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Research Article

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Morphologic Relationship between Toe Exercises and the Medial Longitudinal Arch

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Abstract

Introduction: This randomized controlled clinical trial aimed to investigate the relationship between toe exercises and morphological variations of the medial longitudinal arch (MLA) of the foot.

Methods: We enrolled 39 participants with a mean age of 20.5 ± 0.10 years and weight of 57.9 ± 1.6 kg and examined 78 feet. Participants were assigned to 1 of 4 groups as: the Towel Curl Exercise group (TCE), Great Toe Exercise group (GTE), Lesser Toe Exercise group (LTE), or Control Group (CG). Subjects in the CG performed no exercises and the other groups performed exercises for 5 weeks. Groups were compared using the Modified Navicular Drop Test (MNDT) value, Arch Height Index (AHI), and range of Dorsiflexion (DF).

Results: In the GTE group, no significant differences post exercise were noted. In the LTE group, the MNDT value decreased significantly from 5.03 mm to 3.13 mm ($p<0.01$). In the TCE group, the MNDT value did not differ significantly. The AHI and DF (from 2.46 to 3.10; $p<0.01$ and from 9.7° to 14.1°; $p<0.10$, respectively) significantly increased in the TCE group.

Conclusion: Subjects in the GTE did not show an MLA response. Subjects in the LTE showed a significant MLA response.

Keywords: Medial Longitudinal Arch of the Foot; Navicular Drop Test; Arch Height Index; Toe Function

Abbreviations: TCE: Towel Curl Exercise group; GTE: Great Toe Exercise group; LTE: Lesser Toe Exercise group; CG: Control Group; MNDT: Modified Navicular Drop Test; AHI: Arch Height Index; DF: Dorsiflexion; MLA: Medial Longitudinal Arch; PIP: Proximal Interphalangeal; DIP: Distal Interphalangeal; IP: Interphalangeal; EMG: Electromyography; NDT: Navicular Drop Test; FDL: Flexor Digitorum Longus; FHL: Flexor Hallucis Longus; TP: Tibialis Posterior; TA: Tibialis Anterior; SFE: Short Foot Exercise

Introduction

Anatomically, the medial longitudinal arch (MLA) is supported by the calcaneal, talus, navicular, medial cuneiform, and 3 medial metatarsal bones. The plantar fascia, calcaneonavicular (spring) ligament, tibialis posterior, medial tarsometatarsal joint, and extrinsic and intrinsic muscles of the foot all assist in maintaining height and shape of the MLA [1-8]. The risk of pes planus is associated with many sports injuries [9,10].

Many studies of the foot and ankle are available in the literature. However, studies of the toes, the most distal joints, are limited [5,6,9,11-14] and although all 5 toes are considered as a rigid structure during movement, the toes were not analyzed separately in these studies. Anatomically, the first tarsometatarsal joints have separate joint capsules [8] from those of the other tarsometatarsal joints. Each lesser toe has 2 joints, the proximal and distal interphalangeal joints (PIP and DIP joints, respectively). The great toe has only the interphalangeal (IP) joint. The kinematics is difficult to assess without classifying the toes. The toes have many muscles, and their mapping is complicated. The wide range of bones and ligaments adds to the complexity. Because toe function involves a combination of many elements, the toes must be analyzed in as much detail as possible. However, the small toe joints make it difficult to perform electromyography (EMG) and studies to analyze toe movements separately are limited [13-22]. As a result, their function is poorly understood. Hence, separate exercises for plantar flexion were developed for the great toe and for the lesser toes [16,17]. However, these studies did not involve measurements of morphological variations. As a result, the impact of these exercises on MLA morphology remains unclear. Thus, this study focused on MLA morphological variations.

Material and Methods

Design

MLA morphology was evaluated using the Modified Navicular Drop Test (MNDT) and Arch Height Index (AHI) measurements. The dependent variables included the MNDT value, AHI and Dorsiflexion (DF) during knee extension, measured at baseline and after 5 weeks.

