



Adaptive changes of foot pressure in hallux valgus patients

Jianmin Wen^a, Qicheng Ding^b, Zhiyong Yu^a, Weidong Sun^a, Qining Wang^c, Kunlin Wei^{b,*}

^a Wangjing Hospital of China Academy of Chinese Medical Sciences, Beijing, China

^b Department of Psychology, Peking University, Beijing, China

^c Intelligent Control Laboratory, College of Engineering, Peking University, Beijing, China

ARTICLE INFO

Article history:

Received 31 August 2011

Received in revised form 16 February 2012

Accepted 1 March 2012

Keywords:

Hallux valgus
Plantar foot pressure
Orthopedics
Gait analysis
Motor adaptation

ABSTRACT

Background: Hallux valgus (HV) is one of the most common deformities in podiatric and orthopedic practice. Plantar pressure technology has been widely used in studying the pressure distribution in HV patients for better assessment to plan interventions. However, previous studies produced an array of controversial findings and most of them only focused on the forefoot.

Methods: We examined the dynamic changes of foot pressure of the whole foot with a large-sample investigation (229 patients and 35 controls). Foot pain, which has been largely neglected previously, was used to group the participants.

Results: Compared to healthy controls, patients had significantly higher loading of the first and second metatarsals, where the transverse arch usually collapses, and significantly less loading of the hallux. Moreover, forces in most regions reached their maximum late, indicating a slow build-up of loading. Patients shortened the loading duration on their forefoot, loaded more on the medial foot starting from early foot contact, and delayed the medial-to-lateral load transition. Notably, nearly all these changes were more pronounced in patients with pain.

Conclusions: Biomechanical changes in HV patients are not only caused by physical deformity but also by modified neural control strategies, possibly to alleviate discomfort and to accommodate the foot deformity. Our results suggest that dynamic evaluation of the whole foot and consideration of foot pain are necessary for the functional assessment of foot pressure in HV patients. The foot balance changes have important clinical implications.

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1. Introduction

Hallux valgus (HV) is one of the most common deformities in podiatric and orthopedic practice [1]. It is characterized by a lateral deviation of the hallux with a corresponding medial deviation of the first metatarsal [2]. It is often, accompanied by collapse of the forefoot transverse arch during quiet standing, metatarsal pain and callus formation [3]. The most common diagnostic procedure is radiological assessment of anatomical angles including the HV angle (the angle between the first metatarsal and proximal phalanx), 1–2 intermetatarsal angle (between the first and second metatarsals) and distal metatarsal articular angle [4,5]. However, these anatomical angles can only serve as a reference during assessment. Severity of HV and intervention are determined by several other factors such as age, gait deviations, pain location and duration [4].

Plantar foot pressure measurement is invaluable in investigating foot and ankle function during gait and other functional

activities [6]. It can be used for evaluation and management of patients with a wide variety of foot impairments associated with neurological and musculoskeletal disorders [6], including HV [7–12]. Previous studies found an altered plantar pressure pattern at the forefoot of HV patients [13–15], but their findings were inconsistent. Hutton and Dhanendran [8] conducted the first quantitative study of plantar pressure in HV and found significantly lower peak force under the great and second toes and higher peak force under the third to fifth metatarsals. However, other studies found decreased peak pressure under the fourth and fifth metatarsals and increased pressure under the first to third metatarsals [7,10–12,16]. Pressure time integral and force time integral were also reported to be higher under the second and third metatarsals [17]. By comparison, another study reported reduced loading of the medial forefoot in HV [18]. These discrepancies between different studies have not been systematically addressed.

There are several potential factors contributing to these discrepancies. First, previous studies did not distinguish between patients with foot pain and those without. Pain can significantly affect the gait pattern and the proportion of participants with foot pain in a study can affect its overall results. Second, different studies employed different normalization methods. Most parameters in gait

* Corresponding author. Tel.: +86 10 6275 3617.
E-mail address: wei.kunlin@pku.edu.cn (K. Wei).

analysis, foot pressure measures in particular, are affected by body weight and walking speed [19,20]. Body weight can be normalized by dividing parameters by the subject's body weight; walking speed can be controlled by asking participants to walk either at their preferred speed or at a pre-determined speed. However, preferred speeds vary widely across individuals. Pre-defined speed, when significantly deviated from preferred speed, can alter the normal gait pattern of the individual. Third, most previous studies measured a limited number of HV feet. Large variations between patients may have led to different findings.

