In Vivo Plantar Pressures in Adult-Acquired Flatfoot Compared to Control Using an Intraoperative Pedobarographic Device

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Abstract *Background:* Intraoperative pedobarography has the potential to aid surgical decisions, but no parameters exist to guide its use. *Questions/Purposes:* This study compared supine plantar pressures between flatfoot patients and controls using a previously validated intraoperative pedobarographic device and examined associations between supine, walking, and standing plantar pressures. *Methods:* Ten preoperative patients with stage II adult-acquired flatfoot deformity (AAFD) were compared to ten healthy controls. Supine plantar pressures were assessed using the pedobarographic device. Standing and walking plantar pressures were assessed with an EMED-Xt sensor array (Novel). Maximum force (MF) and peak pressure (PP) were calculated for nine anatomical foot regions adjusting for age and BMI. *Results:* No differences in plantar pressures

were found between flatfoot patients and controls in the supine or standing positions. During walking, flatfoot patients had greater MF of the first, second, and third metatarsals ($p \leq 0.018$) and greater PP of the first and second metatarsals than controls ($p \leq 0.010$). Supine MF and PP were both strongly positively correlated with their respective pressure measurements for both standing and walking in multiple foot regions ($p \leq 0.05$, all analyses). Correlations in the first metatarsal region were generally weak and not statistically significant. *Conclusion:* This device did not show differences in supine plantar pressures of flatfoot patients and healthy subjects, highlighting the limitations of intraoperative devices in guiding flatfoot correction. The differences between flatfoot and controls during walking and the correlations between supine and walking conditions suggest that dynamic plantar pressures are a more useful parameter in guiding flatfoot reconstruction.

Level of Evidence: Level III: prospective case-control study.

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Introduction

Achieving successful correction of foot deformity during surgical reconstruction is challenging, especially for conditions requiring precise mechanical balancing of the foot such as adult-acquired flatfoot deformity (AAFD). Currently, surgeons use a combination of parameters to achieve optimal alignment including radiographic measurements [3, 4] and clinical assessment. However, reconstructive surgical procedures for AAFD also depend heavily on surgical experience in order to optimize outcomes. Many of these deformities are complex and have pathology at multiple levels in the foot requiring reconstruction with multiple procedures [5]. The use of an intraoperative plantar pressure assessment device has the potential to aid in such reconstruction [15]. However, it is currently unknown whether intraoperative

plantar pressures assessed in the supine position relate to postoperative standing or walking plantar pressures, which are likely to ultimately determine outcomes [11, 20].

Richter et al. previously developed a pedobarographic device called the Kraftsimulator Intra-Operative Pedographie® (KIOP) to assess supine intraoperative plantar pressures [15]. This apparatus tests the leg with the knee bent with the direction of the force determined by the operator. The system has been validated [16] and has also been tested in vivo on anesthetized patients [16, 17]. That group has shown in a prospective study that improved outcomes can be obtained when using that device [18]. However, no specific criteria (i.e., numbers/parameters) have been established upon which to base intraoperative decisions with that device, with the aimed force distribution outcomes based approximately on previously reported standing plantar pressures in healthy subjects [2, 18], nor have normal versus pathologic conditions been compared with this device to provide quantitative parameters for correction.

Another intraoperative pedobarographic system has been designed which tests the leg while supine in an operator-independent fashion with the knee straight [6]. This system grounds the leg by holding it just above the knee with a specially designed cuff. It advances a plantar pressure sensor against the bottom of the foot using a force plate. In a previous study, this system was shown to be accurate, linear, and reliable [6].

The purpose of this study was to determine whether this latter intraoperative pedobarographic device could help guide surgical decisions using AAFFD as a model. First, we sought to evaluate whether the system could detect supine plantar pressure differences between flatfoot patients and controls. We also aimed to assess plantar pressure differences between the flatfoot and control groups during both standing and walking, and whether there were correlations between plantar pressures in the supine with standing or walking conditions that could serve as parameters to guide intraoperative correction of AAFFD.

Patients and Methods

This project was approved by the Institutional Review Board at the investigator's institution. All subjects gave written informed consent prior to participating in the study.