Subjects

A sample of 40 subjects (20 men and 20 women) volunteered for the study. The study exclusion criteria were any sign of leg pain, medical history of sprain, ligament injury, fracture, and surgery, and evidence of musculoskeletal disease or neurological disease that could affect the motor function within the previous 6 months. None of the subjects had prior personal experience with the toe exercise training utilized in the study. This study received approval from the Ethics Committee for Human Research of Gunma Paz University (10-7). All subjects provided informed consent to participate.

The participants were assigned to 1 of 4 groups: Great Toe Exercise group (GTE), Lesser Toe Exercise group (LTE), Towel Curl Exercise

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group (TCE), and Control Group (CG). Each group had 10 participants. However, 1 participant in the GTE dropped out immediately after initiating the intervention due to an ankle sprain.

Thus, the LTE, TCE, and CG groups included 10 participants (representing 20 feet; 5 men and 5 women), and the GTE group included 9 participants (representing 18 feet; 5 men and 4 women). Each group recorded their daily exercise and followed the instructions provided by a physiotherapist. The characteristics of the participants are shown in Table 1.

Measured parameters

MNDT value, AHI, and DF measurements for each foot were obtained.

Modified Navicular Drop Test (MNDT): The navicular bone is the key to the MLA and plays a pivotal role in subtalar joint pronation and supination. The Navicular Drop Test (NDT) was introduced by Brody [18] and many researchers have reported on its reliability [19-21]. The NDT value was defined as the distance between the navicular tuberosity height in the sitting position and the standing position. In addition, the navicular bone is relatively easy to palpate due to the fact that few gaps exist in the surrounding soft tissue. Narvaez et al. [22] used radiography to validate navicular bone height measurements; however, some researchers reported that the reliability of the NDT was not as high as what was reported previously [23,24]. The reliability of the NDT was 0.51-0.77; therefore, NDT measurements might be insufficiently reliable in some settings.

The foot loads were not defined in any reports for the sitting position. To compensate for this limitation, the NDT was performed, and the results were compared at 15%, 20% and 25% foot loads. The intra- and inter-class reliabilities of a 20% load were the highest for both testers: 0.88 (1,1), 0.78 (1,1) and 0.86 (2,1). Hence, in this study, NDT measurements while sitting were made at a 20% load with 10% of the weight borne on each foot. The test was redefined as the MNDT.

For this study, the navicular tuberosity level was marked by a physiotherapist specializing in foot and ankle disease with more than 15 years' experience. The examiners in this study were 4 fourth-year physiotherapy students who were not able to predict results; each was assigned 1 group to measure. The students received 1 month of measurement training with the specialized physiotherapist. The physiotherapist randomly chose 1 subject in each group (4 subjects in total) and measured the navicular bone height of each to help minimize measurement errors (Figure 1A).

The measurements were made using a digital caliper (AD-5765-150; A&D Company, Tokyo, Japan), 2 digital scales, and an elevating bed (KC-237; Paramount Bed Company, Tokyo, Japan).

Arch Height Index (AHI): The MLA was assessed using AHI measurements. The AHI was developed by Williams and McClay [25] by dividing the dorsum foot height at 50% of the foot length by the truncated foot length. Williams and McClay reported relatively high interclass reliability and high validity.

Characteristics	CG	GTE	LTE	TCE	
N	10	9	10	10	
Height (cm)	163.8 ± 2.4	167.2 ± 3.4	164.0 ± 2.3	165.2 ± 3.2	NS
Weight (kg)	57.9 ± 3.1	59.3 ± 4.3	58.9 ± 2.8	55.5 ± 3.2	NS
Age (years)	20.6 ± 0.3	20.4 ± 0.2	20.6 ± 0.2	20.5 ± 0.2	NS
BMI (kg/m^2)	21.4 ± 0.7	21.0 ± 1.0	21.8 ± 0.8	20.2 ± 0.7	NS
TFL (cm)	167.5 ± 2.6	171.4 ± 2.6	171.0 ± 3.3	171.2 ± 4.4	NS

Data are presented as mean ± SD, CG: Control Group; TCE: Towel Curl Exercise; GTE: Great Toe Exercise; LTE: Lesser Toe Exercise; TFL: Truncated Foot Lengths. Results are reported as mean ± SE.