The present study aimed to systematically control the aforementioned confounding factors and comprehensively examine foot pressure pattern in a large sample, taking both the hindfoot and the forefoot into account. The effect of foot pain was investigated by dividing patients into two separate groups, with and without pain. The study also aimed to assess the dynamic gait pattern in HV using foot pressure measurement alone. Previous studies on plantar foot pressure mostly evaluated parameters that carried little temporal information (such as peak force/pressure and their time integrals), leaving the temporal force unchecked.

2. Method

2.1. Subjects

Our study was a cross-sectional one. 679 HV patients were recruited from the Beijing Wangjing Hospital. The first intermetatarsal and the HV angles were measured on weight-bearing anterior–posterior X-rays. HV diagnosis was based on an HV angle $>15^\circ$. Participants with underlying motor disorders or musculoskeletal deformities were excluded. Furthermore, we only included patients with bilateral HV and this reduced the number of participants to 229. The analyses were based on individual feet.

We further divided patients into two groups (Table 1): a group with self-reported pain in the forefoot (*Pain*) and the other without (*NoPain*). Most patients in *Pain* group reported pain in the second and third metatarsal joints (27.4% patients in both second and third joints; 65.3% only in second joint; 2.8% only in third joint; 4.5% in other joints). 95.2% of patients were female, which is consistent with the usual gender distribution of HV patients [4].

Normative data were gathered from 35 symptom-free adult volunteers (*Normal* group). Before recruitment, HV angles were examined qualitatively through clinical examination (the Manchester scale), which has been shown to have excellent inter-observer repeatability [1,21,22].

Informed consent was obtained from each participant before data collection and the experimental procedures were approved by the ethical committee of Peking University.

2.2. Data collection

A plantar pressure measuring plate (RsScan Inc.) was mounted flush in the middle of a 10 m long carpet. The plate was 1 m $\times$.4 m in dimension with a sensor density of about 2.7/cm² and a sensor size of 5 mm (lateral) $\times$ 7 mm (anterior–posterior). The data were sampled at 250 Hz. Participants were asked to walk barefoot on the carpet at self-selected speed. Formal data collection started after some familiarization runs. A minimum of three valid trials per foot was collected [23]. A trial was considered as valid when the following criteria were met: (1) two complete footprints, (2) presence of a heel–strike pattern, (3) no visible adjustment in gait pattern when crossing the plate [24].

Table 1

Demographical description of participants. Mean and standard deviation (in parenthesis) within each group are shown. The *Pain* and *No pain* groups have significantly longer foot contact duration ($p < .05$ for both paired *t*-tests) and less body weight ($p < .05$ and $p < .005$, respectively) as compared to the *Normal* group. There is no significant difference between the two patient groups.

Characteristics	Groups		
	<i>Pain</i>	<i>NoPain</i>	<i>Normal</i>
Number of feet	248	210	70
Sex (male/female)	12/236	8/202	13/22
Age (yr)	51.2 (12.14)	49.4 (16.14)	46.7 (9.76)
Body weight (kg)	61.9 (7.71)	60.4 (8.16)	66.5 (13.17)
Contact duration (ms)	692.6 (96.75)	704.9 (107.52)	661.6(77.93)
HV angle ($^\circ$)	33.15 (9.50)	30.90 (8.16)	
First intermetatarsal angle ($^\circ$)	11.77 (3.24)	12.18 (2.88)	

2.3. Data analysis

The pressure area under the foot was divided into 10 anatomical regions semi-automatically by the RsScan software system (Fig. 1). All division results were visually inspected and inappropriate divisions were manually adjusted by two assessors independently (a graduate student and an experienced podiatrist) following a standard analysis procedure. We confirmed that inter-observer differences did not affect our general results [25]. Foot regions included the hallux (T1), the second to fifth toe (T2–5), metatarsal joints 1–5 (M1 to M5), middle foot (MF), medial heel (HM) and lateral heel (HL) [26].

