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Original Paper

Intrinsic Foot Muscle Training Affects Plantar Pressure Distribution during Walking: A Single-group Clinical Trial

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Key words: foot muscle training, short foot exercise, plantar pressure, three-dimensional motion capture, gait

Abstract

This study aimed to test the hypothesis that intrinsic foot muscle training would improve the spring-like function of the foot arch and successfully distribute dynamic plantar loading. A single-group repeated measures pre- and postintervention and a study design was utilized for 20 asymptomatic subjects. Dynamic barefoot plantar pressures, toe grip strength, and three-dimensional (3D) motion capture of medial longitudinal arch (MLA) angle during walking were collected at baseline and after a 4-week intervention. The subjects completed the 4-week Short Foot Exercise training program, which is designed to raise the MLA by drawing in the metatarsal heads toward the calcaneus without flexing the toes. The significance of pre- and post-training differences was analyzed using paired *t*-tests ($p<0.05$). Peak plantar pressure significantly increased at the 2nd and 4th metatarsal heads, the mid-foot, and the rear foot after intervention. The toe grip strength significantly increased. The MLA angle showed no significant change. These results suggested that intrinsic foot muscle training produced sufficient force to reduce MLA deformation and decreased total contact area of the plantar surface, consequently increasing plantar pressure during walking.

1. Introduction

The plantar intrinsic foot muscles are parts of the active support system for the medial longitudinal arch (MLA) of the foot. Recent studies have reported that activation of these muscles counteracts MLA deformation during early stance phase of walking and running, absorbing mechanical energy as ground reaction force increases[1-4]. Training of these muscles has been traditionally used as toe flexion exercises such as marble pick-ups and towel curls. However, these exercises also involve substantial activation of extrinsic foot muscles such as the long toe flexors. Recently, a Short Foot Exercise (SFE) has been introduced to isolate contraction of the intrinsic foot muscles[5]. This exercise is performed by contracting the intrinsic foot muscles to draw the metatarsal heads back toward the heel. This motion should cause foot arch elevation without flexing the toes. It has been well documented that SFE helps to control MLA

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deformation[6-9]. However, less is known regarding the effectiveness of this training in contributing to shock absorbing function, which is one of the most important functions of the foot arch. This function distributes the pressure applied to the plantar foot during anti-gravitational movement. Therefore, the purpose of this study was to test the hypothesis that intrinsic foot muscle training would improve the spring-like function of the foot and successfully distribute dynamic plantar loading.

2. Methods

Pre-and postintervention and a study design was used for the current study. The independent variable was a 4-week SFE training program. The dependent variables were plantar pressure, 3-dimensional (3D) motion capture of MLA angle during walking, and toe grip strength (TGS) measured at baseline and after a 4-week intervention.

2.1 Participants

A total of 20 subjects (10 males, 10 females) aged between 18 and 26 years were recruited from college communities. They were free of lower extremity injuries and neurological disease in the prior 6 months and had no history of lower extremity surgery. The study was approved by the ethics committee of the Kawasaki University of Medical Welfare (No. 15-052) and all research was carried out in accordance with approved guidelines and regulations. Written informed consent was obtained from each subject.

2.2 Procedures

2.2.1 Intervention

All subjects were required to attend a 30-min training session prior to baseline assessment. Each subject had to demonstrate appropriate technique without compensatory extrinsic foot muscle contribution before the training session. Then, each subject performed a 4-week unsupervised SFE training program, consisting of raising the MLA by drawing in the metatarsal heads toward the calcaneus without flexing the toes[5] (Figure 1). The exercise was performed by holding isometric contraction for 5 s during each session, repeated 30 times. The exercise training began in a sitting position (1st week) and progressed to a double- (2nd week), then single-leg stance position (3rd & 4th week). Intervention compliance was recorded by using a monthly self-exercise calendar.

