



Original Article

Validity of two-dimensional analysis using a tablet computer for estimation of foot arch height during walking

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Abstract. [Purpose] To examine the validity of two-dimensional analysis using a tablet computer for the estimation of arch height during walking by comparing it with a motion capture system and static foot alignment screenings. [Participants and Methods] Fourteen healthy males and 15 healthy females participated in this study. The arch height of the right foot while walking was simultaneously measured using a tablet computer and motion capture system. Dynamic foot alignment, including arch height, at the mid-stance and pre-swing phases was calculated from the kinematic data measured using the tablet computer and motion analysis system. Static foot alignment was also assessed by screening tests including arch height index and foot posture index. [Results] Arch height measured using a tablet computer showed a significant high correlation with that measured using the motion capture system at the mid-stance and pre-swing phases. Arch height index showed a significant moderate correlation with arch height measured using the motion capture system at the mid-stance phase. Meanwhile, foot posture index showed no relationship with arch height measured by the motion capture system. [Conclusion] These results demonstrate the high validity of dynamic foot analysis using a tablet computer for the estimation of arch height during walking. Such gait analysis can be effective for assessing dynamic foot alignment in clinical practice.

Key words: Tablet computer, Arch height, Gait analysis

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INTRODUCTION

The foot and ankle contain a large number of bones and joints; it is the only part of the human body that contacts the ground during standard locomotion, thus articulation within this region is important. While walking, the foot and ankle act to absorb much of the impact force at the early stance phase as well as to generate propulsion force during late stance¹⁻³⁾. In addition, foot dysfunction and malalignment is related to decreased function or injury throughout the whole lower limb⁴⁻⁶⁾. Thus, foot alignment is usually assessed in physical therapy practice for lower limb injuries, Arch Height Index (AHI) and Foot Posture Index (FPI) are commonly used as screening tests⁷⁻⁹⁾. These tests estimate static foot alignment during standing.

Previous studies report that AHI, arch height during relaxed standing, is correlated with the trajectory of planter pressure during gait¹⁰⁾. Meanwhile, foot malalignment including excessive foot supination relate to change in the alignment of the knee joint, resulting in increased load to lower limb joints under weight-bearing conditions¹¹⁻¹³⁾. Thus, foot malalignment can be related to both lower leg injuries including medial tibial stress syndrome and Achilles tendon inflammation^{4, 5)}, and also to knee joint injuries including patellofemoral joint pain¹⁴⁻¹⁶⁾.

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However, several studies indicate that static foot posture bears a low relevance to dynamic foot alignment during walking, because of foot posture change due to ground reaction force and tibial motion^{17, 18}). Thus, in addition to static assessment, dynamic alignment assessment is required for an accurate estimation of foot function. Although foot alignment during gait has been analyzed using a three-dimensional motion capture system in previous studies^{19–21}), motion capture systems are not used widely in clinical practice because of the required time for measurement and processing, limitation of measurement space, and economic cost. In clinical practice, two-dimensional (2D) analysis using videos recorded using a video camera or tablet computer are usually utilized to assess gait function, in place of a motion capture system^{22–24}). 2D analysis is easily measured anywhere, and feedback can be given to patients immediately. However, the validity of dynamic assessment of foot alignment using 2D analysis is unclear due to the lack of previous studies^{25, 26}). The aim of this study was to examine the validity of 2D analysis using a tablet computer for the estimation of arch height during walking, while making a comparison with a motion capture system and foot alignment screening tests. We hypothesized that arch height, as measured by a tablet computer, would be highly correlated with results obtained from a motion capture system, as opposed to static screening, including AHI and FPI.

PARTICIPANTS AND METHODS

Fourteen healthy males (age, 24.9 ± 3.2 years; weight, 67.5 ± 9.5 kg; height, 1.73 ± 0.05 m) and 15 healthy females (age, 23.2 ± 1.4 years; height, 1.60 ± 0.04 m; weight, 49.4 ± 4.4 kg) participated in this study; their right foot was measured. Individuals with orthopedics or neurological disorders were excluded. Informed consent was obtained from all participants before their inclusion in the study, and the ethics committee of the Faculty of Medicine, Kagoshima University approved the study protocol (ref no. 359). The preprint version of this article can be found at <https://www.researchsquare.com/article/rs-27020/v1>.