For each region, we calculated its time-series of force, peak force (F_{peak}), time of peak force (T_{peak} , as a percentage within a foot contact duration), contact duration (percentage of time with respect to total foot contact duration), and absolute impulses (I , time integral of the force). The peak force was calculated for a region, instead of a calculation based on a single sensor grid within a region, which is commonly used. Time series data were interpolated to a uniform length of 400 data points by piecewise cubic spline interpolation. All force-related parameters were normalized by the total force (Z_{avg}). Z_{avg} was calculated as the sum of all force readings divided by the total number of data frames (before interpolation) during a single trial. The frame number captures how fast participants walk over the pressure plate (The frame number is proportionate to the foot contact duration, the percentage of which in a gait cycle is relatively constant over walking speeds). As such, Z_{avg} captures individual differences in body weight and walking speed and is superior to the commonly-used body weight.

We further derived two relevant parameters for HV assessment. Foot balance captures the force difference between the medial and the lateral part of the foot: $(F_{M1} + F_{M2} + F_{HM} - F_{M3} - F_{M4} - F_{M5} - F_{HL}) \times 100 / Z_{avg}$. It serves as a measure of balance within the foot during contact. Meta loading is defined as the force difference between the region of M2–3 and that of M1, M4 and M5: $(F_{M2-3} - (F_{M1} + F_{M4} + F_{M5})) \times 100 / Z_{avg}$. This relative measure is relevant to HV patients as an important feature of their feet is the depressed M2 and M3.

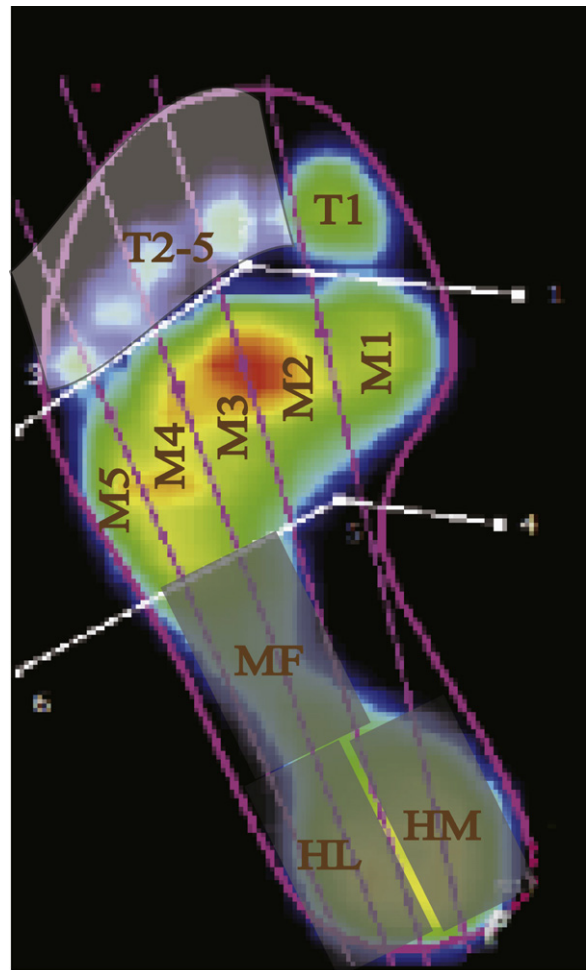


Fig. 1. The 10 anatomical regions of the foot (see Methods). The color contour shows a typical trial; the pink outline and white lines depict the division mask [24]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

We selected peak force because it has higher reliability than peak pressure [27]. The temporal profile of loading can be characterized equally well with force or pressure.

Independent two-sample *t*-tests were used to study the differences between groups with a significance level at .05.

3. Results

3.1. Force development

Starting from initial foot contact, the force progression in individual foot regions differed between groups (Fig. 2). For the two heel regions and the middle foot region, there was a tendency of higher peak force (F_{peak}) in patients but only the lateral side (HL) reached statistical significance. For these regions, the time of peak force (T_{peak}) was progressively later in the order of *Normal*, *NoPain* and *Pain* with significant differences.

The metatarsal regions were directly affected by HV deformity. Interestingly, there was no difference in M1. For all other metatarsal regions T_{peak} was significantly delayed, even more so for the *Pain* group. In M4 and M5, the force even rose up slower in both patient groups. In terms of F_{peak} , M2 and M3 exhibited significantly higher force in two patient groups (except that *Pain*-vs-*Normal* comparison did not reach significance in M3); M4 and

M5 did not differ much in patient groups except that the *Pain* group had significantly smaller F_{peak} in M4.

In the toe regions, both patients groups had significantly delayed T_{peak} . T1 had significantly lower F_{peak} and the force in T1 was relatively small throughout the contact period. The remaining toe regions T2 to T5 showed no difference in force.