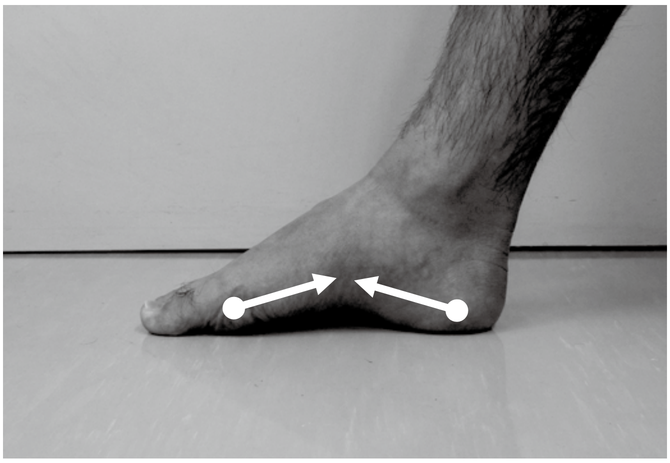

Figure 1 Short Foot Exercise

The white arrows represent the isolated contraction of the intrinsic foot muscles.

2.2.2 Plantar pressure assessment

A Footscan pressure plate (RSscan International, Olen, Belgium) was used to obtain barefoot plantar pressures. The platform was located in the middle of a 3.6-m wooden walkway. Each subject was tested using a 2-step gait initiation protocol. This involved a 2-step approach to the platform in which contact was made on the second step after initiation of gait[10]. This protocol has shown intra- and inter-rater reliability similar to that of the commonly used midgait protocol[10]. Subjects were required to walk at self-selected speeds. All subjects completed 3 test trials to become familiar with the protocol and to determine the starting position on the platform for successful performance before recording the data. Four repeated trials were collected for each subject. The data were analyzed using Scientific Footscan software (RSscan International, Olen, Belgium), which automatically split the foot into 10 masked zones: medial heel (MH), lateral heel (LH), midfoot (MF), first to fifth metatarsals (M1, M2, M3, M4, and M5), hallux (T1), and toes 2-5 (T2-5). The outcome variables quantifying plantar pressure included: peak pressure (N/cm^2), total contact area (cm^2), and gait speed (m/sec). Mean values of these variables were calculated by averaging of 4 trials.

2.2.3 Foot arch measurement

3D motion capture of the MLA angle was collected 4 times for each subject during the 2-step gait protocol trial. Four colored markers (9-mm diameter) were placed on the upper central ridge of the posterior calcaneal surface, the most medial apex of the sustentaculum tali, the base of the first metatarsal, and the head of the first metatarsal according to a multi-segment foot model developed to describe motion of the foot arch[11] (Figure 2). This model has been shown to have a high inter- and intra-rater reliability in healthy adults[12]. Kinematic data were captured at 1,000 Hz using a 3D motion analysis system (KinemaTracer; KISSEI COMTEC, Matsumoto, Japan). The MLA angle was defined as the sagittal plane rotation of the first metatarsal relative to the calcaneus. MLA compression was calculated by subtracting the MLA angle at initial contact from the maximum MLA angle recorded during each stance phase. Mean MLA compression was calculated by averaging the MLA compression over 4 trials.

Figure 2 Foot marker positions used to compute MLA compression

2.2.4 Toe grip strength measurement

TGS was measured by using a T.K.K.3362 toe-grip dynamometer (Takei Scientific Instruments, Niigata, Japan) (Figure 3). The reliability of this measurement has been described as "almost perfect"[13]. Each subject sat on a chair with hips and knees flexed approximately 90 ° . The ankles were fixed in neutral position with a strap. The first proximal phalanx was positioned at the grip bar, and a heel stopper was adjusted to fit the heel. Then, each subject gripped the bar with maximum toe flexor contraction for about 3 s. The toe-grip dynamometer was stabilized by assessors during the measurements. All subjects completed 2 test trials at submaximum effort to become familiar with the measurement. Two TGS measurements were recorded and averaged for each subject.

Figure 3 Measurement of toe grip strength

2.3 Statistics

After confirmation of normality using the Kolmogorov-Smirnov test, the significance of differences between measurements taken at baseline and after the 4-week intervention was analyzed with paired t-tests. Statistical differences were established at $p<0.05$.

3. Results

The demographics of the subjects did not differ at baseline (Table 1). The subjects reported a daily exercise compliance of 67.2%. At baseline, the mean TGS was 23.2 ± 8.1 kg, with a significant increase to 25.2 ± 7.9 kg at 4 weeks ($p=0.02$) (Table 2). The gait speed during the 2-step protocol did not differ at baseline. Peak pressure significantly increased at the 2nd and 4th metatarsal heads, the mid-foot, and the heels at 4 weeks ($p<0.05$). The total contact area of the foot significantly decreased ($p=0.01$). The MLA compression was not statistically different between baseline and 4 weeks.

