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Acute effects of running 10 km on the medial longitudinal arch height: dynamic evaluation using a three-dimensional motion capture system during gait

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Abstract: In previous studies, static evaluations of changes in the navicular height by long-distance running have shown that the navicular height decreases after long-distance running. However, few studies have performed dynamic evaluations of the changes in the supportive function of the medial longitudinal arch (MLA) height. Therefore, to evaluate the changes in the MLA height of healthy recreational runners before and after running 10 km, we performed static and dynamic evaluations. Nineteen runners underwent MLA height measurements before and after running 10 km on a treadmill. The measurements of MLA height were performed using three-dimensional motion analysis while the participants were barefoot in the sitting, standing, and walking positions. The heel contact value, minimum value, difference between the heal contact and minimum values, dynamic navicular drop (DND) height, and time when the minimum MLA height was reached during the stance phase of gait (timing) were calculated. After running 10 km, the standing MLA height decreased (18.04-16.86 mm; $p<0.05$), DND increased (6.32-7.77 mm; $p<0.05$), and timing was delayed (82.6%-85.2%; $p<0.05$). The DND, which is a dynamic measure of the MLA support function, increased with long-distance running, thereby decreasing the support function. The degree of deformation of the foot morphology in the terminal stance when the tissues comprising the MLA are stressed may influence injuries.

Keywords: running, foot, medial longitudinal arch, dynamic evaluation

1. Introduction

Foot injuries frequently occur in long-distance runners (Willwacher et al., 2022). Approximately one-third of all running injuries are foot and ankle injuries, such as Achilles tendinopathy, plantar fasciopathy, and ankle sprains, which are three of the most common injuries sustained by runners (Matias et al., 2016). Pes planus and high arches of the foot have been identified as factors associated with foot injury (Taunton et al., 2016; Williams et al., 2001). Therefore, it is necessary to evaluate the foot arch of long-distance runners and perform appropriate exercise to prevent injury.

Traditionally, static measurements of the medial longitudinal arch (MLA) height in the standing position have been used to evaluate arch flattening under loads (Saltzman et al., 1995). Static evaluations of MLA height have shown that the MLA height decreases after long-distance running, thus suggesting that morphological changes occur in the arch support mechanism (Cowley et al., 2013). However, there have been few dynamic evaluations of changes in the MLA height during the stance phase of gait or running.

Dynamic evaluations are advantageous because they provide information regarding the MLA morphology not only during the foot plantar grounding phase of gait but also during the pre-swing phase after heel release. Recently, a three-dimensional motion capture system was used to measure the dynamics of the MLA during the stance phase of gait (Okamura et al., 2018). The change in the MLA height from the initial contact height to the minimum height during the stance phase, that is, the dynamic navicular drop (DND) was used as a dynamic measurement of the MLA (Okamura et al., 2021). The greater the decrease in height, the lower the support function of the MLA. The timing of the minimum height during the stance phase is determined by the degree of activity of the supporting muscles of the MLA during gait (Okamura et al., 2020).

The phase of the greatest tension on the plantar fascia and metatarsals is the propulsive phase (Chen et al., 2015; Weist et al., 2004). Accordingly, the degree of deformation of the arch morphology in the terminal stance when the tissues comprising the MLA are stressed may influence the injury. However, there is a lack of studies investigating MLA motion before and after running. Understanding how arch dynamics are altered by long-distance running is essential for injury prevention.

This study aimed to investigate the changes in the MLA height using a three-dimensional motion capture system to improve the understanding of the mechanical behavior while moving. We hypothesized that the DND increases after running, and that the timing of the MLA height reaching its minimum value during the stance phase after running is delayed.

2. Materials and Methods

Study design —This cross-sectional study used a three-dimensional motion capture system to investigate the dynamics of the change in the MLA height after running 10 km compared to that before running. This study was conducted in a laboratory among 19 healthy long-distance runners. The MLA height was measured during standing, sitting, and gait, and the values of each participant were compared.

Participants and Ethical Consideration — Nineteen recreational runners (16 men and 3 women) were recruited for this study. According to the American College of Sports Medicine guidelines, recreationally active participation was defined as participation in at least 150 min of moderate activity per week for at least 6 months (Pescatello, 2014). The characteristics of the 19 runners are listed in Table 1. The inclusion criteria were as follows: capable of running 10 km and habitually ran at least 10 km/week during the year (Shiotani et al., 2020). The exclusion criteria were a history of lower extremity trauma or injury 6 months before data collection and traumatic or congenital deformities of either lower extremity, a history of prior surgeries, and use of the orthotic insoles. The participants' running experience ranged from 3 to 13 years, and their running distance was obtained from data recorded using a sports watch (Garmin Forerunner; Garmin, Schaffhausen, Switzerland) or retrospectively obtained.