AAFFD was classified using a previously established staging system, which is based on disorder, clinical presentation, and radiographic findings: stage I consists of mild posterior tibial tendon (PTT) swelling and tenderness with no deformity, stage II consists of moderate PTT swelling and tenderness with flexible deformity, and stage III consists of marked PTT tenderness and a fixed deformity [1, 10]. Stage II may be further subdivided into stage IIa, with minimal abduction through the proximal midfoot based on clinical and radiographic examination, and stage IIb, with significant abduction noted on clinical examination and greater than

30% uncovering of the talonavicular head on a standing anteroposterior (AP) X-ray of the foot (Table 1) [5].

Ten consecutive patients with ipsilateral stage II AAFFD scheduled to undergo reconstruction were enrolled. The inclusion of patients in the cohort was those selected by the senior authors (JTD, SJE), both fellowship-trained foot and ankle surgeons, to undergo flatfoot reconstruction for flexible deformity (i.e., stage II). It was based on the surgeons' clinical and radiographic assessment of flexibility and deformity (i.e., that they had flexible deformity). The contralateral foot may have had a low lying arch as typically occurs in patients with AAFFD but was asymptomatic. Patients with a coalition or adolescent deformity were excluded. In this group, there were six males and four females with a mean age of 52.2 (range, 30 to 64) years. The deformity involved the right foot in five cases and the left foot in five cases. The mean BMI was 28.9 (range, 20.7 to 43.8).

Ten healthy volunteers without a history of flatfoot deformity and no other present or past foot or ankle pathology or surgery were recruited for the control group. Both feet for each control were measured independently for a total of 20 feet. This control group included six males and four females with a mean age of 27.2 (range, 21 to 35) years old. The mean BMI in this group was 21.8 (range, 18.4 to 26.6) kg/m². The patients in the flatfoot group were older ($p < 0.001$) and had higher BMI ($p = 0.001$) than those in the control group.

In order to validate that the groups were clinically different and that the study group was comprised of patients with true flatfoot deformity, we also assessed standard weightbearing radiographs of the foot [1, 8, 19, 21]. On the AP view, the talonavicular coverage angle and the talo-first metatarsal angles were assessed. A greater talonavicular coverage angle indicates more abduction, and a greater talo-first metatarsal angle indicates that the first metatarsal is more valgus with respect to the talus [21]. On the lateral view, the talo-first metatarsal angle, talocalcaneal angle, and calcaneal pitch were analyzed. A greater talo-first metatarsal angle indicates greater arch collapse, a greater talocalcaneal angle signifies greater plantar sag, and a greater lateral calcaneal pitch indicates higher pitch (less collapse) [21]. On a hindfoot alignment view, the hindfoot moment arm was calculated [19]. A greater hindfoot moment arm indicates greater hindfoot valgus [19]. Of these, AP talonavicular coverage angle, lateral talo-first metatarsal angle, and calcaneal pitch have been shown to distinguish between flatfeet and normal feet [8, 14, 21].

Supine plantar pressures were collected using a method previously described [6]. Pressures were applied to the supine subject with the knee straight in an operator-independent fashion. The leg was grounded above the knee with a specially designed cuff. A slide rail was used to advance a Pliance 32 sensor array (Novel, Munich, Germany) attached to a plantar [14, 21] plate up against the foot. The total sensor array was 320 × 160 mm². Each sensor was 10.28 mm × 5.28 mm. The mat contained 812 sensors at a resolution of 1.85 sensors/cm². Data was transmitted wirelessly from the sensor array to a laptop computer and was analyzed with standard software (model Pliance

Table 1 Staging of adult-acquired flatfoot deformity [1, 5, 10]