The sum of forces from all 10 regions exhibited a typical double-peak pattern. The time integral of force was roughly equal over the groups, an indication of the effectiveness of Z_{avg} in normalizing force measures. An obvious difference between groups was that the terminal-stance peak (the second peak) was significantly higher for patient groups, reflecting the differences found in M2 and M3.

3.2. Contact duration

Each foot region had a distinct contact duration with the ground (Fig. 3A and B). For HM and HL, *NoPain* group showed no difference from *Normal* group; but *Pain* group had significantly longer contact duration than the other two groups (though HL only yielded marginal significance $p = .05$). Patient groups had significantly shorter contact duration in the forefoot and mid-foot. *Pain* group had longer contact duration than *NoPain* group in M1 and M2 and shorter duration in T1. Taken together, it appears that both patient

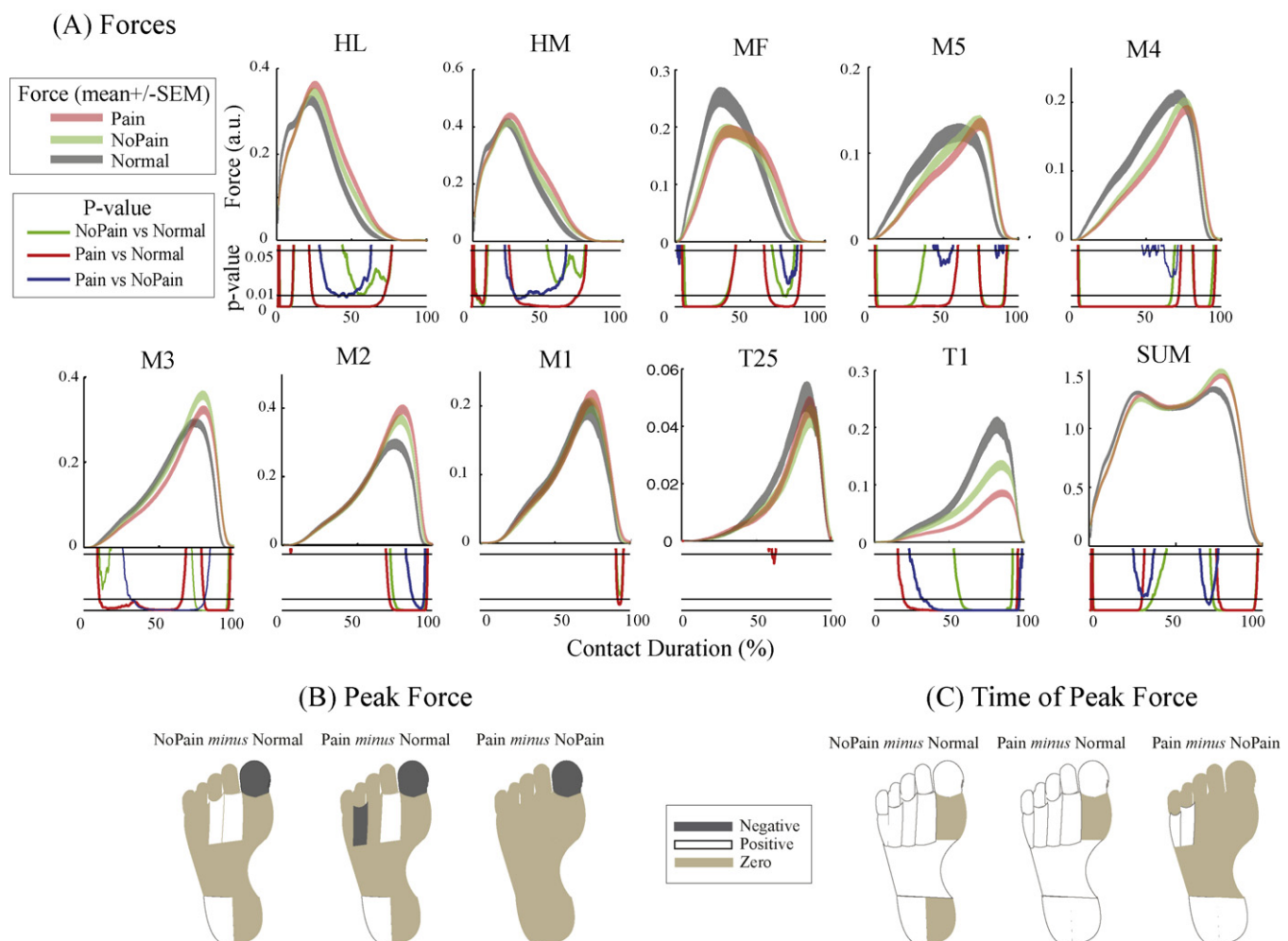


Fig. 2. (A) Time-series normalized force in 10 ft regions and their total sum. The width of these curves stands for mean ± SEM across participants (same below). The lower panels display the *p*-values from pair-wise comparisons between groups (B) and (C). Statistical significance of between-group comparisons in F_{peak} (B) and T_{peak} (C) are displayed in a color-shaded foot model.