Table 1: Characteristics of subjects.

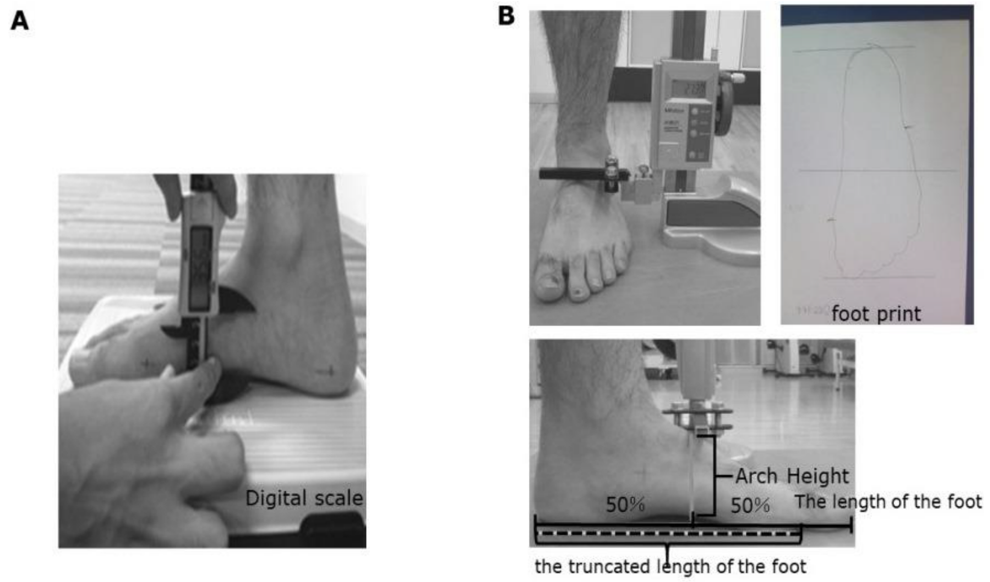


Figure 1: (A) MNDT (Modified Navicular Drop Test), (B) AHI (Arch Height Index). Measurement of navicular height using a digital caliper, 2 digital scales and an elevating bed and measurement of dorsal foot height at 50% of the foot length using a modified digital height gauge.

They recommended that the MLA be measured at both 90% and 10% weight bearing (WB) to be useful when setting a standing value.

A simple footprint of each subject was measured before the AHI measurement was taken. The subject placed their bare foot on blank paper while sitting on a chair. The subject's foot was outlined by the examiner and the distal end of the first metatarsal bone head was marked. To minimize measurement errors, the same footprints were used again after the interventions (Figure 1B).

For posture, the ankle was in plantar flexion if the subject's foot was set forward or in eversion if the subject's foot was set laterally. The subject's posture was set with the feet in a natural standing position so that Arch Height (AH) could be measured with the ankle in mid-position, where possible. The subjects placed approximately 10% and then 90% of WB on the foot to be measured and stabilized their balance by leaning on a bed with both arms.

