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Article

Induced fatigue impact on plantar pressure in females with mild hallux valgus

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Abstract: Fatigue has been established to change plantar pressure distribution, yet its impact on hallux valgus (HV) patients, who exhibit morphological and biomechanical changes in the foot, remains insufficiently studied. Twenty-eight female participants, comprising 16 with mild HV and 12 healthy controls, were recruited. Plantar pressures were recorded pre- and post-fatigue using the Footscan platform during self-selected-speed walking trials, fatigue protocol was performed on a treadmill. Foot was segmented into 10 anatomical regions for calculating parameters including maximal force, peak pressure, impulse, contact duration, contact area, and force time-series, alongside assessing the distribution of medial and lateral contact forces (Foot balance) across the groups. During post-fatigue, patients with mild HV demonstrated adaptive changes in plantar pressure distinct from healthy controls, with significant reductions in maximal force, peak pressure, and impulse in the M1 and M2 regions and increases in the M3–M5 regions. In contrast, the control group exhibited an opposite pattern, concentrating pressure in the M1 and M2 regions post-fatigue. The force time-series analysis revealed significant disparities between HV patients and controls, particularly in the M4 and M5 regions, where HV patients showed a less pronounced and lower passive peak in forces. Results show that women with mild HV demonstrate adaptive changes in plantar pressure post-fatigue, distinctly different from healthy individuals, aiding in preventive strategies for fatigue-induced foot injuries for HV patients.

Keywords: induced fatigue; mild hallux valgus; plantar pressure analysis

1. Introduction

Hallux valgus (HV), a prevalent foot deformity characterized by the lateral deviation of the big toe, has witnessed an escalating incidence rate [1]. This condition is notably more common among females than males [1,2]. HV can be stratified into mild (15°–20°), moderate (21°–39°), and severe (≥40°) categories based on the angulation of the deviated toe [3–6]. Different degrees of valgus and the presence or absence of accompanying pain result in varying adaptive alterations in plantar pressure [7–9], with severe potentially resulting in balance disorders and heightened fall risk [10,11]. Studies such as those by Martínez-Nova et al. [12] have delineated increased average pressures in the first metatarsal and hallux regions during gait in females with mild HV compared to healthy counterparts. Wen et al. [7], incorporating pain as a stratifying factor, observed that HV patients experience significantly elevated loads on the medial and lateral heel, delayed peak force timings, and heightened loads in the second and third metatarsal regions. These alterations in foot structure and consequent shifts in load-bearing patterns represent focal points of ongoing biomechanical research [13]. Furthermore, fatigue is recognized as another critical factor that influences gait and foot biomechanics [14]. This aspect becomes particularly relevant as it may exacerbate the pre-existing biomechanical challenges faced by individuals with HV, leading us to investigate how fatigue specifically alters plantar pressure distributions in this population.

Although fatigue can impact the biomechanical patterns of the foot [15–17], as pointed out by Baur [18], Bisiaux and Moretto [14], the effects of fatigue involve different muscle activation patterns and specific neuromuscular control mechanisms. This leads to short-term changes in plantar pressure, such as significant decreases in peak pressures at the heel and midfoot areas, and significant increases in the forefoot areas. However, existing research on hallux valgus (HV) has not fully considered these aspects. Given the pre-existing biomechanical imbalances, fatigue may have a more pronounced impact on this population, and compared to healthy population, HV patients may exhibit unique adaptive mechanisms in plantar pressure post-fatigue, their inherent structural deviations could lead to a redistribution of plantar pressures, particularly on the medial metatarsal bones (M1 and M2), warranting further investigation in this domain.

Considering the structural abnormalities present in patients with HV, this study aims to explore the effects of fatigue on plantar pressure distribution in female patients with mild HV and compare these effects with those observed in a healthy population.

2. Methods

2.1. Participants

In this study, the participants with HV were recruited from hospitals, and the degree of HV was assessed based on radiological reports of the right foot. Patients with mild HV were defined as 15° < HAA < 30° [19].

The specific inclusion criteria were as follows: 1) No history of foot surgery; 2) For control group, absence of any structural or functional foot disorders, while for HV group, HV did not cause foot pain; 3) No neurological diseases; 4) No foot or lower limb injuries in the six months preceding the date of the experiment; 5) Right leg as the dominant leg.

