40.3)	31.5 (17.2, 45.8)	15.9 (5.9, 26.0)	17.6 (7.4, 27.8)
Flexor hallucis brevis	20.8 (7.6, 33.9)	29.5 (20.8, 38.3)	13.1 (4.3, 22.0)	20.2 (9.6, 30.7)
Interossei and lumbricals	16.7 (4.5, 28.8)	17.3 (6.5, 28.0)	15.0 (9.3, 20.7)	8.9 (3.9. 13.9)

Toes-Spread-Out Exercise

Similarly, the toes-spread-out exercise demonstrated an increase ranging from 17.3% ± 10.8% for the interossei and lumbricals to 35.2% ± 11.6% for the abductor digiti minimi (Figure 3B).

First-Toe–Extension Exercise

The first-toe–extension exercise had a more narrow range for the increase across muscles, with the lowest value being 13.1% ± 8.8% increase for the flexor hallucis brevis and the highest being 18.1% ± 8.6% increase for the flexor digitorum brevis (Figure 3C).

Second- to Fifth-Toes–Extension Exercise

The second- to fifth-toe–extension exercise resulted in an increase that ranged from 8.9% ± 5.0% for the interossei and lumbricals to 22.5% ± 12.6% for the abductor digitorum minimi (Figure 3D).

In addition, heat maps (Figure 4) were created after each exercise depicting the percentage increase in activation for all muscles of each participant. Average percentage increases for each muscle shown on the heat maps were transposed onto corresponding intrinsic foot muscle images (Figure 5) for each exercise. The correlation between pre-exercise activation and the pre-to-post increase in activation was weak ($r = -0.19$).

DISCUSSION

All 4 exercises activated all of the intrinsic plantar foot muscles, with average percentage increases in activation that ranged from 8.9% to 35.2%. To our knowledge, this is the first study to describe intrinsic foot-muscle activity using T2 MRI and the first study to quantify the extent of activation of those muscles after specific exercises designed to target them.