AH, a unitless measurement was calculated by dividing the dorsum foot height by the truncated foot length. The difference between the AH at 10% WB and at 90% WB was defined as the AHI. The dorsum foot height was measured at 50% of the total foot length by using a modified digital height gauge (HDS-30C; Mitutoyo Company, Kanagawa, Japan).

$$\text{Arch height index (AHI): AH(10\%)-AH(90\%)} = \frac{y(10)}{x(10)} - \frac{y(90)}{x(90)}$$

x: Truncated length of the foot

y: Dorsum foot height measured at 50% of the total foot length

Foot DF range of motion: To measure DF, a stationary arm was positioned parallel to the longitudinal axis of the fibula and a moveable arm was placed parallel to the longitudinal axis of the fifth metatarsal. The knee was then extended. A Tokyo University-type goniometer, able to measure to within 1°, was used. DF was measured by 2 examiners: 1 held the subject's foot in the knee joint extension position, whereas the other put the goniometer between the stationary arm and the moveable arm.

Interventions

The intervention varied among groups (TCE, GTE, LTE, and CG).

Towel Curl Exercise (TCE): The subjects remained in a seated position with the hip and knee joints at 90° of flexion. The towel curl exercise was performed from complete toe extension to complete flexion. When the toes were in complete extension, the foot was in complete contact with the floor from the calcaneal to the head of the metatarsal bone. With this setting, compensatory motions at the hindfoot, shin, and knee were restrained [16,17]. Each subject performed the towel curl exercise training sessions at home 3 times a day for 3 min over the course of 5 weeks (Figure 2A).

Great Toe Exercise (GTE): The subjects placed their great toes on a small platform roughly 5 cm in height. In the frontal plane, their tibial tuberosity was set to the front, while their knee and hip joints were set to the mid-position between abduction and adduction. The subjects were seated, and a 3 kg weight was placed on the distal thigh. In the sagittal plane, they tilted their trunk forward and then raised their heels with their great toe.

The IP joint was set to the mid-position and the subjects raised their heels using metatarsophalangeal joint extension. The subjects were instructed to keep their lesser toes as still as possible with little or no contraction [16,17] and to perform the exercise in sets of 10, 3 times a day. It is around 15 minutes for total time per day.

During the intervention, the subjects attached a 2 mm thick PORON soft pad (ROGERS INOAC CORPORATION, Aichi, Japan; 10 × 10 mm) to the head of the great toe. This pad was intended to make the subjects conscious of the great toe during typical daily movements. PORON is a high-density material with a minute and uniform cell structure.

Furthermore, the subjects in this group performed the plantar flexor exercise with a TheraBand resistance using only the great toe. However, this exercise was supplemental, and the subjects did not adhere strictly to the exercise protocol (Figure 2B).

Lesser Toe Exercise (LTE): The lesser toe exercise was similar to the great toe exercise. The subjects placed their lesser toes on a small platform about 5 cm high. In the frontal plane, their tibial tuberosity was set to the front, while their knee and hip joints were set to the mid-position for abduction and adduction. The subjects were seated, and a 3 kg weight was placed on the distal thigh. In the sagittal plane, the subjects tilted their trunk forward and raised their heels with their lesser toes. In the LTE, DIP, and PIP joint extension and flexion positions were set; the subjects then raised their heels. The subjects were instructed to keep their great toes as still as possible with little or no contraction [16,17] and to repeat the exercise in sets of 10, 3 times a day. It is around 15 minutes for total time per day.

During the intervention, the subjects attached 2-mm thick PORON soft pads (10 × 10 mm) to the heads of the lesser toes during daily activities (Figure 2C).

The subjects performed the plantar flexor exercise with a TheraBand resistance using only the lesser toe. However, this exercise was supplemental, and the subjects did not adhere to it strictly.

Control Group (CG): The CG was active as usual during the study period. With the exception of the CG, intervention compliance was monitored with exercise sheets on which the subjects recorded the positions in which they exercised. Moreover, the subjects received training guidance directly every week to confirm that they performed their exercise adequately and to detect whether any problems occurred during the intervention. None of the groups introduced any new fitness training routines over the duration of this study.