4. Discussion

The purpose of the current study was to evaluate the effect of intrinsic foot muscle training on barefoot plantar pressure during gait in healthy adults. We hypothesized that improving intrinsic foot muscle strength would enable better control of the spring-like function of the foot arch and successfully distribute dynamic plantar loading, but the training increased the peak plantar pressure in most of the foot area.

The peak plantar pressure significantly increased at most of the midfoot and heel areas after the intervention. Pressure is equal to the total force divided by the surface area over which the force is applied. In this study, since body weight and gait speed of subjects did not change, the force applied over the plantar surface at 4 weeks stayed the same as at baseline. On the other hand, the total contact area of the plantar surface significantly decreased after intervention. Consequently, the peak plantar pressure during

Table 1 Mean and standard deviations of demographic data at baseline and after 4-week intervention

	Baseline	4 weeks	*p* value
Age (years)	20.0 (2.4)	20.1 (2.6)	0.96
Sex (% female)	50	50	1.00
Body mass (kg)	59.9 (8.8)	60.0 (8.9)	0.82
Height (cm)	166.1 (6.9)	166.3 (6.2)	0.91

Table 2 Means and standard deviations of outcome measures

	Baseline	4 weeks	*p* value
TGS (kg)	23.2 (8.1)	25.2 (7.9)	0.02
MLAC (°)	3.72(6.8)	3.65(9.8)	0.95
TCA (cm^2)	166.5 (14.3)	161.9 (13.1)	0.01
GS (m/sec)	0.33 (0.02)	0.33(0.04)	0.25
PPP (N/cm^2)			
Toe 1	6.6 (2.2)	7.6 (3.4)	0.17
Toes 2 − 5	2.6 (1.1)	3.3 (2.0)	0.12
Meta 1	8.2 (2.3)	9.9 (5.2)	0.15
Meta 2	13.5 (3.1)	15.8 (6.1)	0.04
Meta 3	13.5 (2.5)	15.5 (5.9)	0.06
Meta 4	9.1 (1.9)	10.5 (2.8)	0.03
Meta 5	4.3 (1.6)	5.2 (3.0)	0.07
Midfoot	4.4 (1.1)	5.1 (1.8)	0.04
Medial heel	12.4 (1.7)	16.2 (5.9)	0.01
Lateral heel	11.4 (2.2)	14.3 (4.8)	0.02

TGS-toe grip strength; MLAC-MLA compression; TCA-total contact area; GS-gait speed; PPP-peak plantar pressure

walking increased at those foot areas.

The total contact area of the plantar surface was significantly decreased after intervention. In this study, the toe grip strength significantly increased after intrinsic foot muscle training. A previous study showed that resistance training increased the stiffness of tendon structures[14]. Additionally, other studies have demonstrated that intrinsic foot muscle training helps to control MLA deformation[6-9]. It was suggested that resistance against flattening of the foot arch increased by strengthening of the intrinsic foot muscles, and that the resistance prevented an increase of the total contact area of the plantar surface as the magnitude of ground reaction force acting on the plantar surface increased.

This clinical trial had several limitations. The main limitation is that the current study used a non-blinded, single-group design. Therefore, the results could not be compared between 2 groups. Another limitation is the low exercise compliance of the subjects. It is possible that this low exercise compliance interfered with improvement in MLA compression during walking after the 4-week intervention.

Future research is needed on the impact of intrinsic foot muscle training under running conditions to determine whether changes of MLA morphology correlate with improvements in shock absorbing function of the foot. Furthermore, studies of foot posture type or pathology specific to a population is warranted.

5. Conclusion

An SFE training program was not successful in distributing plantar pressure during walking. Conversely, the peak plantar pressure increased over most of the foot area after intervention. This is because intrinsic foot muscle training increased the stiffness of the foot arch, which maintained its structure in response to the magnitude of loading forces encountered during walking, and consequently decreased the total contact area of the plantar surface.

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Conflict of interest

The authors declare no conflict of interest.

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