The relation between arch height during walking as measured by a tablet computer and motion capture system, and static foot alignment tests were estimated in order to test the validity of dynamic assessment using 2D analysis. Arch height of the right foot during walking was simultaneously measured using a tablet computer (iPad Air2, Apple, Inc., CA, USA) and motion analysis system consisting of 6 cameras (VICON MX3, Oxford Metrics, Oxford, UK) and 2 force plates (BP600400, OR6-7, AMTI Inc., MA, USA). Prior to gait measurement, reflective markers were attached to the lateral and medial epicondyle, the lateral and medial malleolus, the first and fifth heads of the metatarsal bone, the medial and dorsal point of the calcaneus, and the navicular, according to a previous study²¹). The tablet computer was placed vertically on the floor at the left side of the walkway and 1.3 m from the midline, so that it could capture the medial aspect of the foot (Fig. 1). One central stance phase during an 8 m comfortable walking gait was analyzed. The measurement was performed after a warm-up period, and the mean of 10 samples was adopted as the representative value. The sampling frequencies of the motion capture system and the tablet computer were 100 Hz and 120 Hz, respectively.

Static foot posture was assessed using the arch height index (AHI) and foot posture index (FPI) during relaxed standing after several steps. AHI was the ratio calculated by dividing the dorsal arch height at 50% of total foot length, as measured by a height gage (VHK-15, Niigata Seiki Co, Ltd, Niigata, Japan), by the total foot length⁹). The FPI consisted of 6 components: talar head palpation, supra and infra lateral malleolar curvature, calcaneal frontal plane position, bulging in the region of the

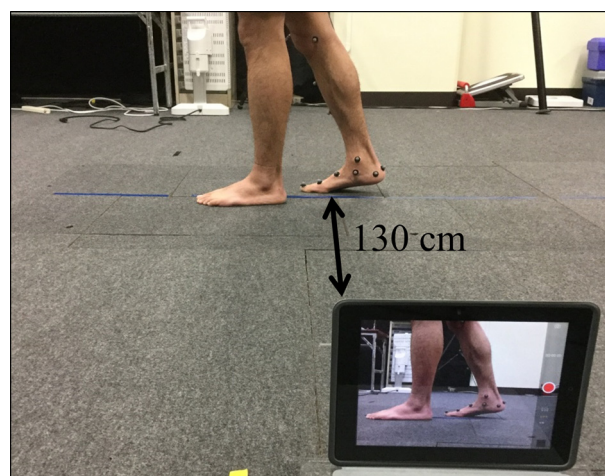


Fig. 1. Measurement of foot alignment during walking using a tablet computer and motion capture systems. The tablet computer was placed vertically on the floor at the left side of the walkway and 1.3 m from the midline, in order to capture the medial aspect of the foot.

talo-navicular joint, height and congruence of the medial longitudinal arch, and abduction/adduction of the forefoot on the rearfoot⁷). Each component was scored on a scale ranging from -2 to +2, and the total score ranged from -12 to +12; a low value indicated pronation, high values indicated supination.

Arch height at the mid-stance (Mst) phase, the moment when the right tibia is positioned vertically, and at the pre-swing (PSw) phase, the moment of heel strike of the opposite side, were obtained from kinematic data measured by the tablet computer and motion analysis system, respectively. In 2D analysis using the tablet computer, arch height was calculated as the distance between the navicular tuberosity and the baseline connecting to the medial aspect of the calcaneus and the first metatarsal head, and calculated as a percentage of the baseline using ImageJ (National Institute of Mental Health, MD, USA) by Windows PC (FMV-BIBLO NF/G50, Fujitsu, Kanagawa, Japan). In three-dimensional (3D) analysis, arch height was calculated as the distance between the navicular tuberosity and a plane consisting of the first metatarsal head, fifth metatarsal head, and the dorsal point of the calcaneus.

Pre-statistical analysis showed no gender difference in foot alignment, therefore we treated males and females as one group. Furthermore, we performed power analysis to estimate the validity of sample size by referring to a previous study, which reports that the correlation coefficient between 2D analysis and 3D analysis, and between static foot alignment and dynamic foot alignment, were 0.76 and 0.56, respectively²⁵). Thus, power analysis was performed using the G*Power, $r=0.50$, $\alpha=0.05$, and power $(1 - \beta)=0.8$, indicated that the required sample size was 26. Thus, we accepted that this study had a suitable sample size.

To examine the validity of foot assessment using 2D analysis, we conducted correlation analysis between the arch height at Mst and PSw as measured by a tablet computer and a motion capture system. Meanwhile, FPI and AHI were used to test the relation to arch height at Mst as measured by a motion capture system because of the similarity of their measurement posture. These relationships were analyzed using Pearson's correlation coefficient or Spearman's rank correlation coefficient after data were tested for normality using the Shapiro-Wilk test. All statistical analyses were performed using R (2.8.1) statistical software, and significance was set at 5%. The results were described by average and standard deviation.

RESULTS

Gait velocity was 1.32 ± 0.14 m/s, and step length was 0.67 ± 0.06 m. Regarding dynamic foot alignment, arch height as measured by the motion capture system was 17.7 ± 4.7 mm at MSt, and 15.0 ± 4.7 mm at PSw. Arch height as measured by 2D was $11.0 \pm 2.8\%$ at MSt, and $9.7 \pm 3.0\%$ at PSw. With regard to foot alignment screening, AHI was $24.3 \pm 1.8\%$ and FPI was 3.3 ± 2.1 points (Table 1).