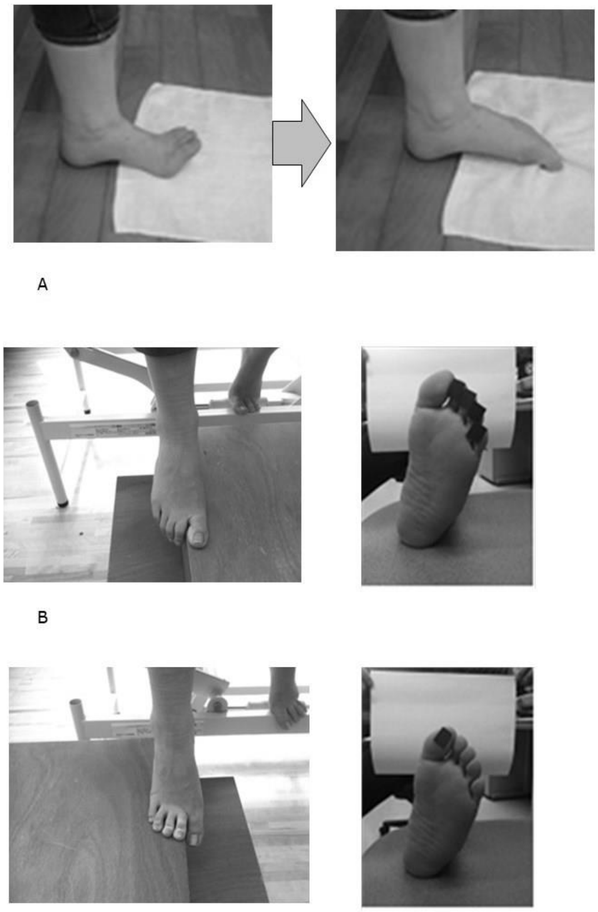
Data analysis

The data were assessed for normality using the Kolmogorov-Smirnov and Shapiro-Wilk tests. Thus, the data from each group (GTE, LTE, TCE, and CG) were analyzed using one-way ANOVA and then further analyzed with post hoc Dunnett tests to determine if statistically significant differences existed between the varied measurements of each group taken at baseline and at 5 weeks post-intervention. Paired t-tests were used to determine whether the measured parameters changed significantly between pre- and post-intervention within each group. For all statistical analyses, p-values for significance were set at <0.05, and IBM SPSS Statistics 21 software was used for statistical analyses.

Results

In the GTE group, no parameters changed significantly following the 5 week exercise program. The TCE group had a mean DF of 9.7 ± 4.5° at baseline, which increased to 14.1 ± 1.9° after 5 weeks ($p<0.01$). Furthermore, the mean AHI significantly increased after the 5 week exercise program ($p<0.05$). The LTE group had a mean MNDT value of 5.03 ± 0.31 mm at baseline, which significantly decreased to 3.13 ± 0.31 mm after the 5 week period ($p<0.01$).

The varied measurements of each group taken at the baseline and at 5 weeks post-intervention were compared with that of the CG



A

B

C

Figure 2: (A) Towel curl exercise, (B) Great toe exercise and (C) Lesser toe exercise.

	TCE		GTE		LTE		CG	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
MNDT value (mm)	5.22 ± 1.93	5.16 ± 1.62‡	4.32 ± 1.80	4.31 ± 1.19†	5.11±1.62	**3.13 ± 1.15‡†#	4.87 ± 1.11	5.34 ± 1.18#
AHI (× 10^{-2})	2.07 ± 0.99	*3.10 ± 0.80	2.33 ± 0.78	2.88 ± 1.24	2.53 ± 1.10	2.50 ± 1.22	2.82 ± 0.39	2.97 ± 0.29
DF (°)	9.8 ± 7.3	*13.3 ± 7.5§	8.6 ± 7.4	8.8 ± 4.9	12.4 ± 8.6	12.4 ± 5.8	10.0 ± 3.5	9.1 ± 3.8§