Following stringent screening based on the inclusion criteria, a total of 28 female participants were enrolled in this study at an accessible sample size, encompassing 16 individuals with mild HV and 12 healthy females (**Table 1**). The study was conducted in strict adherence to the ethical principles of the World Medical Association (Declaration of Helsinki). Informed consent was obtained from all patients and participants. This research received ethical review and approval from the Ethics Committee of Research Academy of Grand Health at Ningbo University (RAGH2023071701211.8).

Table 1. Participant demographics.

	HV group (*N* = 16)	Control group (*N* = 12)	*P*-value
Height (cm)	166.25 (5.97)	167.67 (4.62)	0.702
Weight (kg)	59 (6.98)	59 (7.94)	0.832
Age (yr)	21.88 (4.67)	24.67 (1.63)	0.119
BMI (kg/m^2)	21.3 (1.53)	21 (2.76)	0.186

2.2. Experimental procedures

Plantar pressure during walking was measured using a Footscan® plantar pressure plate operating at 480 Hz (RsScan International, Olen, Belgium). The pressure plate was centrally positioned on a 10-meter walkway. Prior to the experiment, participants were asked to perform multiple walk trial to familiarize themselves with the experimental conditions. Then, participants were instructed to walk at a self-selected speed and avoid intentionally stepping on the plate. A minimum of five sets of plantar pressure data were collected for each participant before and after fatigue. Successful trials met the following criteria: (1) No apparent gait adjustments were observed by the researchers throughout the process; (2) Two complete footprints were recorded. To avoid fatigue, a 15-second interval was maintained between each data collection session.

2.3. Fatiguing protocol

The fatigue protocol in this study was adapted from the method used by Hajiloo et al. [20]. Specifically, participants first wore standard running shoes and a Polar heart rate monitor provided by the lab, followed by a 2-minute warm-up at an adaptive running speed. Subsequently, they started walking at 6 km/h on a treadmill, with heart rate being recorded. The speed was gradually increased by 1 km/h every 2 minutes, transitioning to running. Every 2 minutes in the last 10 seconds, researchers asked the participants about their subjective perception using the Rating of Perceived Exertion (RPE) scale and monitored real-time heart rate changes. The speed corresponding to an RPE score of 13 was maintained as a steady running pace until the participant reached an RPE of 17% or 80% of their maximum heart rate (220-age). Upon reaching this criterion, participants were asked to continue running at this pace for 2 minutes, followed by a 2-minute cooldown at a self-selected speed.

2.4. Data analysis

Footscan 7 Gait software automatically divided the foot into 10 regions [21,22]: the hallux (T1), lateral toes (T2-5), the first to fifth metatarsals (M1-M5), the midfoot (MF), the medial heel (HM), and the lateral heel (HL). To avoid variability due to subjective division, the entire process was carried out by the same researcher.

Subsequently, we computed various parameters for each foot region, including maximal-force (FM), peak-pressure (PP), time integral of the force (impulse), percentage of contact time of each region relative to total plantar contact duration (CD), and contact area (CA) of each region. To normalize CA, we standardized each region’s contact area against the total foot area to mitigate the influence of varying foot sizes on data analysis. All force-related parameters were standardized using the Zavg method, as detailed in Wen's study [7]. This normalization approach has been proven to effectively eliminate variations in participant body weight and walking speed [23].

For the time-series data normalized by Zavg, interpolation was uniformly performed in Python (Version 3.8) to standardize the data to 101 frames. Subsequent normality testing was conducted on these interpolated time series. Analysis of plantar pressure data for different regions pre- and post-fatigue in the HV group and Control group was carried out in MatlabR2016b (The MathWorks, MA, USA) using the open-source Statistical Parametric Mapping 1d (SPM1d). This involved two-factor repeated measures analysis of variance (anova2rm) or its non-parametric counterpart to compare temporal pressure profiles. Given the consistent findings of altered plantar pressure patterns in HV patients [24,25], we introduced the Foot Balance index to quantitatively assess the distribution of pressure between the medial and lateral aspects of the foot. This metric offers a comparative analysis of pressure distribution, which is crucial in understanding the biomechanical implications of HV pathology.