Table 1. Participants' characteristics

Variable	Overall (n=19)		Men (n=16)		Women (n=3)	
	Mean	SD	Mean	SD	Mean	SD
Age (years)	21.1	1.7	20.3	1.7	22.3	1.9
Height (cm)	169.6	6.0	171.4	5.0	160.7	2.5
Weight (kg)	59.2	6.3	60.9	5.9	53.2	3.5
BMI (kg/m^2)	20.6	1.5	20.7	1.6	20.6	0.7
Running experience (years)	8.2	2.9	7.7	2.8	10.3	2.4
Running distance (km/week)	26.1	20.5	27.2	21.3	20.0	14.1
Foot length (mm)	251.9	12.8	255.2	10.1	234.3	7.6
Foot width (mm)	102.6	6.0	103.8	5.6	96.1	3.3

BMI, body mass index; SD, standard deviation. The running distance represents the total running distance for 1 week.

The sample size was calculated using G*power 3.1.9.4 software (Heinrich-Heine-University Düsseldorf, Düsseldorf, Germany). The effect size, mean power, and alpha error were 0.80, 0.80, and 0.05, respectively. The analysis revealed that a sample size of at least 15 participants was acceptable.

The study protocols complied with the principles of the Declaration of Helsinki and were approved by the Ethical Committee for Epidemiology of Hiroshima University (approval number: E2020-2267). Informed consent for participation was obtained from all participants before the experiment. All participants were informed that they could withdraw from the study at any time.

Procedures—The experimental protocol is illustrated in Figure 1. The experiment commenced at 6:00 p.m. for all subjects, and they were instructed not to engage in any exercise prior to the experiment. All participants underwent measurements of the right leg, which was considered the dominant leg (mainly used to kick a ball). Reflective markers (diameter, 14 mm) were attached to the right foot using double-sided tape so that the MLA height could be measured. Markers were placed on the navicular tuberosity, distal first metatarsal, distal fifth metatarsal, and most prominently on the heel of the foot in Figure 2 (Simkin et al., 1989). The markers were circled with a permanent marker so that they could be replaced before running 10 km, and attached by the same researcher. The researcher is trained so that there is no difference in attachment position between trials.

The MLA height values during standing, sitting, and gait were measured before the participants ran 10 km on a treadmill (Valiant 2 Sport; Lode BV, Groningen, the Netherlands). Ten infrared motion analysis cameras (VICON MX T20-S; Vicon Motion Systems, Culver City, CA, USA) with a sampling frequency of 100 Hz recorded the marker positions, and ground reaction forces were collected using eight force plates (OR-6, 1000 Hz; Amti International Inc., Watertown, MA, USA) at 1000 Hz. The force plates played a crucial role in synchronizing the gait cycle phases. First, a static standing trial was performed three times for five seconds each time. Participants were required to stand in a relaxed upright position with a shoulder-width stance, and each foot was placed on an individual force plate. Next, the participants sat on a chair with the knee joint at 90° of flexion and the right leg resting on a force plate. This sitting trial was also recorded three times for five seconds each time. Finally, all participants walked on a force plate. The participants were directed to step across eight adjacent plates and walk on the plates using four steps. They performed two steps before gait on the force plates. Gait measurements were performed during three trials.

After completing the measurements before running, the reflective markers on the foot were removed, and the participants wore their shoes. Each participant selected a comfortable treadmill running speed ranging from 10 to 13 km/h (Cowley et al., 2013; Okamura et al., 2018; Wu et al., 2007). After running, the participants removed their shoes, and the reflective markers were again placed on the foot in their original locations. Then, measurements were performed under the same conditions as those used before running, and collection of static data began within 3 min and dynamic data within 6 min.