Arch height as measured using both the tablet computer and motion capture system were highly correlated (MSt, $r=0.90$, $p<0.001$; PSw, $r=0.94$, $p<0.001$). A significant correlation between foot alignment screening and arch height as measured by the motion capture system at MSt was indicated in AHI ($r=0.50$, $p=0.005$), but not in FPI ($r_s=-0.34$, $p=0.075$).

DISCUSSION

We examined the validity of 2D analysis of arch height during walking using a tablet computer, by making a comparison with a motion capture system and static screenings in healthy subjects. The present study showed that arch height, as measured by a motion capture system, was significantly correlated with that measured by a tablet computer or AHI, especially the former. Meanwhile, FPI showed no relation to arch height as measured by the motion capture system. These results indicated the validity of dynamic assessment of foot alignment by using a tablet computer, and this was consistent with our hypothesis.

Arch height as measured by 3D was lowest during the later stance phase, which was similar to the findings of a previous study²¹). In the current study, arch height measured by the tablet computer showed a high correlation with the motion capture system. This relation was greater than that in the previous study. 2D analysis decreases accuracy for measuring a motion containing transverse rotation. However, the foot showed only slight transverse rotation during the stance phase of walking, because it was placed firmly on the floor. In addition, the tablet computer has high resolution in time and space. These factors contributed to the accuracy of the 2D analysis in this study.

With regard to foot alignment screening, AHI was 24.3 ± 1.8 (22.5–26.1) % and FPI was 3.3 ± 2.1 (1.2–5.4) points. Previous studies report standard values for each assessment^{26, 27}); AHI was $25.1 \pm 2.0\%$ and FPI ranged from 1 to 7 points, where most participants showed a neutral foot alignment, with no excessive varus or valgus foot symptoms. In the correlation

Table 1. Arch height during gait

	Motion capture system (mm)	Tablet computer (%)
Arch height at mid stance	17.7 ± 4.7 ($25.4 \pm 7.4\%$ of stance phase)	11.0 ± 2.8
Arch height at pre-swing	15.0 ± 4.7 ($82.0 \pm 2.1\%$ of stance phase)	9.7 ± 3.0

analysis, AHI was correlated with arch height, as measured by the motion capture system, but the correlation coefficient was lower than that measured by the tablet computer. Moreover, FPI were not correlated with arch height as measured by the motion capture system; this was consistent with a previous study¹⁷⁾. The static screening estimates foot alignment during relaxed standing with bilateral limb support, thus, one half of total body weight was loaded on each foot. Dicharry¹⁷⁾ indicates that foot alignment during relaxed standing is influenced by gravity, but foot alignment during antigravitational activities including gait is influenced by muscle force and acceleration of the center of mass in addition to gravity. The maximum load on the foot during walking is almost 120% of body weight. Meanwhile, it is well known that motion of the shank affects alignment of the foot while the foot is placed on the floor, as a closed kinematic chain²⁸⁾. The difference in the load of the foot and the alignment of the shank between static standing and gait are the cause of a slight correlation between the static screenings and the arch height during gait.

To examine foot load, we focused on arch height at MSt and PSw. MSt is a single support phase when the full body weight loads to the unilateral lower limb; PSw is the end of the single support phase when arch height has decreased due to the ground reaction force acting on the forefoot. Malalignment of the foot becomes apparent at this time as opposed to relaxed standing, thus arch height at MSt and PSw is a relevant indicator reflecting dynamic foot alignment. Our comparison among static assessment, including AHI and FPI, and dynamic assessment by two-dimensional analysis using tablet PC to seek an appropriate method to assess the dynamic foot alignment revealed the high validity of assess using tablet PC. Gait analysis obtained using a tablet computer could easily estimate arch height at these time points, therefore, such analysis is useful in clinical practice.

There were some limitations to this study. Since participants were healthy individuals, we made no analysis for varus and valgus foot deformities. In addition, we analyzed foot alignment only during walking, and not during sporting activities such as running or landing in which excessive force acts on the foot. Future investigations that address these issues are required for 2D analysis of foot alignment using a tablet computer in clinical practice. The present study contributes to the development of physical therapy for lower limb injuries.

In conclusion, we examined the validity of 2D analysis for measurement of arch height, dynamic foot alignment, during walking using a tablet computer in this study. Results showed that arch height, measured using a tablet computer, was highly correlated with measurements taken using a motion capture system, while static foot alignment screening showed a lower correlation with arch height during walking. Consequently, 2D analysis using a tablet computer proved useful in the assessment of dynamic foot alignment during gait in clinical practice.

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Conflict of interests

We have no conflict of interest to declare.

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