$$Zavg = \frac{\text{sum of all force}}{total\ number\ of\ data\ frames\ (before\ interpolation)}$$

$$\text{Foot Balance} = [(HM + M1 + M2) - (HL + M4 + M5)] \times 100/Zavg$$

The discrete parameters Fp, Pp, impulse, and CD, as well as Contact Area (CA), were statistically analyzed using IBM SPSS Statistics version 25.0 (IBM, Armonk, NY, USA). Prior to performing the statistical tests, assessments were made to verify the assumptions of normality and homogeneity of variances. Following this, the data underwent a two-way repeated-measures ANOVA and descriptive analysis to investigate the effects of the studied factors. To ascertain the appropriateness of the ANOVA model, Mauchly's test was employed to examine the sphericity condition. In instances where sphericity was upheld, a univariate method was chosen for the analysis of variance. Conversely, if this assumption was breached, an appropriate correction was utilized to modify the degrees of freedom. For significant interaction effects, post-hoc analysis was performed using the Bonferroni method with a significance level set at 0.025.

3. Results

3.1. Force discrete parameters

3.1.1. Maximal-force (FM)

Analysis of maximal force in each region revealed significant group effects in T1 ($P < 0.001$), T2-5 ($P = 0.002$), and M1 ($P < 0.001$) (**Table 2**). The HV group exhibited significantly higher FM compared to the control group, both pre- and post-fatigue intervention. In contrast, the FM of the HV group was significantly lower in the M3 ($P < 0.001$), M5 ($P = 0.004$), and MF ($P = 0.044$) regions. Fatigue notably impacted T2-5 ($P = 0.004$) and MF ($P = 0.015$), with a significant decrease in FM post-fatigue in T2-5 and an increase in MF. Interaction effects between group and fatigue were observed in M1 ($P = 0.004$), M5 ($P = 0.003$), and HM ($P = 0.023$), with subsequent analysis indicating higher FM in the HV group compared to controls in M1, both pre- and post-fatigue (pre-fatigue: $P < 0.001$, post-fatigue: $P = 0.009$). In M5, the HV group showed significantly lower FM pre-fatigue ($P < 0.001$), with a notable decrease post-fatigue in the HV group (*P* = 0.002) and a non-significant increase in the control group (*P* = 0.138). In the HM region, the control group exhibited a significant increase in FM post-fatigue (*P* = 0.008).

Table 2. Maximal force (FM), peak pressure (PP), and force-time integral (Impulse) during walking between control group and HV group pre- and post-fatigue.