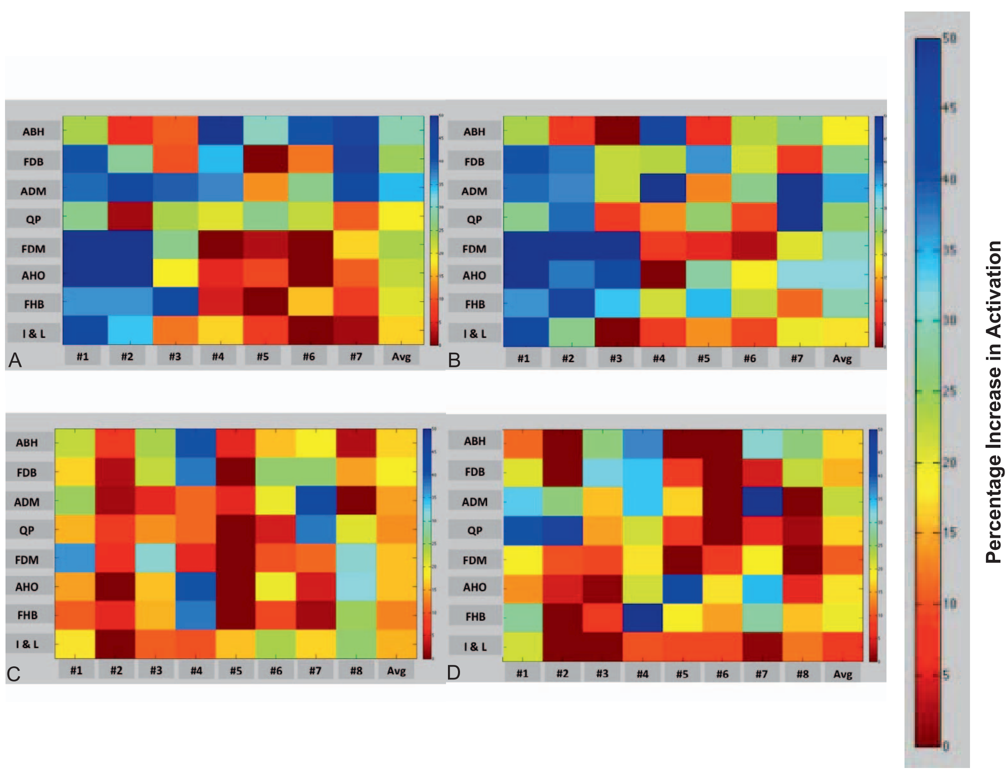

Figure 3. Percentage increase in activation: A, short-foot exercise; B, toes-spread-out exercise; C, first-toe extension; D, second- to fifth-toe extension. Abbreviations: ABH, abductor hallucis; ADM, abductor digiti minimi; AHO, adductor hallucis oblique; FDB, flexor digitorum brevis; FDM, flexor digiti minimi; FHB, flexor hallucis brevis; I&L, interossei and lumbricals; QP, quadratus plantae.

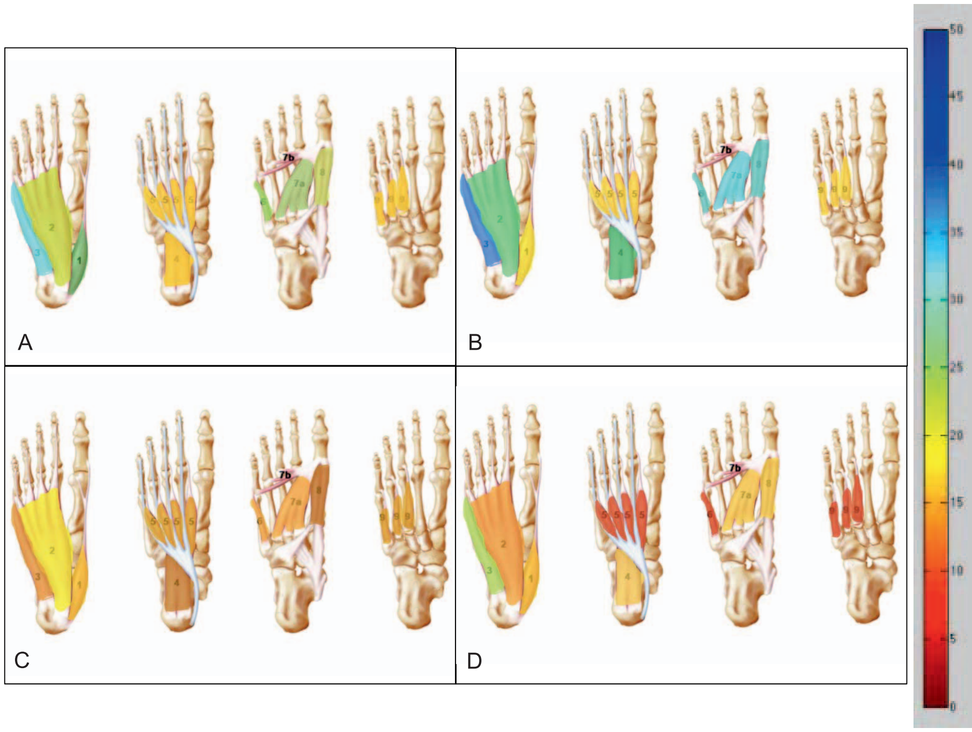

Figure 4. Anatomic representation of heat maps for group mean muscle-activation increases for each exercise. A, Short foot. B, Toes spread out. C, First-toe extension. D, Second- to fifth-toe extension. Reprinted with permission from BMJ Publishing Group Ltd.[2]

These findings are important and relevant for clinicians involved in the assessment and treatment of foot and lower extremity conditions that may involve dysfunction of the intrinsic foot muscles and in the prevention of lower extremity injury.