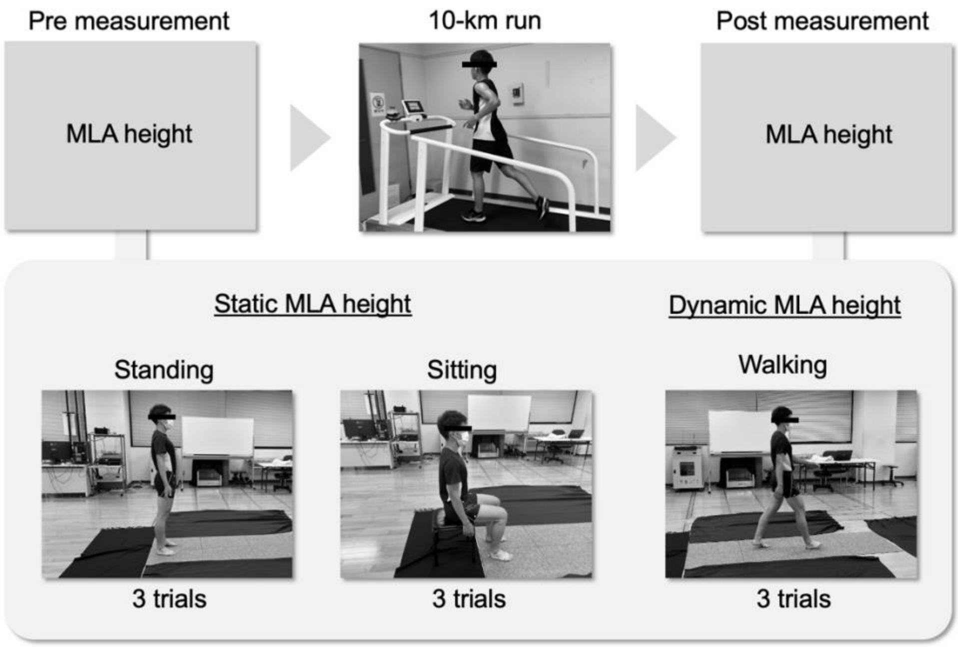

Figure 1. Schematic of the present study. MLA, medial longitudinal arch; Post, after; Pre, before.

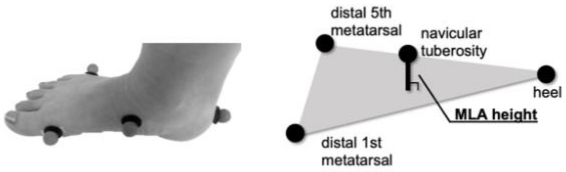

Figure 2. The location of the markers and the definition of the MLA height.

Measurement of MLA height —

Dynamic measurement of MLA height —The primary outcome was MLA height during gait. The MLA height was defined as the perpendicular distance of the navicular tuberosity marker above the plantar plane of the foot bisecting markers on the distal first metatarsal, distal fifth metatarsal, and heel (Simkin et al., 1989). The positional coordinates of the marker and force plate data were processed using Vicon Nexus version 1.8.5 software (Vicon Motion Systems). The MLA height during gait was determined during the stance phase between heel contact and toe-off, which was defined using the ground reaction force data. Heel contact and toe-off were defined as points at which the ground reaction force was zero or more. The definitions of the MLA height measurements are shown in Figure 2. The MLA height at heel contact and the minimum value of the MLA during the stance phase (minimum MLA height), the DND, which was defined as the difference between the MLA height at heel contact and the minimum value of the MLA during the stance phase, and the time when the MLA reached the minimum value (timing) were calculated as dynamic variables (Okamura et al., 2020; Eichelberger et al., 2018). The DND indicates the degree of MLA deformation during the stance phase of gait.

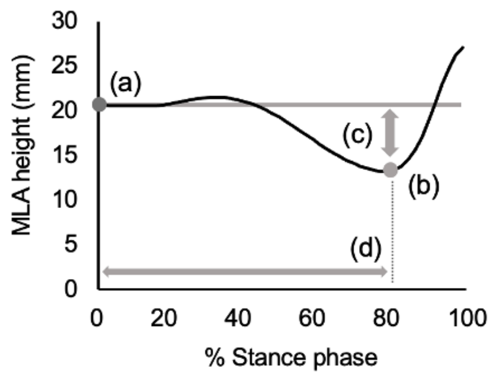

Figure 3. The medial longitudinal arch (MLA) height at heel contact (a), minimum MLA height (b), dynamic navicular drop (c), and timing of the minimum MLA height (d).