Variable	Stage I	Stage IIa	Stage IIb	Stage III
Pain	Mild, medial	Moderate, medial	Moderate, medial	Severe, medial, and lateral
Swelling and tenderness along PTT	Mild	Moderate	Moderate	Not much swelling, marked tenderness
Deformity	None	Flexible: minimal abduction through the proximal midfoot, hindfoot valgus	Flexible: significant abduction through the proximal midfoot, hindfoot valgus	Fixed: minimization or elimination of passive inversion of the triple joint complex (talonavicular, calcaneocuboid, and subtalar joints)
Pathology of PTT	Normal tendon length, paratendinitis	Elongation with longitudinal tears	Elongation with longitudinal tears	Disruption with visible tears
Imaging	No changes	<30% uncovering of talonavicular head on standing AP X-ray	≥30% uncovering of the talonavicular head on standing AP X-ray	Deformity and diffuse arthritis

PTT posterior tibial tendon, AP anteroposterior

Expert®, Novel). Three trials were performed on each foot. The weight of the patient had been previously recorded, and the foot was loaded to 50% of the patient's weight and data collected for 10 s. The plantar pressure distribution was captured and averaged over six frames (0.25 s) starting at the point when the target force had been achieved. The sampling rate for all tests was 24 Hz.

For standing, patients stood on an EMED-XT sensor array (Novel, Munich, Germany). The total sensor area was $475 \times 320 \text{ mm}^2$, and each sensor was $5 \text{ mm} \times 5 \text{ mm}$. The mat contained 6080 sensors at a resolution of 4 sensors/ cm^2 . This data was analyzed with standard software (model EMED X/R®, Novel). Patients were asked to stand comfortably with the feet shoulder width apart and the arms at the side. Three trials were performed for each foot for 10 s.

Finally, walking trials were performed. Using the same EMED-XT platform, patients were asked to walk across the sensor array at a comfortable self-selected speed. Again, three trials for each foot were performed.

For all three test conditions (supine, standing, walking), a 12-region auto mask was applied which divided the foot into: (1) first toe, (2) second toe, (3) third through fifth toes, (4) first metatarsal, (5) second metatarsal, (6) third metatarsal, (7) fourth metatarsal, (8) fifth metatarsal, (9) lateral hindfoot, (10) medial hindfoot, (11) lateral midfoot, and (12) medial midfoot (Fig. 1) [7]. The hallux and toes were not included in the analysis, as they were not considered clinically relevant, leaving nine regions for analysis. For each anatomical mask region, maximum force (MF) (N) and peak pressure (PP) (N/cm^2) were assessed [12, 13]. Additionally, the ratios of the measurements for each group in the following anatomical regions were calculated: first to fifth metatarsal, medial to lateral hindfoot, and medial to lateral midfoot.

Continuous variables are reported as means and 95% confidence intervals unless stated otherwise. Univariate comparisons for age, BMI, and radiographic parameters were performed using the Wilcoxon rank sum test. The chi-squared test was used to compare sex distribution between the two groups. Repeated measures mixed models were developed to examine the effect of patient type (flatfoot or control) and position (supine, standing, or walking) on MF and PP adjusting for age, sex, and BMI. Post hoc pairwise comparisons were performed using the Bonferroni adjustment for multiple comparisons. Pearson correlation coefficients were calculated for supine MF and PF with their respective standing and walking measurements. Correlation coefficients were categorized as weak ($\rho < 0.40$), moderate ($0.40 \leq \rho < 0.70$), or strong ($0.70 \leq \rho < 1.00$). Significance level was set at $\alpha = 0.05$. All analyses were performed using SAS Software version 9.3 (SAS Institute, Inc., Cary, NC).

Results

Assessments of radiographic parameters confirmed flatfoot deformity in the patient group and the absence of deformity

Fig. 1. Plantar pressure profile with masking. *M01* first toe, *M02* second toe, *M03* toes 3 through 5, *M04* metatarsal 1, *M05* metatarsal 2, *M06* metatarsal 3, *M07* metatarsal 4, *M08* metatarsal 5, *M09* lateral hindfoot, *M10* medial hindfoot, *M11* lateral midfoot, *M12* medial midfoot.

in the control group (Table 2). All radiographic parameters in the flatfoot group were consistent with stage II AAFFD based on the radiographic parameters previously described [8, 14, 19, 21] and higher than in the controls, except for the lateral calcaneal pitch.

