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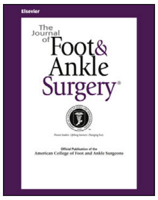

Original Research

The Sensitivity of Thresholds by Ground Reaction Force and Postural Stability in Subjects With and Without Navicular Drop

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ABSTRACT

Understanding plantar pressure changes is an important component of the functional evaluation of subjects with flat foot. However, the altered postural control determined by the threshold from the vertical ground reaction force (GRF) requires clarification. The purpose of our study was to investigate the various GRF thresholds in subjects with and without flat foot during 1-leg standing. We included 34 control subjects and 30 subjects with flat foot in the present study. They performed the 1-leg standing test for 30 seconds, with the contralateral hip and knee flexed approximately 90°. The sensitivity of the various GRF thresholds (3, 7, 15, 50, and 100 N) for the postural stability index was analyzed with and without visual input. The standing times for the control and flat foot groups were 23.76 ± 4.42 and 21.78 ± 6.59 seconds, respectively, with no significant differences ($t = 1.23$; $p = .22$). The 2 groups demonstrated a significant interaction between the visual condition and the threshold levels ($F = 11.40$; $p = .001$). The postural stability index was significantly different in the eyes-open condition (0.95 ± 0.08 for the control group versus 0.84 ± 0.23 for the flat foot group; $t = 2.29$; $p = .02$). However, no difference was found in the eyes-closed condition (0.94 ± 0.10 for the control group versus 0.81 ± 0.30 for the flat foot group; $t = 1.45$; $p = .15$). These results indicate that GRF thresholds less than the 15N setting are sensitive to detect postural stability between groups, especially in the eyes-open condition. The GRF threshold setting, in addition to the visual condition, could alter the outcomes of sensitive plantar pressure changes in subjects with flat foot.

Flat foot (pes planus) problems have been reported as common concerns, and the incidence level has ranged from <1% to ≤78% (1,2). This variation refers to the poor agreement regarding the definition of flat foot and increased lower limb motion (3). Clinicians usually assess foot mobility using the navicular drop (ND) test, specifically, pronation of the foot (4,5). This foot mobility problem is commonly associated with postural instability, which could contribute to injury because of the altered motion of the lower limbs. However, understanding is lacking regarding the foot pressure changes and postural stability in subjects with and without flat foot.

It has been reported that individuals with pes planus have greater foot mobility compared with those without flat foot (3,6). Previous studies have reported a relationship between foot mobility and the lower limbs, because an arched foot could be an intrinsic risk factor for postural stability (3,7). However, this assessment was not conclusive owing to heterogeneity between studies, small effect sizes with the risk of bias, and, more importantly, the lack of sensitive measures (1,3,8). Thus, postural stability and flat foot dysfunction should be assessed using reliable and valid procedures.

The clinical manifestation of flat foot dysfunction results from insufficient support of the medial longitudinal arch, which is confirmed by the ND test (5). Flat foot has been reported as a valgus deformation usually accompanied with mechanical imbalance and pain (6,9). Other studies have evaluated various postural stability according to the stabilization time (10–12). The stabilization time was defined as the time required to minimize the resultant ground reaction force (GRF) of a perturbation to within a range of the static baseline of the GRF. As an aspect of motor control for the lower limbs, the stabilization time depends on proprioceptive feedback and preprogrammed muscle patterns, as well as reflexive and voluntary muscle responses (13,14).

However, the various thresholds of GRF were not carefully assessed. In our previous studies, the vertical GRF was analyzed during 1-leg standing between subjects with and without flat foot dysfunction (8,15). However, it is unclear how the specific threshold changes might be sensitive to differentiate postural stability changes, in addition

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to different visual input. During standing balance, the postural behaviors were observed to change across visual conditions and perturbation parameters (16). Postural stability with other outcome measures has been obtained with kinetic assessments (17–19). The sensitive changes of the various GRF thresholds (3, 7, 15, 50, and 100 N) for postural stability have not been carefully analyzed. Most studies analyzed kinetic outcomes using either body weight or the lowest level of the threshold to compare the signal from the GRF (18,20).

Although the accuracy of the GRF and center of pressure (COP) measurements has been demonstrated, selecting a threshold from the force data could improve the validity of detection from the optimal GRF threshold (19,21,22). Several studies have reported contradictory results regarding the relationship between force plate data and standing balance measures, although they all reflected the performance of postural stability (7,12,23). Other reports have indicated that a consistent lower threshold might be better for comparing the postural reaction to quantify the slip potential (24). Kinetic analysis data investigating flat foot pressure changes according to the levels of the sensitive threshold are lacking. The sensitive measure of postural stability is important for developing effective rehabilitation strategies and understanding compensatory mechanisms (19).

The upright standing posture based on visual input potentially prompts an uncoordinated bracing effect with poor proprioception (7,19). However, very little information is available in the scientific data regarding the visual differences from the sensitivity of thresholds from force plates to assess the postural balance in subjects with flat foot. Three-dimensional GRF analysis would be helpful to produce reliable and valid results. Also, a comparison of sensitive thresholds and 1-leg standing time could contribute to a further understanding of the postural adjustability in subjects with flat foot.

Therefore, the purpose of the present study was to investigate the differences in standing time and the postural stability index using the levels of threshold from the GRF according to the visual condition of the subjects with and without flat foot. Our hypothesis was that the subjects with flat foot would demonstrate decreased standing time and sensitivity of higher thresholds from the GRF in the eyes-open condition.