	Control-group		**HV-group**			**Ranova**	
	Pre-fatigue	**Post-fatigue**	**Pre-fatigue**	**Post-fatigue**	**Group**	**Fatigue**	**G × F**
$F_{M(\text{Maximal force/Zavg} \times 100)}$							
T1	11.3 (9.31)	17.19 (13.58)	30.78 (21.8)	27.6 (9.29)	**<0.001**※	0.530	0.089
T2-5	4.84 (2.74)	2.97 (1.65)	7.26 (5.68)	5.43 (3.40)	**0.002**※	**0.004**※	0.979
M1	14.55 (10.14)	17.24 (10.48)	35.28 (15.16)	25.61 (12.48)	**<0.001**※	0.094	**0.004**※
M2	42.22 (10.20)	48.4 (13.76)	47.63 (19.78)	45.68 (10.58)	0.634	0.401	0.109
M3	44.91 (9.62)	45.40 (13.04)	32.97 (9.90)	37.95 (11.95)	**<0.001**※	0.165	0.255
M4	27.08 (9.61)	23.35 (11.49)	18.52 (9.18)	20.30 (10.08)	0.100	0.556	0.099
M5	14.50 (8.20)	10.50 (7.78)	6.48 (2.56)	8.61 (6.32)	**0.004**※	0.344	**0.003**※
MF	31.54 (20.77)	35.867 (17.04)	21.49 (18.28)	26.19 (9.00)	**0.044**※	**0.015**※	0.916
HM	50.06 (9.05)	59.03 (11.29)	59.06 (21.5)	57.01 (17.06)	0.321	0.150	**0.023**※
HL	47.51 (11.70)	44.18 (5.68)	46.66 (14.89)	44.13 (9.91)	0.837	0.144	0.84
$P_{P(\text{Peak pressure/Zavg} \times 100)}$							
T1	14.82 (10.00)	18.04 (12.22)	28.08 (19.18)	22.28 (7.78)	**0.007**※	0.534	**0.034**※
T2-5	4.29 (1.97)	3.23 (1.44)	5.33 (3.37)	4.17 (1.98)	0.095	**0.002**※	0.880
M1	11.57 (4.44)	16.80 (6.9)	27.83 (13.48)	21.18 (10.13)	**<0.001**※	0.643	**<0.001**※
M2	56.14 (18.02)	61.76 (22.91)	50.05 (16.19)	47.21 (9.71)	0.120	0.602	0.117
M3	58.59 (12.13)	61.32 (12.47)	44.96 (11.74)	44.64 (13.18)	**<0.001**※	0.570	0.473
M4	31.95 (9.02)	33.26 (14.85)	23.28 (8.47)	25.60 (15.50)	**0.005**※	0.407	0.817
M5	16.42 (5.94)	15.72 (8.03)	11.54 (8.43)	12.94 (7.59)	**0.035**※	0.777	0.397
MF	10.45 (6.05)	14.65 (8.67)	9.12 (3.96)	9.52 (2.81)	**0.029**※	**<0.001**※	**0.004**※
HM	37.97 (6.62)	45.74 (9.13)	40.49 (12.91)	36.97 (11.42)	0.214	0.210	**0.001**※
HL	39.77 (8.55)	39.70 (4.92)	37.29 (9.28)	33.35 (6.64)	**0.007**※	0.181	0.195
$\text{Impulse}_{(\text{Force time integral/Zavg} \times 100)}$							
T1	0.89 (0.75)	1.22 (1.04)	1.44 (1.12)	1.16 (0.46)	0.231	0.855	**0.044**※
T2-5	0.19 (0.09)	0.15 (0.09)	0.21 (0.17)	0.16 (0.09)	0.617	**0.022**※	0.877
M1	0.81 (0.34)	1.28 (0.65)	2.05 (1.11)	1.4 (0.9)	**0.001**※	0.500	**<0.001**※
M2	4.15 (1.45)	4.51 (1.41)	3.43 (0.79)	3.13 (0.68)	**<0.001**※	0.892	0.135
M3	4.76 (0.93)	5.11 (0.82)	3.23 (0.63)	3.24 (1)	**<0.001**※	0.224	0.243
M4	2.87 (0.92)	3.2 (1.33)	1.89 (0.64)	2.03 (1.05)	0.052	0.167	0.62
M5	1.13 (0.41)	1.15 (0.68)	0.76 (0.64)	1.01 (0.64)	0.074	0.188	0.27
MF	0.56 (0.27)	0.8 (0.47)	0.51 (0.17)	0.61 (0.24)	0.117	**<0.001**※	0.084
HM	2.05 (0.34)	2.38 (0.47)	2.6 (0.67)	2.37 (0.81)	0.082	0.556	**0.003**※
HL	2.07 (0.44)	2.1 (0.36)	2.29 (0.41)	2.07 (0.45)	0.300	0.237	0.145

Note: Statistical significance was set to $p < 0.05$. The bold represents significant differences.

3.1.2. Peak pressure (PP)

Significant group and fatigue effects were observed in PP analysis. The HV group displayed significantly higher PP in T1 ($P = 0.007$) and M1 ($P < 0.001$) (**Table 2**), while significantly lower in M3 ($P < 0.001$), M4 ($P = 0.005$), M5 ($P = 0.035$), MF ($P = 0.029$), and HL ($P = 0.007$). Fatigue substantially affected PP in T2-5 ($P = 0.002$) and MF ($P < 0.001$), with a 25% reduction in the control group and 22% in the HV group post-fatigue in T2-5, and a 40% increase in the control group versus a 4% increase in the HV group in MF. Significant interaction effects were found in T1 ($P = 0.034$), M1 ($P < 0.001$), MF ($P = 0.004$), and HM ($P = 0.001$). Post-hoc analysis revealed that (**Figure 1**), under the simple effect of fatigue, the HV group exhibited significantly higher PP than the control group in T1 and M1 post-fatigue (T1: $P = 0.005$, M1: $P < 0.001$), but significantly lower in MF and HM (MF: $P = 0.004$, HM: $P = 0.005$). Additionally, under the simple effect of group, the HV group showed a significant decrease in PP in M1 post-fatigue ($P = 0.002$), whereas the control group exhibited significant variations in PP pre- and post-fatigue in MF ($P < 0.001$) and HM ($P = 0.003$).