Each group (GTE, LTE, TCE, and CG) was analyzed using Kruskal-Wallis tests and Mann-Whitney U analyses at baseline and 5 weeks post-intervention in each parameter of ND, AHI and DF. ‡p<0.01, TCE vs. LTE in post-MNDT. †p<0.01, GTE vs. LTE in post-MNDT. #p<0.01, CG vs. LTE in post-MNDT. §p<0.01, TCE vs. CG in post-DF. For each parameter (MNDT value, AHI, and DF) at baseline compared to five weeks post-exercise training intervention using Wilcoxon signed rank test. * p < 0.05, pre vs. post. **p<0.01, pre vs. post. Data are expressed as mean ± SEM, n=10 per group.

TCE: Towel Curl Exercise; GTE: Great Toe Exercise; LTE: Lesser Toe Exercise; MNDT: Modified Navicular Drop Test; AHI: Arch Height Index; DF: Dorsiflexion. Results are reported as mean ± SE.

Table 2: Statistical analyses.

parameters. A significant difference in the MNDT value was observed between the LTE and CG groups (p<0.01). Regarding the DF value, a significant difference was observed between the TCE and CG groups (p<0.01), as shown in Table 2.

Therefore, the GTE did not show that the relationship between with neither functional, nor non-functional parameter of the MLA. The LTE showed the relationship between functional parameter of the MLA, MNDT. The TCE showed the relationship between non-functional parameter, DF.

Discussion

This study examined the relationship between toe exercises and MLA morphology after a 5 week intervention. MNDT and AHI assessments were performed to measure morphological variations in the MLA.

Towel Curl Exercise (TCE)

The towel curl exercise did not induce a significant change in the MNDT value. Furthermore, no relationship was found between the MLA and towel curl exercise measurements. However, the TCE showed significantly increased AHI compared with the other groups. Thus, the towel curl exercise might cause a greater MLA drop, which facilitates flat foot development.

Jam [4] reported findings similar to those of the present study. Anatomically, Jarrett et al. [11] reported that, in a cadaver, the DIP joint flexed only when the FDL was affected. These exercise activities tend to affect the extrinsic FHL and FDL muscles rather than the intrinsic muscles.

In one study, 15 cases of a painful accessory navicular were assessed with provocative tests using a visual analogue scale before and after the towel curl exercise. Of them, 14 subjects showed no alteration in pain levels and 1 subject reported aggravated pain [16].

Additionally, the results of the towel curl exercise showed that DF increased significantly after 5 weeks. The mechanisms underlying this finding are uncertain.

Great Toe Exercise (GTE)

The MLA of subjects in the GTE did not respond to the intervention. The effect of the FHL is clear as it attaches to the distal phalanx of the hallux. The FHL passes through the groove for the tendon of the hallucis longus flexor, and it is the most posterior and lateral of the supinator group muscles (TP, FDL, and FHL). Therefore, anatomically, the FHL has a longer lever arm in plantar moment and a shorter lever arm in inversion moment than the TP or FDL. Thus, its plantar moment may be more active than its inversion moment, whereas the FHL might be more advantageous for plantar flexion than inversion in supination movements.

Previous EMG analyses revealed that peroneus longus muscle activity was significantly increased by the great toe exercise [17]. As the great toe exercise might affect the peroneus longus muscle in eversion rather than inversion, it did not affect the MLA.

Lesser Toe Exercise (LTE)

The MNDT value significantly decreased for subjects in the LTE, indicating that lesser toe exercise facilitated rigidity in the MLA. This finding is remarkable and has not been observed in previous studies.

For a painful accessory navicular, lesser toe exercise resulted in significantly reduced pain in more than 70% of the subjects [16]. Many patients with a painful accessory navicular also have pes planus. The findings of this study support the findings of earlier studies.