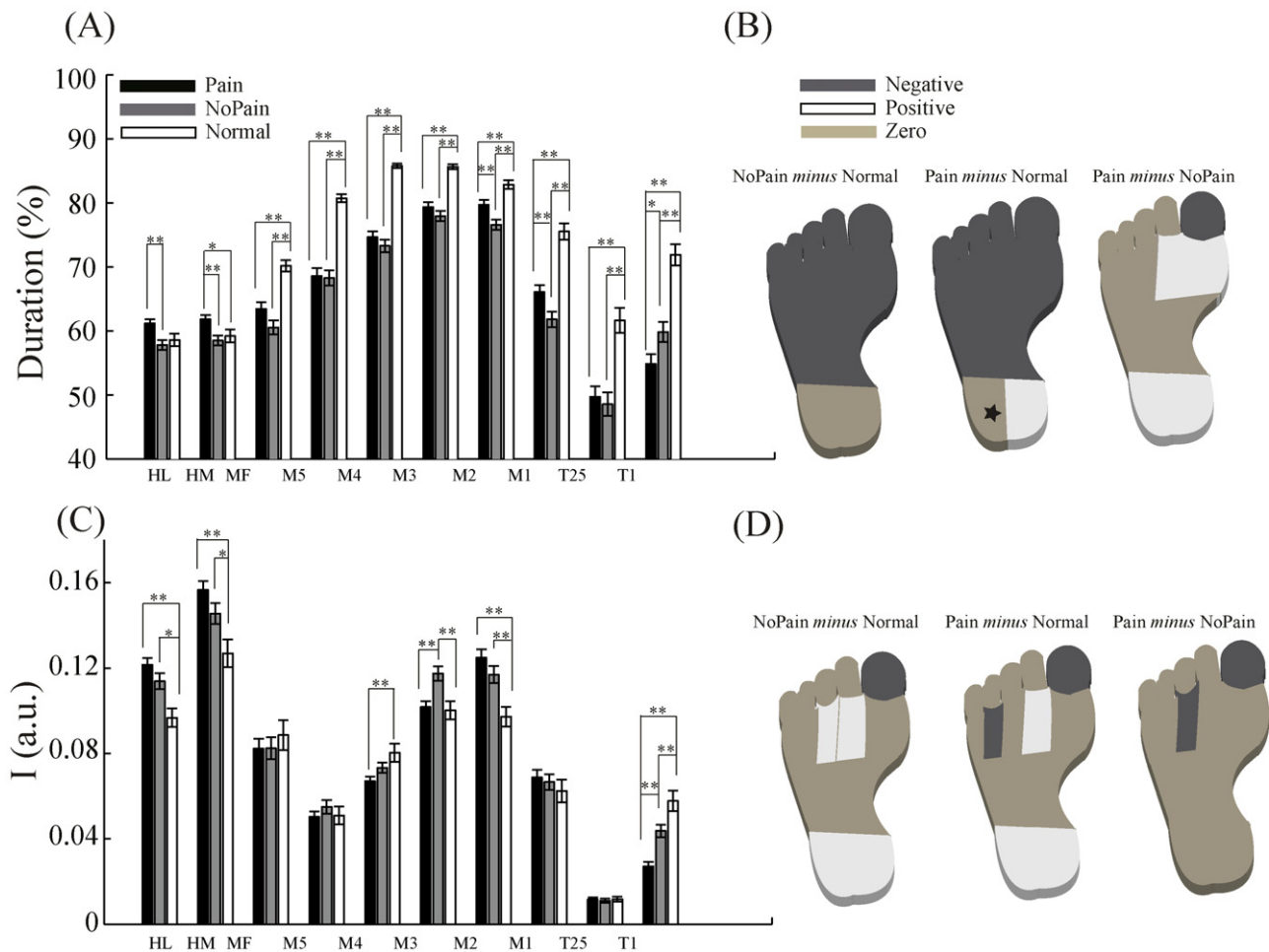


Fig. 3. Contact duration and impulse in different regions (A). The contact duration from different groups (B). Statistical significance for between-group comparisons is displayed in a color-shaded foot model (* stands for a marginal significance) (C). The impulse from different groups (D). Statistical significance plotted in a similar format as in (B).

groups had less contact duration in the front part of the foot and only *Pain* group dwelled significantly longer in the hindfoot.

3.3. Impulse

Between-group comparisons in impulse resembled, to a large extent, those of peak force (Fig. 3C and D). The only difference was that both patient groups had significantly higher impulse in HM and *Pain* group had significantly less impulse in M3 than *NoPain* group. Overall, the two heel regions (HM and HL), M2 and M3 (only for *NoPain* group) had significantly higher impulse in patients; T1 showed loading deficiency and it was more severe in *Pain* group than in *NoPain* group.

3.4. Foot balance

Foot balance characterizes the relative loading between the medial and lateral sides during foot contact. Both patient groups showed increased loading on the medial side of the foot compared to normal and this was shown as a more positive foot balance over time (Fig. 4A). Increased medial loading was present from the very beginning of foot contact, long before forefoot loading. Furthermore, the transition from positive to negative balance was significantly delayed for patients. We also calculated the time of maximum offset in balance during the push-off (after 80% gait cycle in Fig. 4A) and found that it appeared later in patients ($p < .05$ for both *Pain* vs. *Normal* and *NoPain* vs. *Normal*).