The short-foot exercise showed the greatest mean percentage activation in the abductor digiti minimi (34.9%), abductor hallucis (29.7%), and flexor digitorum (24.8%). This could be a result of the parallel anatomical orientations these muscles have to the longitudinal arches in

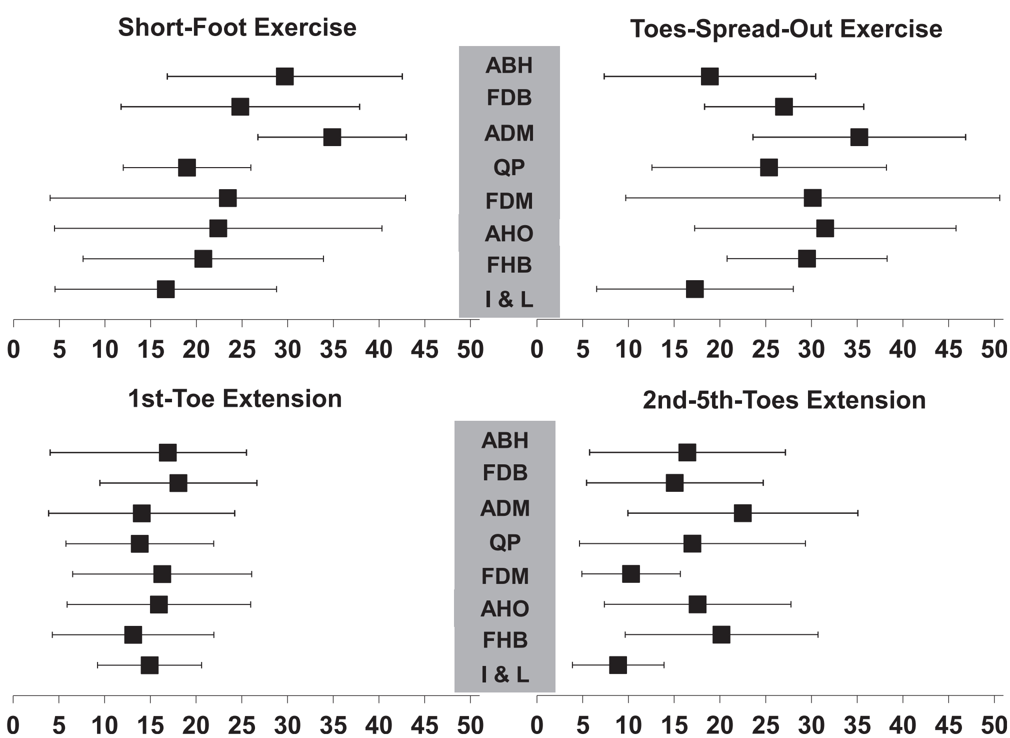

Figure 5. Muscle-activation increases (%), group means, and associated 95% confidence intervals for each exercise. Abbreviations: ABH, abductor hallucis; ADM, abductor digiti minimi; AHO, adductor hallucis oblique; FDB, flexor digitorum brevis; FDM, flexor digiti minimi; FHB, flexor hallucis brevis; I&L, interossei and lumbricals; QP, quadratus plantae.

the foot. The toes-spread-out exercise showed the highest percentage mean activation in the abductor digiti minimi (35.2%), adductor hallucis oblique (31.5%), and flexor digiti minimi (30.2%). Due to the circumferential motion that occurs at the first and fifth toes as these digits are extended, abducted, and then flexed back to the floor, it is not surprising that the intrinsic plantar foot muscles that insert on the first and fifth toes demonstrated the greatest levels of activation with the toes-spread-out exercise. The first-toe–extension exercise showed the greatest percentage mean activation in the flexor digitorum brevis (18.1%), abductor hallucis (16.9%), and flexor digiti minimi (16.3%). As the first toe is extended, the intrinsic plantar flexors for the second to fifth toes are likely being used to keep these toes flat on the floor. Similarly, the abductor hallucis may be activated to either stabilize the great toe during extension or keep the first metatarsal head on the floor. The second- to fifth-toe–extension exercise had the highest mean percentage activation in the abductor digiti minimi (22.5%), flexor hallucis brevis (20.2%), and adductor hallucis oblique (17.6%). For the completion of this exercise, the flexor hallucis brevis and adductor hallucis oblique may play roles in stabilizing the great toe on the ground as the other 4 toes extend.