There were no statistical differences found in plantar pressures between flatfoot patients and controls in the

supine (Figs. 2 and 3) or standing conditions (Figs. 4 and 5). However, in the supine condition, there were trends seen towards less MF in the lateral midfoot (16.03 [−26.96, 59.01] N vs. 54.88 [11.54, 98.21] N; $p > 0.999$) and fifth metatarsal (4.55 [−1.41, 10.50] N vs. 16.96 [10.95, 22.96] N; $p = 0.397$) in flatfoot patients compared to controls and greater MF in the lateral

Table 2 Radiographic results in flatfoot and control groups

		Flatfoot	Control	<i>p</i> value
AP	Talonavicular coverage angle (degrees)	32.80 (25.3, 36.2)	20.55 (12.2, 24.7)	0.005
	Talo-1st metatarsal angle (degrees)	21.75 (19.6, 28.5)	11.65 (6.6, 14.9)	0.004
Lateral	Talo-1st metatarsal angle (degrees)	21.70 (15.0, 25.2)	3.90 (−2.0, 5.5)	<0.001
	Talocalcaneal angle (degrees)	45.90 (45.1, 47.5)	36.60 (34.0, 38.6)	<0.001
	Calcaneal pitch (degrees)	15.65 (12.2, 16.9)	17.55 (16.4, 21.1)	0.054
Hindfoot	Hindfoot moment arm (mm)	15.00 (10.0, 17.2)	2.60 (0, 4.4)	0.001

Data given as means with interquartile ranges (IQR). Italic numbers represent statistically significant differences between groups ($p < 0.05$)

Fig. 2. Maximum forces in flatfoot patients and controls during the supine condition. Data are presented as means with 95% confidence intervals.

hindfoot (158.44 [129.76, 187.13] N vs. 77.86 [48.93, 106.79] N; $p = 0.059$) and medial hindfoot (162.13 [120.09, 204.18] N vs. 84.06 [41.68, 126.44] N; $p = 0.639$) in flatfoot patients compared to controls. In the standing condition, there were also trends towards greater MF in the lateral hindfoot (132.58 [105.43, 159.73] N vs.

Fig. 3. Peak pressures in flatfoot patients and controls during the supine condition. Data are presented as means with 95% confidence intervals.

Fig. 4. Maximum forces in flatfoot patients and controls during the standing condition. Data are presented as means with 95% confidence intervals.

77.20 [49.88, 104.52] N; $p = 0.439$) and medial hindfoot ($p > 0.999$) in flatfoot patients compared to controls, although none of these reached statistical significance.

Fig. 5. Peak pressures in flatfoot patients and controls during the standing condition. Data are presented as means with 95% confidence intervals.

Fig. 6. Maximum forces in flatfoot patients and controls during walking. Data are presented as means with 95% confidence intervals. Differences were significant between groups in the first, second, and third metatarsals ($p = 0.012$, $p = 0.003$, and $p = 0.018$, respectively).

In the walking condition, flatfoot patients had greater MF than controls in the first metatarsal ($p = 0.012$), second metatarsal ($p = 0.003$), and third metatarsal ($p = 0.018$, Fig. 6). Flatfoot patients also had greater PP than controls in the first

Fig. 7. Peak pressures in flatfoot patients and controls during walking. Data are presented as means with 95% confidence intervals. Differences were significant between groups in the first and second metatarsals ($p = 0.010$ and $p = 0.005$, respectively).

metatarsal ($p = 0.010$) and second metatarsal ($p = 0.005$, Fig. 7). There were no differences found in the calculated ratios of mean plantar pressures between flatfoot patients and controls in any of the test conditions (data not shown).

Strong correlations were found between supine and standing conditions, as well as between supine and walking conditions, in the MF of the third metatarsal, lateral midfoot, and medial midfoot ($p \leq 0.0006$, all analyses). Moderate correlations were found between supine and standing, and between supine and walking conditions, in the MF of the second metatarsal, fourth metatarsal, lateral hindfoot, and medial hindfoot ($p \leq 0.0479$, all analyses). A moderate correlation was also found between supine and walking in the MF of the fifth metatarsal ($p = 0.003$). Correlations between MF in the supine with that in the standing or walking conditions in the first metatarsal were weak and not statistically significant ($p = 0.114$ and $p = 0.615$, respectively) (Table 3).