3.5. Meta loading

Meta loading quantified the relative force distribution under the two central metatarsals (M2 and M3) compared to the lateral metatarsals. We found that both patient groups exhibited higher meta loading compared to *Normal* group, starting from early contact (Fig. 4B). The peak of meta loading was significantly higher in patients ($p < .01$ for both *Pain* vs. *Normal* and *NoPain* vs. *Normal*). The time of the peak was also significantly delayed ($p < .01$) in patients.

4. Discussion

The present study assessed foot loading patterns in HV patients. Significantly increased loading (quantified by F_{peak} and I) was found in M2 and M3, where the transverse arch usually collapses. Significantly decreased loading was found in T1 where the hallux deformity is present. The temporal pattern of loading was consistently altered: the forces in most regions reached their maximum late, which indicates a slow build-up of loading. Patients spent less time loading the forefoot and mid-foot. They tended to load more on the medial foot from initial contact and the medial-to-lateral loading transition was delayed. Furthermore, the specifically-designed parameters, meta loading and foot balance, revealed that patients showed decreased forefoot loading from early contact. Notably, these patient-specific changes were more pronounced in *Pain* group.

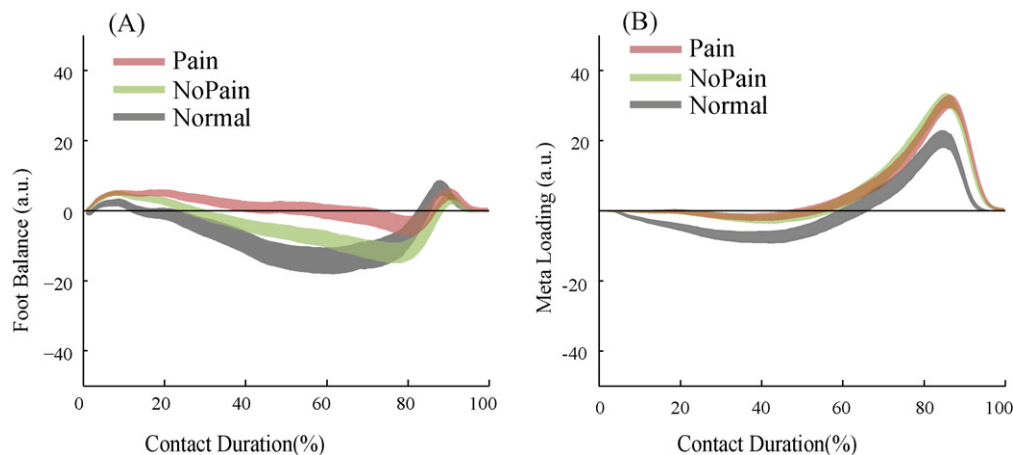


Fig. 4. (A) Foot balance curve versus time. (B) Meta loading versus time. Both plots are shown for different groups separately.