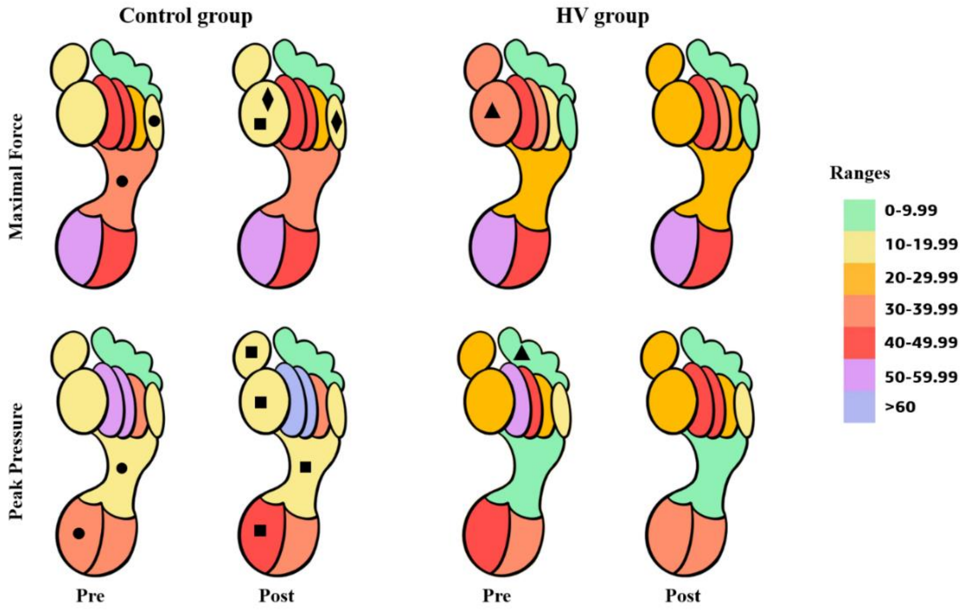

Figure 1. Plantar pressure distribution during walking Between Control Group and HV Group Pre- and Post-Fatigue. Significant post-hoc differences ($p < 0.025$) are indicated as follows: solid black diamond denotes significant differences between the Control group and the HV group in the pre-fatigue state; solid black square denotes significant differences between the Control group and the HV group in the post-fatigue state; within-group analysis shows a statistical difference pre- versus post-fatigue in the Control group (denotes by solid black circle) and in the HV group (denotes by solid black triangle).

3.1.3. Time integral of the force (impulse)

In the analysis of plantar impulse, significant group and fatigue effects were also observed, particularly in the M1 ($P = 0.001$), M2 ($P < 0.001$), and M3 ($P < 0.001$)

regions (**Table 2**). The HV group exhibited higher impulse values in the M1 region both pre- and post-fatigue compared to the control group, whereas impulse values were lower in the M2 and M3 regions.

Fatigue also influenced impulse distribution in the T2-5 ($P = 0.022$) and MF ($P < 0.001$) regions. Following fatigue intervention, both groups showed a decrease in impulse in the T2-5 region and an increase in the MF region.

Regarding interaction effects between group and fatigue, significant interactions were noted in T1 ($P = 0.044$), M1 ($P < 0.001$), and HM ($P = 0.003$) regions. Post-hoc testing revealed no significant differences in the T1 region. Under the simple effect of fatigue, a significant difference was observed between the HV and control groups in the M1 region pre-fatigue, with the HV group displaying considerably higher impulse. Additionally, pre-fatigue, the HV group had significantly higher impulse in the HM region ($P < 0.001$). Under the simple effect of group, a significant reduction in impulse was noted in the HV group in the M1 region post-fatigue ($P < 0.001$), whereas the control group showed an increase ($P = 0.021$). The control group also exhibited significant differences in impulse at the HM region pre- and post-fatigue ($P = 0.015$).