We did not identify any noticeable trends among participants in terms of which muscles were activated the most or least during each of the 4 exercises. Unfortunately, this limits our ability to make specific recommendations about which exercise may be best suited to target specific intrinsic foot-muscle insufficiencies. However, the distinct variability in the extent of muscle activation across participants underscores several key considerations when interpreting the percentage activation after submaximal exercises. Although we can conclusively identify which muscles were being used for the specific exercises, we cannot speculate about whether increased or decreased levels of activation among participants indicated how difficult the task was for each individual to complete or the muscle force required to complete the exercise. For example, 1 participant may have better neuromuscular control (able to recruit a greater proportion of the motor-neuron pool) of the intrinsic foot muscles and require less activation to complete the 40 repetitions than participants with worse neuromuscular control. Conversely, if a participant has better neuromuscular control, he or she may also be capable of activating more of the motor-neuron pool over the course of 40 repetitions. In addition, the different strategies that could be used to complete these exercises should also be considered when interpreting the present results. For example, the second- to fifth-toe–extension exercise is designed to target the intrinsic plantar foot muscles attached to the hallux. As the participant extends the second through fifth toes off the ground, the muscles acting on the hallux can be activated in an attempt to resist first-toe extension from activation of the extensor hallucis longus, which often occurs simultaneously with activation of the extensor digitorum longus. However, as an individual's fine motor skill improves, he or she could, in theory, accomplish this task by selectively activating the extensor digitorum longus without concurrent extensor hallucis recruitment, which would minimize the activation required of the plantar intrinsic muscles acting on the hallux.

Previous researchers[13] used sEMG to compare muscle activation of the abductor and adductor hallucis when participants with mild hallux valgus performed the short-foot and toes-spread-out exercises. In that study,[13] the toes-spread-out exercise showed greater activation of the abductor hallucis than did the short-foot exercise (mean difference = 44.96%). Whereas it was not our aim to compare the extent of activation across exercises, the average percentage increases of the abductor hallucis for the short-foot and toes-spread-out exercises had similar means and associated 95% CIs with substantial overlap, suggesting that the magnitude of difference between these 2 exercises was minimal in our healthy sample. Our results demonstrated that all of the intrinsic plantar foot muscles were activated when both exercises were completed and, thus, crosstalk from deeper or adjacent muscles may have influenced previous sEMG results or differences between healthy and injured populations may need to be examined further.

Kelly et al[5] recently demonstrated that the extent of activation of the intrinsic foot muscles increases as postural demands increase up to 150% of normal body weight. They also showed[5] that when electrically inducing a contraction of the muscles of the medial longitudinal arch, arch height and length during weight bearing could be restored to similar dimensions as during non–weight bearing. These findings were instrumental in illustrating the collective role of the intrinsic foot muscles in maintaining the structure of the medial longitudinal arch. Our results have now demonstrated that, regardless of which motion segment of the foot is being moved during the execution of these 4 exercises, all of the intrinsic plantar foot muscles were activated after the task was completed. This finding is important because it indicates how the functional roles of the intrinsic foot muscles cannot simply be described by their anatomical origin and insertion. Our results support the idea that the intrinsic foot muscles act as functional units during exercises[2]; however, we cannot identify the exact functional contribution (eg, eccentric control, isometric stability) of each muscle. Although the mechanisms for coordinated motor control among the intrinsic foot muscles are not fully understood, our results suggest that their shared neural innervation may make it more difficult to isolate individual muscles; however, this should be evaluated further.