Materials and Methods

Target Population

The subjects were recruited from the university community through advertisements and completed a health history questionnaire to determine eligibility from 06/2010 to 12/2012. Subjects with flat foot were eligible to participate if they (1) had >9 mm of ND on the dominant foot, (2) were aged 20 to 55 years, (3) had no diagnosis of any lower extremity injury, and (4) had no acute pain or dysfunction surrounding the ankle or foot at the time of the study.

Individuals were excluded from participation if they (1) had nonsymmetric feet (25), (2) had continuous pain in, or had undergone surgery on, a lower limb within the past 2 months, (3) had a diagnosed psychological illness that might have interfered with the study protocol, (4) had experienced overt neurologic signs (i.e., sensory deficits or motor paralysis), or (5) had an active medical, surgical, or neurologic illness, history of peripheral neuropathy, or any disorders affecting the central nervous system.

The subjects were withdrawn from the study if they requested withdrawal. The control group was recruited based on similar individual characteristics as the subjects with flat foot. Those subjects who met the study inclusion criteria received information regarding the study and signed a copy of the institutional review board–approved consent form. Lower limb dominance was also determined in the present study, because a previous study confirmed that dominance could be a confounding factor (26). The participant's right lower limb was regarded as the dominant side for all subjects because they preferred to use the right limb to kick a ball to a target (27). This study was approved by the Institutional Review Board (KUIRB-0816A2), and the data were previously collected and reanalyzed from a study at Korea University.

Experimental Setup

Each participant's subtalar joint was measured for the navicular height. The distance between the tubercle of the navicular bone and the floor was measured with the participant in the sitting (non-weightbearing) and standing (full weightbearing) positions. The normal range of ND was defined as 5 to 9 mm (28). Therefore, subjects with an ND >9 mm on the dominant foot were included in the flat foot group.

The subjects were instructed to stand quietly on the right leg for 30 seconds on a force plate surface with the left hip and knee flexed approximately 90° for the single-leg standing assessment (19). The subjects were allowed to practice 1-leg standing before testing and performed the task 3 times to test for reliability. Each participant was tested with an intersession interval of ≥1 minute. The baseline measures of the static 1-leg stance were then recorded at 200 Hz on a force plate for 30 seconds. The subjects stood barefoot on the force plate and kept their arms at their sides during the initial standing and task performance. If a participant lost balance and touched the floor with the contralateral limb, the trial was discarded and repeated. However, compensatory arm movements were accepted, and the investigator stood close to each subject throughout the experimental session to prevent falls and injuries.

A total of 34 retroreflective markers were used to model the body as a system of rigid segments. The markers were placed over the 2 hands, 2 lateral humeral epicondyles, 2 radial styloid processes, 2 acromioclavicular joints, the seventh cervical vertebra, and the midmanubrium sterni. In addition, other markers were placed bilaterally on the anterior superior iliac spines, posterior superior iliac spines, iliac crests, greater trochanters, lateral thighs, lateral epicondyles, medial epicondyles, lateral shanks, lateral malleoli, medial malleoli, heels, and toes.

Data Processing and Analysis

Force plate information represents instantaneous disturbance of postural stability during the test. Before the experiment, the plantar pressure changes imposed during 1-leg standing were measured using a 6-channel force platform, and the recordings lasted 30 seconds. The AMTI OR6-5 (Advanced Mechanical Technology, Inc., Newton, MA) force plate was used to record the GRF (Fx, Fy, and Fz) in orthogonal directions at a sampling frequency of 50 Hz. The signals were low pass filtered (zero lag fourth order Butterworth filter) with a cutoff frequency of 6 Hz to reduce the measurement noise.

The sensitivity of the various GRF thresholds (3, 7, 15, 50, and 100 N) for the postural stability index was analyzed with and without visual input. The threshold setting analysis could have resulted in different sensitive plantar pressure changes for standing stability in the subjects with and without flat foot. The stabilization time was used to compare the range of the static baseline from the resultant GRF. The plantar pressure changes on the force plate were computed as 3 directional forces (Fx, Fy, and Fz) from the platform using the sum of the square root of the aggregated forces (F_{xyz}; Fig.). Therefore, the postural stability index on a force plate was the ratio between the time at which the Fxyz was less than the threshold and the total successful standing time during the 1-leg standing test (19). The operational definition for the normalized postural stability index was based on the ratio between the standstill time (less than the threshold indicated by the gray line) and the successful standing time. The summation of the standstill time was less than the threshold and was calculated as the square root of the value subtracted from each force plate mean to compute the Fxyz (Eq. 1).

$$Fxyz = \sqrt{(F_x - F_{x\_mean})^2 + (F_y - F_{y\_mean})^2 + (F_z - F_{z\_mean})^2} \quad (1)$$

Therefore, the thresholds of force plate stability were determined based on qualitative observation of the threshold sensitivity. This postural stability index was compared for the balance test with different visual conditions to allow individual differences to be fairly compared between the groups. The reliability of this index has been reported, with the intraclass correlations calculated to determine the force plate measurements (29).

Statistical Analysis

Statistical analyses were completed using IBM Statistics, version 22 (IBM Corp., Armonk, NY). Normality was assessed for the dependent variables (1-leg standing time and stability of various thresholds on the force plate). An independent *t* test was used to analyze the dependent variables according to the group differences.

A mixed repeated measure design was used for the threshold and visual conditions. All continuous dependent variables were evaluated using the general linear model, in which the basic design involved a by-group factorial experiment. Assumptions of repeated measures, including homogeneity of variance, normal distribution of data, and sphericity, were tested using Mauchly's test.

An independent *t* test was used to compare the differences between the groups for the index with visual input. For all statistical tests, the type I error rate was set at 0.05.

Results

Sample Description

A total of 64 subjects, including 34 control subjects (14 females, 20 males) and 30 subjects with flat foot (11 females, 19 males),