3.2. Force time-series

The results from SPM1d highlighted distinct force development patterns in different foot regions during the stance phase, comparing the HV group with the Control group, pre- and post-fatigue (**Figure 2**). A notable group effect was observed in the T1 region during 44%–93% of the stance phase ($P < 0.001$), where the FM of the HV group at the hallux pre-fatigue was significantly higher than that of the Control group. At T2, significant group effects were detected during 54%–60% ($P = 0.047$) and 66%–82% ($P < 0.001$) of the stance phase, with the HV group exhibiting higher peak forces and a delayed occurrence, and a significant fatigue effect at 61%–65% ($P = 0.038$) where forces declined post-fatigue in both groups.

In the metatarsal region, M1 showed significant group effects at 8%–30% and 50%–99.9% of the stance phase ($P < 0.001$). At 8%–30%, the HV group had a higher loading rate and peak force compared to the Control group. An interaction effect between group and fatigue was noted at 53%–57% ($P = 0.049$). In M2, a significant group effect was seen at 30%–53% of the stance, with the HV group’s forces being consistently lower than the Control group, and a significant fatigue effect at 69%–92% ($P = 0.032$), where peak forces increased post-fatigue. In M3, significant group effects spanned 7%–97% of the stance phase ($P < 0.001$), with the HV group consistently showing higher forces than the Control group both pre- and post-fatigue. In M4 (10%–59%) and M5 (23%–57%), the Control group displayed a typical pattern of passive and active peak forces during walking, whereas the HV group’s first peak was not pronounced and considerably lower.

Foot balance effectively mirrored the distribution of forces during the medial and lateral phases of foot contact. SPM results showed that, across 29%–99% of the gait cycle, the HV group concentrated forces more medially compared to the Control group ($P < 0.001$). Post-fatigue intervention, a significant increase in lateral foot loading in the HV group was noted at 26%–74% of the gait cycle ($P < 0.001$).