To our knowledge, we were the first to specifically examine activation of the intrinsic foot muscles through the use of T2 MRI after performing exercises designed to target those muscles. A previous feasibility study[24] showed that T2 changes were greater in young participants' foot muscles (105.8% ± 3.3%) than in those of elderly participants (103.9% ± 3.2%). The authors[24] also found a longer time to peak T2 signal intensity in elderly participants (157.1 ± 109.9 seconds) than in younger ones (95.1 ± 77.6 seconds), suggesting that age may influence T2 peaks and the time to return to baseline. Heat mapping through T2 percentage-activation change has shown[25] varying activation levels in the medial gastrocnemius (13.3% ± 1.3%), lateral gastrocnemius (7.8% ± 1.2%), and soleus (6.3% ± 2.1%) after unilateral heel raises, which are comparable to the percentage increases in the intrinsic plantar foot muscles in our study. Emerging evidence has shown that for T2, higher-intensity exercises result in a quicker rate of change[26] as well as a larger overall increase[21] when compared with lower-intensity exercises. In our study, all exercises were performed without resistance to the beat of a metronome in an attempt to standardize the rate of contraction and contraction intensity across participants. When performing intrinsic foot-muscle exercises, it is common to increase task difficulty by progressing from a seated position to double-leg stance and finally to single-leg stance and, thus, it may be beneficial to examine activation levels of the intrinsic foot muscles throughout this progression. In addition, it would be worthwhile to use T2 MRI to compare the intrinsic foot-muscle function of healthy and injured (plantar fasciopathy, hallux valgus, or other foot and ankle disorders) populations and in tasks such as walking, running, or other functional exercises so that we can expand our evidence-based recommendations for intrinsic foot-muscle exercises.

Our study had some obvious limitations due to the nature of T2 MRI. The overall cost of the MRI scans and the large amount of data-processing time required the relatively small sample size. Our participants were a relatively homogeneous, healthy sample of athletic young adults, and this may limit our ability to generalize our results to less physically active or injured populations as well as to individuals with different arch morphologies.

CONCLUSIONS

All of the plantar intrinsic muscles assessed in our study showed increased activation with each of the 4 exercises. The short-foot exercise, toes-spread-out exercise, first-toe–extension exercise, and second- to fifth-toe–extension exercise each caused activation of all of the intrinsic plantar foot muscles and can be recommended as a means of exercising these muscles.