4.1. Foot pressure pattern

The heel region has been largely neglected in previous studies, though two studies reported an increase in loading [8,17]. We found that HL and HM had significantly increased loading, delayed T_{peak} and increased contact duration. The changes were more pronounced in *Pain* group. These results suggest that patients relied more on the hindfoot for loading, possibly as an adaptive strategy to alleviate the discomfort and deficiency in the forefoot. This interpretation is supported by the decreased contact duration and delayed T_{peak} in the forefoot. In contrast to previous findings, patients exhibited no change in mid-foot loading [8,17]. A large variability across participants may have contributed to this difference in findings.

Previous studies have reported inconsistent results on loading of the metatarsal regions. The first metatarsal has been shown to have significantly increased [11,12], decreased [18], or unchanged [10] loading. M2 and M3 have been reported to have increased [7,10,11] or decreased [12,18,28] loading. Our large-sample study found no difference in M1 but higher loading in M2 and M3 (in both force and impulse). The differences found in M1 loading could be attributed to different walking speeds. This region plays an important role in push-off and its loading is sensitive to walking speed. For M2 and M3, we propose to consider the relative loading in M2–3 to Using meta-loading as a measure of the relative loading of M2–3 compared to the other metatarsals we confirmed that M2–3 were loaded more in HV patients. This was the case from initial foot contact, suggesting that structural collapse under the second and third metatarsals caused increased loading [3]. We found a tendency towards decreased loading of M4 and this was especially apparent in *Pain* group. The reduced loading in M4 [10,17] can be attributed to the relatively elevated M4 caused by the collapsed transverse arch. The M5 loading was unchanged probably because it is relatively away from the affected region.

In accordance to previous studies we demonstrated that loading of the hallux was deficient [8,9,17]. Some studies suggested increased loading of the hallux [7,12]. This discrepancy cannot be accounted by differences in measuring systems (insole vs plantar), since both systems were used in the aforementioned studies [29]. Confounding factors may include limited sample size and varying normalization methods [4]. Deficiencies in hallux have been attributed to decreased power of short flexors [8]. We suggest that reduced contact areas of the hallux caused by deformity and inflammation of the first metatarsal are also possible reasons. *Pain* group showed an even greater deficiency in hallux loading

compared to *NoPain* group, which may reflect pain avoidance at M2 and M3. We did not find any change in T2–5 region probably because this area only carries a small percentage of loading.

4.2. Foot balance and timing

We found that HV patients loaded more the medial side of the foot, starting from the early phase of foot contact. Their balance transition from medial to lateral was significantly delayed. These findings are consistent with clinical observations in our hospital, suggesting that patients opt for an altered control strategy for heel strike and subsequent roll-off to accommodate their deformity/discomfort in the forefoot. This adaptation may greatly affect foot stability and transition from pronation to supination.

A consistent change in timing of loading was evident: nearly all foot regions reached maximum loading late. This was reflected by force measurement or its derivative measures, foot balance and meta loading. Along with prolonged contact duration in the hind- and mid- foot, these results suggest that patients changed their gait pattern.

5. Conclusion and summary

The present study measured foot plantar pressure in a large sample of HV patients using normalized parameters for both walking speed and body weight. Foot pain was identified as a critical factor in determining the loading pattern; increased loading in the second and third metatarsals and reduced force at the hallux were confirmed. Adaptive changes in foot loading were found: reduced contact duration at the forefoot, delayed peak forces, and altered within-foot balance to the medial side. These changes can be viewed as adaptations of control strategies to alleviate the discomfort and accommodate deficiency. However these changes have a negative impact on gait stability and hold important clinical implications. Cautious interpretation of biomechanical assessments is recommended since our results are suggestive of an adapted neural control of walking in these patients.

Acknowledgements

The study was supported by the National Natural Science Foundation of China (nos. 31000456, 61020106005, 61005082, and J1103602), the Fundamental Research Funds for the Central Universities.

Conflict of interest statement

Authors declare no conflicting financial interests.

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