Statical measurement of MLA height —The secondary outcome was the MLA height during standing and sitting. The standing and sitting MLA heights were averaged over a 3-second interval, excluding the first and last seconds of the recorded 5-second periods. The MLA height in the sitting position minus that in the standing position was used as the result of the navicular drop (ND) test. The ND test, as introduced by Brody, is a clinical test that was developed to estimate foot pronation under dynamic conditions (Brody et al., 1982).

Statistical analysis —All statistical tests were performed using SPSS Statistics software version 28.0 (IBM Japan Co., Ltd., Tokyo, Japan). The Shapiro-Wilk test was performed to confirm the normality of all variables. Intraclass correlation coefficients (ICCs) (1, 1) were calculated to confirm the intraclass reliability of the MLA height at heel contact, minimum MLA height, DND, time required to achieve the minimum MLA height during standing and sitting, and ND. The ICC (1, 1) was regarded as almost perfect at 0.81 to 1.00, substantial at 0.61 to 0.80, moderate at 0.41 to

0.60, fair at 0.21 to 0.40, and slight at 0.0 to 0.20 (Landis et al., 1977). Additionally, the standard error of the measurement was calculated for the MLA height to evaluate its accuracy using the following formula: $s\sqrt{1-ICC}$. A paired t-test was performed to compare measurements before and after 10 km running. The significance level was set at $p<0.05$. The effect size (d) was calculated using Cohen's d and defined as follows: small, d>0.20; medium, d>0.50; and large, d>0.80.

3. Results

The average speed of running on the treadmill during the measurements was 10.6 km/h (standard deviation, ±1.8 km/h). The inter-rater reliability of the dynamic evaluations was substantial for the minimum value of the MLA height, and it was almost perfect for the MLA height at heel contact, DND, and timing of reaching the minimum MLA height [ICC (1, 1) = 0.787, 0.980, 0.837, and 0.895, respectively]. During the static evaluations, standing, sitting, and ND had almost perfect inter-rater reliability [ICC (1, 1) = 0.998, 0.997, and 0.723, respectively]. The standard errors of the measurement were as follows: MLA height at heel contact, 0.99 mm; minimum value, 2.86 mm; DND, 1.25 mm; timing, 1.43%; standing, 0.99 mm; sitting, 0.94 mm; and ND, 1.54 mm.

Table 2 shows the results of each variable before and after running 10 km. The static measurements showed a significant decrease in the MLA height in the standing position and no change in the sitting position or ND after running ($p<0.05$, $p=0.65$, and $p=0.11$, respectively). A comparison of the dynamic measurements before and after running showed that the DND increased significantly ($p<0.05$) and that timing was significantly delayed after running ($p<0.05$). The MLA height at heel contact and the minimum value did not change significantly ($p=0.25$ and $p=0.07$, respectively).

Table 2. Means of the parameters of the static and dynamic MLA heights pre- and post-running 10 km

Variable	pre-running 10 km		post-running10 km		95%CI		p	d
	Mean	SD	Mean	SD	Lower	Upper		
Static measurement								
MLA height in standing (mm)	18.04	5.50	16.86	5.05	-2.04	-0.30	<0.05	0.63
MLA height in sitting (mm)	20.97	5.97	20.67	5.38	-1.66	1.06	0.65	0.11
ND (mm)	2.93	2.52	3.61	2.49	-0.22	1.97	0.11	0.58
Dynamic measurement								
MLA height at heel contact (mm)	20.71	7.00	21.24	6.30	-0.40	1.46	0.25	0.13
Minimum MLA height (mm)	14.39	6.19	13.47	5.88	-1.93	0.09	0.07	0.44
DND (mm)	6.32	3.09	7.77	2.81	0.41	2.50	<0.05	0.86
Timing (% stance phase)	82.60	4.41	85.20	2.77	0.22	3.50	<0.05	0.78

MLA, medial longitudinal arch; Pre, before; Post, after; CI, confidence interval; SD, standard deviation; d, Cohen's d; ND, navicular drop; DND, dynamic navicular drop.

4. Discussion

This study used a three-dimensional motion capture system to examine the possibility that navicular bone dynamics decreased after running 10 km. The DND increased by approximately 1.45 mm after running 10 km. The timing of the minimum MLA height was delayed by approximately 2.6%. This is the first study to dynamically capture changes in the MLA height during the stance phase before and after running. The static MLA height has been reported to decrease after long-distance running; however, the dynamics of the MLA during the stance phase, including the pre-swing phase when the metatarsophalangeal joint dorsiflexes, also changed.