Traditionally, passive factors (bones and ligaments) including the plantar fascia have been considered to be vitally important to the MLA [1]. Some reports, however, indicate that the extrinsic muscles (TP, TA, FHL, and FDL) are important for MLA support. In particular, the TP is a well-known key muscle. The TP does not insert on the first metatarsal or the great toe. When the TP is resected, severe flat foot could occur [22,26]. When an insertion abnormality is present, a painful accessory navicular commonly occurs [12]. Many reports have shown such connections between the TP and the MLA. Indirectly, the above reports argue that an active factor (muscles) is important. A discrepancy currently exists between the 2 theories regarding active and passive factors.

Fiolkowski et al. [2] tested 10 normal subjects and found that a tibial nerve block injection from the posterior malleolus medialis ablated intrinsic muscle activity. This decrease corresponded to a significant increase of 3.8 mm on the NDT. In another study of 21 normal participants, exercise-induced fatigue of the plantar intrinsic musculature correlated with a significant increase of 1.8 mm (from 10.0 ± 3.8 to 11.8 ± 3.8 mm) on the NDT [3]. These findings suggest that intrinsic muscles play an important role as a support mechanism for the MLA. Thus, a conceptual discrepancy also exists about the roles of the extrinsic and intrinsic muscles as active factors in supporting the MLA.

An exercise to strengthen the intrinsic muscles, reported by Jam [4], emphasized MP and PIP joint flexion while minimizing DIP joint flexion in the lesser toes, along with MP joint extension while minimizing IP joint flexion in the great toe. Such exercises have been recommended as a method of training the intrinsic muscles to increase foot strength. The exercise is similar to the short foot exercise (SFE).

The SFE is performed by the subject using the intrinsic muscles of the foot to draw the metatarsal heads back toward the heel. This exercise aims to "shorten the foot" without curling the toes [6,7,27-29]. This motion creates a slight arch elevation without engaging the FDL or FHL. Mulligan and Cook [29] reported that the NDT value significantly decreased for 21 normal participants at the end of a 4 week SFE training intervention and again 4 weeks after the end of the intervention. The toe position for the lesser toe exercise (the DIP joint extension and PIP joint flexion positions) is similar to that for the SFE; the lesser toe exercise used might have strengthened the intrinsic muscles, however, the lesser toe exercise does not use the great toe, as only the lesser toe and the ankle are held in a plantar flexion position. In the clinical setting, the SFE is difficult to accurately perform for patients. In contrast, the lesser toe exercise is deemed an easy-to-perform exercise.

Limitations

First, a priori power calculations *via* G*Power were conducted with a statistical power of 80% and a significance of 0.05. Cohen's d effect size of 0.25 was also calculated. More than 180 subjects would be required for the study; therefore, this study was considered to have a small sample size.

In the post hoc test, however, the power of LTE *vs.* CG with respect to MNDT was 0.99, and that of TCE *vs.* CG with respect to DF was 1.00 (one-way ANOVA test). Furthermore, the power of LTE in MNDT was 0.85, that of TCE in AHI was 0.81, and that of TCE in DF was 0.81 (paired tests). Second, we used students to take most of the measurements and a physiotherapy specialist to assess one random subject from each group, which may increase the risk of measurement errors. Third, all subjects in the study were young; thus, findings may not apply to older people. Finally, during the AHI measurements, it was difficult to obtain accurate measurements because of the uncertainty of the amount of pressure applied to the lever of the gauge to measure the dorsum foot height. Moreover, it was difficult for subjects to maintain partial WB while standing.

Conclusion

The 5 week training program using lesser toe exercise supported the MLA. The findings of this study indicate that the lesser toes should be the therapeutic focus for improving the MLA. The towel curl exercise did not support the MLA; however, it did increase the DF. In clinical settings, use of the towel curl exercise and lesser toe function may require reconsideration. Lesser toe exercise might benefit the plantar intrinsic muscles of the foot as reported here and in several previous reports. Further clarification of these results is needed in the near future.

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Declaration

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