REFERENCES

1. Jam B. Evaluation and retraining of the intrinsic foot muscles for pain syndromes related to abnormal control of pronation. Posturology Web site. Published 2006. http://posturology.nl/fileadmin/user_upload/IntrinsicMuscles_Pain_Syndromes.pdf. Accessed June 10, 2015.
2. McKeon PO, Hertel J, Bramble D, Davis I. The foot core system: a new paradigm for understanding intrinsic foot muscle function. *Br J Sports Med*. 2015;49(5):290.
3. Chang R, Kent-Braun JA, Hamill J. Use of MRI for volume estimation of tibialis posterior and plantar intrinsic foot muscles in healthy and chronic plantar fasciitis limbs. *Clin Biomech (Bristol, Avon)*. 2012;27(5):500–505.
4. Fiolkowski P, Brunt D, Bishop M, Woo R, Horodyski M. Intrinsic pedal musculature support of the medial longitudinal arch: an electromyography study. *J Foot Ankle Surg*. 2003;42(6):327–333.
5. Kelly LA, Cresswell AG, Racinais S, Whiteley R, Lichtwark G. Intrinsic foot muscles have the capacity to control deformation of the longitudinal arch. *J R Soc Interface*. 2014;11(93):20131188.
6. Headlee DL, Leonard JL, Hart JM, Ingersoll CD, Hertel J. Fatigue of the plantar intrinsic foot muscles increases navicular drop. *J Electromyogr Kinesiol*. 2008;18(3):420–425.
7. Lees A, Lake M, Klenerman L. Shock absorption during forefoot running and its relationship to medial longitudinal arch height. *Foot Ankle Int*. 2005;26(12):1081–1088.
8. Mann R, Inman VT. Phasic activity of intrinsic muscles of the foot. *J Bone Joint Surg Am*. 1964;46:469–481.
9. Kelly LA, Kuitunen S, Racinais S, Cresswell AG. Recruitment of the plantar intrinsic foot muscles with increasing postural demand. *Clin Biomech (Bristol, Avon)*. 2012;27(1):46–51.
10. Mulligan EP, Cook PG. Effect of plantar intrinsic muscle training on medial longitudinal arch morphology and dynamic function. *Man Ther*. 2013;18(5):425–430.
11. Grey T, Redguard D, Wengle R, Wegscheider P. Effect of plantar flexor muscle fatigue on postural control. *WURJ: Health Nat Sci*. 2013;4(1):1.
12. Stewart S, Ellis R, Heath M, Rome K. Ultrasonic evaluation of the abductor hallucis muscle in hallux valgus: a cross-sectional observational study. *BMC Musculoskelet Disord*. 2013;14:45.
13. Kim MH, Kwon OY, Kim SH, Jung DY. Comparison of muscle activities of abductor hallucis and adductor hallucis between the short foot and toe-spread-out exercises in subjects with mild hallux valgus. *J Back Musculoskelet Rehabil*. 2013;26(2):163–168.
14. Donatelli R. Abnormal biomechanics of the foot and ankle. *J Orthop Sports Phys Ther*. 1987;9(1):11–16.
15. Jung D, Koh E, Kwon O. Effect of foot orthoses and short-foot exercise on the cross-sectional area of the abductor hallucis muscle in subjects with pes planus: a randomized controlled trial. *J Back Musculoskelet Rehabil*. 2011;24(4):225–231.
16. Michelson JD, Durant DM, McFarland E. The injury risk associated with pes planus in athletes. *Foot Ankle Int*. 2002;23(7):629–633.
17. McKeon PO, Fourchet F. Freeing the foot: integrating the foot core system into rehabilitation for lower extremity injuries. *Clin Sports Med*. 2015;34(2):347–361.
18. Jung D, Kim M, Koh E, Kwon O, Cynn H, Lee W. A comparison in the muscle activity of the abductor hallucis and the medial longitudinal arch angle during toe curl and short foot exercises. *Phys Ther Sport*. 2011;12(1):30–35.
19. Solomonow M, Baratta R, Bernardi M, et al. Surface and wire EMG crosstalk in neighbouring muscles. *J Electromyogr Kinesiol*. 1994;4(3):131–142.
20. Price TB, Kamen G, Damon BM, et al. Comparison of MRI with EMG to study muscle activity associated with dynamic plantar flexion. *Magn Reson Imaging*. 2003;21(8):853–861.
21. Damon BM, Wadington MC, Hornberger JL, Lansdown DA. Absolute and relative contributions of BOLD effects to the muscle functional MRI signal intensity time course: effect of exercise intensity. *Magn Reson Med*. 2007;58(2):335–345.
22. Jacobi B, Bongartz G, Partovi S, et al. Skeletal muscle BOLD MRI: from underlying physiological concepts to its usefulness in clinical conditions. *J Magn Reson Imaging*. 2012;35(6):1253–1265.
23. Dicharry J. *Anatomy for Runners: Unlocking Your Athletic Potential for Health, Speed, and Injury Prevention*. New York, NY: Skyhorse Publishing, Inc; 2013.
24. Heo H, An D. The effect of an inclined ankle on the activation of the abductor hallucis muscle during short foot exercise. *J Phys Ther Sci*. 2014;26(4):619–620.
25. Soysa A, Hiller C, Refshauge K, Burns J. Importance and challenges of measuring intrinsic foot muscle strength. *J Foot Ankle Res*. 2012;5(1):29.
26. Kos S, Klarhofer M, Aschwanden M, Scheffler K, Jacob AL, Bilecen D. Simultaneous dynamic blood oxygen level-dependent magnetic resonance imaging of foot and calf muscles: aging effects at ischemia and postocclusive hyperemia in healthy volunteers. *Invest Radiol*. 2009;44(11):741–747.

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