In these results showed that the DND was increased by 1.45 mm. The ND at rest was 2.93 mm, and the DND before running 10 km was 6.32 mm. A previous study compared static and dynamic MLA heights of 3.3 mm and 5.4 mm, respectively (Rathleff et al., 2012). In present study, the dynamic descent was slightly larger; however, it was reasonable. The DND indicates the degree of MLA deformation during the stance phase of gait, and its change is related to the activation of intrinsic muscles that support the MLA height during the propulsive phase of gait (Okamura et al., 2020). In addition, other support mechanisms of the MLA, such as stress on the plantar fascia, may also be contributing factors (Walte et al, 2021). While further research is needed to elucidate factors such as plantar fascia stiffness and intrinsic muscle activity, this study is significant in that it dynamically captured changes in MLA height, which could be affected by multiple factors.

The timing of reaching the minimum MLA height was delayed by 2.6% in the terminal stance. During the stance phase, the plantar fascia appears to continue to be extended stressed by the dorsiflexion of the metatarsophalangeal joint (Lin et al., 2014). However, during the last half of the propulsive phase, the plantar fascia length, which is one indicator of extension stress, shortens between 55% to 85% compared to that of the stance phase (Fessel et al., 2014). One reason for the lack of plantar fascia elongation in proportion to dorsiflexion during this phase may be the intrinsic and extrinsic muscles of the foot that control the plantar fascia elongation stress. The impact of the muscle fatigue resulting from long-distance running on the elongation stress of the plantar fascia and the maintenance of MLA is intriguing.

Strengthening the intrinsic and extrinsic foot muscles involved in arch formation and retention is useful (Okamura et al., 2018; Okamura et al., 2020). However, muscle fatigue occurs during long-distance running, and muscle exertion that sufficiently supports the MLA is difficult to achieve. On the other hand, arch support with insoles or taping for decreased MLA height after long-distance running may decrease the load on the plantar fascia, promote early recovery from transient plantar fascia injury, and prevent further injury (Lewinson et al., 2019).

This study had several limitations. First, it did not measure the muscle fatigue of the intrinsic and extrinsic foot muscles involved in MLA retention or stress on the plantar fascia. Measuring changes in both the plantar fascia and muscles involved in arch retention may result in an understanding of the reasons for dynamic changes in the MLA. Second, the MLA was not measured during running; only the dynamics during running could be estimated. Third, the number of women subjects is small. This gender disparity could potentially introduce bias, particularly considering the influence of the menstrual cycle on ligament laxity and the supportive structures of the plantar arch (Tagawa et al., 2024). Fourth, the morphology of the foot was only visually confirmed. This was because the protocol of this study was to compare the "amount of change" before and after exercise, and we did not place much emphasis on the effect of each individual's foot morphology on the results. In the future, by incorporating measurements of running dynamics for each individual and considering their running patterns, researchers may enhance the potential for injury prevention in runners. Additionally, by utilizing the force platform to gather detailed information about the load on the foot, future studies could explore the relationship between this load and changes in the arch, potentially leading to a deeper understanding of the mechanisms behind injuries like plantar fasciitis. Moreover, future studies with larger and more diverse samples should strive to address limitations such as gender disparities, variations in menstrual cycles and foot morphology, thereby providing a more comprehensive understanding of the observed effects and advancing our knowledge in this area.

5. Practical Applications.

Improvement of Training and Rehabilitation Strategies —The decrease in dynamic MLA support after long-distance running can contribute to enhancing training and rehabilitation strategies. Specifically, training or exercises targeting muscles supporting the foot arch may be considered.

Development of Running Gear —Focusing on dynamic changes in the foot arch provides an opportunity to contribute to the design of new running shoes and insoles, aiming to improve support functions for runners' feet.

Proposing Injury Prevention Strategies —The research results offer valuable information for injury prevention strategies related to foot health. Particularly, insights into specific changes in MLA parameters after long-distance running can inform the development of appropriate preventive measures and recovery plans.

6. Conclusions

The dynamics of the navicular height during gait were measured using a three-dimensional motion capture system before and after running 10 km. The DND during gait increased significantly, and the timing of reaching the minimum MLA height was delayed. These findings indicated the decreased ability to support the MLA during the terminal stance. By focusing on the decreased ability to support the dynamic MLA caused by long-distance running, we can gain insight into the prevention of foot injuries in runners.

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Conflicts of Interest: The authors declare no conflict of interest.

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