Strong correlations were also found in the PP of the second metatarsal, third metatarsal, lateral midfoot, and medial midfoot between supine and both standing and walking ($p \leq 0.0005$, all analyses). There was also a strong correlation between supine and standing in the PP of the fourth metatarsal ($p < 0.0001$). Moderate correlations were found between supine and standing, and between supine and walking, in the PP of the fifth metatarsal, lateral hindfoot, and medial hindfoot ($p \leq 0.0089$, all analyses). In the first metatarsal, correlations between PP in the supine condition with that in the walking and standing conditions were weak to moderate and not statistically significant ($p = 0.130$ and $p = 0.055$, respectively).

Discussion

This study compared supine plantar pressures between flatfoot patients and controls with a validated intraoperative pedobarographic device but found no significant differences in supine or standing plantar pressures between flatfoot patients and controls. There were significant differences in walking plantar pressures found. There were also significant correlations found in the supine condition with standing and walking conditions.

A strength of this study was the use of a validated intraoperative plantar pressure device. Also, we controlled for age, sex, and BMI in our comparison of plantar pressures between groups. There were also several limitations to this study. There was a small sample size of ten subjects in each group, but the significant differences in the radiographic parameters and walking plantar pressures between the groups suggest that our sample size was sufficiently large. The device was also not tested intraoperatively, which is its intended use, and we did not assess pre- to postoperative changes in plantar pressures in the flatfoot patients. This can be done in future studies.

The intraoperative pedographic device (KIOP) developed by Richter et al. was previously validated in the supine position in comparison with standing and walking in healthy volunteers [16]. This device was subsequently shown to improve clinical outcomes in patients undergoing various types of foot and/or ankle corrections and/or arthrodeses in a prospective, randomized trial. However, intraoperative plantar pressure measure-

Table 3 Correlations in maximum force (MF) and peak pressure (PP) between the supine condition with standing and walking conditions

	Maximum force				Peak pressure			
	Standing		Walking		Standing		Walking	
	Correlation coefficient	<i>p</i> value	Correlation coefficient	<i>p</i> value	Correlation coefficient	<i>p</i> value	Correlation coefficient	<i>p</i> value
Metatarsal 1	0.365	0.114	0.120	0.615	0.436	0.0546	0.351	0.130
Metatarsal 2	0.609	0.0044	0.596	0.0056	0.853	<.0001	0.796	<.0001
Metatarsal 3	0.768	<.0001	0.702	0.0006	0.957	<.0001	0.787	<.0001
Metatarsal 4	0.580	0.0073	0.571	0.0085	0.802	<.0001	0.237	0.315
Metatarsal 5	0.426	0.0611	0.629	0.003	0.694	0.0007	0.593	0.0059
Lateral hindfoot	0.671	0.0012	0.606	0.0046	0.581	0.0072	0.587	0.0065
Medial hindfoot	0.576	0.0079	0.447	0.0479	0.569	0.0089	0.654	0.0018
Lateral midfoot	0.887	<.0001	0.808	<.0001	0.860	<.0001	0.705	0.0005
Medial midfoot	0.941	<.0001	0.869	<.0001	0.795	<.0001	0.813	<.0001

Italic numbers represent statistically significant correlations between supine with standing or walking ($p < 0.05$)

ments were not reported [18] and that device had several limitations: the positioning of the foot was operator-dependent, and the leg had to be bent, such that flexion-extension angles were variable, which affected the force distribution of the foot. The standardized computerized mapping (i.e., “masking”) of foot regions in that system also did not distinguish between medial and lateral hindfoot or between medial and lateral midfoot and only provided overall medial and lateral measurements. The strengths of the device utilized in this study are that the foot is assessed with the knee in full extension and in an operator-independent fashion [6] and that the assessed regions of the foot include the medial and lateral hindfoot as well as the medial and lateral midfoot. These features increase its objectivity, precision, and utility [16].

We only found significant differences in plantar pressures between flatfoot patients and controls in the walking condition. This may simply be due to the fact that the load applied to the supine foot using the device as well as that received by the foot in shared stance (i.e., 50% body weight on each foot) is insufficient to detect significant differences. However, trends towards differences in plantar pressures between flatfoot patients and controls observed in the supine and standing conditions also suggest that this study may have had insufficient numbers to detect differences in these conditions.

Previous findings have shown that flatfoot reconstruction leads to alterations in dynamic plantar pressures, highlighting the importance of assessing the walking parameters in the setting of flatfoot reconstruction. A study by Matheis et al. investigating how flatfoot stage IIb reconstruction alters MF and PP during standing and walking found more and greater magnitudes of changes in walking than in standing plantar pressures in the forefoot and midfoot, suggesting that dynamic plantar pressures are more significantly affected by flatfoot reconstruction than static ones [11]. Although we did not assess pre- to postoperative changes in plantar pressures, our results suggest that only walking plantar pressures, and not standing or supine plantar pressures, differ between flatfoot and control patients and thus that walking plantar pressures are likely more useful in evaluating flatfoot than standing or supine plantar pressures.

The regional differences we found in walking plantar pressures between flatfoot patients and controls correspond to previous studies in the literature. Using an in vitro model of the foot and ankle, Imhauser et al. found that a simulated flatfoot deformity led to an increase in the medial to lateral forefoot ratio [9]. They also found that unloading the PTT, which simulated complete rupture, resulted in a medial shift in the force acting on the forefoot, as well as an increase in the rearfoot to forefoot force ratio [9]. We similarly found that flatfoot patients had significantly greater plantar pressures in the medial forefoot. These past findings also correspond to the trends we observed of greater MF of both the medial and lateral hindfoot in flatfoot patients compared to controls in the supine condition, although this did not reach statistical significance. We did not find differences in the ratios, perhaps because the magnitudes of the differences may not have been high enough to detect significant differences.

The strong correlations found in both PP and MF between the supine and walking conditions in the medial and

lateral midfoot suggest that such devices could theoretically guide intraoperative correction of AAFD using the relationships between the measurements in the two conditions. However, this device was unable to distinguish between supine plantar pressures of AAFD patients and controls possibly due to the lighter load applied in that condition, as noted above. Although a heavier load could potentially allow this device to distinguish between pathological and normal plantar pressures, such a load could be detrimental to surgical reconstruction. This highlights the limitations of intraoperative pedobarography and suggests that preoperative dynamic plantar pressure assessments may be more useful to help determine the degree of flatfoot pathology and thus guide surgical reconstruction.

In conclusion, there were no significant differences between plantar pressures of flatfoot patients and controls in the supine or standing positions, but flatfoot patients had greater medial forefoot plantar pressures than controls while walking. Together with the strong correlations in plantar pressures between the supine and walking conditions in multiple foot regions, these findings suggest that dynamic plantar pressures may be more useful than static ones to guide reconstruction of AAFD. Our findings also suggest that in general, caution should be exercised when utilizing intraoperative pedobarographic devices, as intraoperative supine plantar pressures may not be analogous to physiologic plantar pressures. Further studies are required to investigate whether other intraoperative devices [16] are able to distinguish between supine plantar pressures of controls and patients with foot/ankle pathology.

Compliance with Ethical Standards

Conflict of Interest: Aoife MacMahon, BA, Howard J. Hillstrom, PhD, Jeremy Y. Chan, MD, and Scott J. Ellis, MD, have declared that they have no conflict of interest. Huong T. Do, MA, reports grants from Clinical and Translational Science Center, outside the work. Jonathan T. Deland, MD, reports personal fees from Arthrex, Zimmer, and Integra and personal fees and other from Tornier, outside the work.

Human/Animal Rights: All procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1975, as revised in 2008 (5).

Informed Consent: Informed consent was obtained from all patients for being included in the study.

Required Author Forms Required Author Forms Disclosure forms provided by the authors are available with the online version of this article.

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