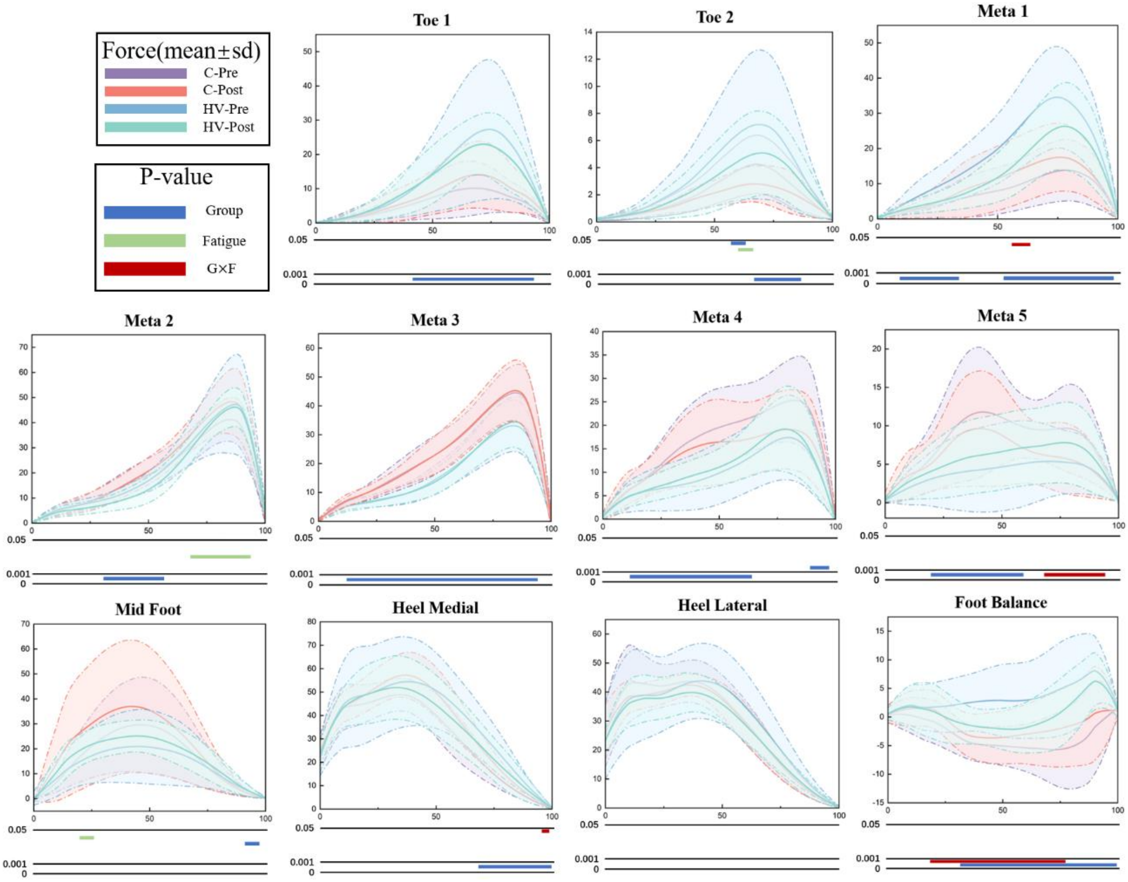

Figure 2. Results of SPM1d for normalized force time-series in 10 plantar regions for Control and HV groups pre- and post-fatigue.

3.3. Contact duration (CD) and contact area (CA)

3.3.1. CD

Significant group effects were observed in T2-5, M3, and HM regions. The Control group exhibited significantly higher CD than the HV group in the T2-5 and M3 regions, both pre- and post-fatigue ($P = 0.003$ and $P = 0.005$, respectively), while the HV group had a higher CD in the HM region ($P = 0.05$).

Significant fatigue effects were noted in the M1, M2, M3, and M4 regions. Specifically, post-fatigue, the Control group showed an increase in CD in the M1 and M4 regions, while the HV group showed a decrease ($P = 0.028$ and $P = 0.013$, respectively). In the M2 and M4 regions, CD increased post-fatigue in both groups ($P < 0.001$ and $P = 0.004$, respectively).

Interactions between group and fatigue were also found in M1 and M4 regions ($P = 0.003$ and $P = 0.006$, respectively). Post-hoc comparisons revealed that post-fatigue, the HV group's CD in M4 was significantly lower than that of the Control group ($P = 0.013$). For the group effect, the Control group exhibited a significant increase in CD in the M1 region post-fatigue ($P < 0.001$), whereas the HV group showed a decline ($P = 0.523$). The Control group showed a significant change in CD at M4 pre- and post-fatigue, with an increase post-fatigue.

3.3.2. CA

When examining the contact area of the plantar surface, significant group effects were found in T2-5, M1, M3, HM, and HL regions. Specifically, the Control group general-ly had a smaller CA than the HV group in these regions (**Table 3**): T2-5 ($P <$ 0.001), M1 ($P < 0.001$), M3 ($P = 0.003$), HM ($P < 0.001$), and HL ($P < 0.001$). Post-fatigue, an increase in CA was observed in the MF region, which was significant ($P <$ 0.001).

Significant interactions were noted in T1 and HL regions ($P = 0.008$ and $P =$ 0.021, re-spectively) (**Table 3**). Post-hoc analyses showed that post-fatigue, the HV group's CA in the T1 region was significantly higher than the Control group ($P =$ 0.009). In the HL region, sig-nificant differences between the HV and Control groups were found both pre- and post-fatigue, with the HV group consistently having higher CA ($P < 0.001$, $P < 0.001$). How-ever, no significant differences were found in the group effect upon post-hoc analysis.

Table 3. Contact duration (CD) and contact area (CA) between control group and HV group pre- and post-fatigue.

	Control-group		**HV-group**		**RANOVA**		
	Pre-fatigue	**Post-fatigue**	**Pre-fatigue**	**Post-fatigue**	**Group**	**Fatigue**	**G×F**
CD							
T1	55.95 (18.62)	64.77 (18.91)	63.07 (16.7)	61.41 (15.97)	0.630	0.269	0.108
T2-5	44.95 (9.18)	45.09 (8.54)	37.78 (13.57)	37.63 (11.56)	**0.003**※	0.948	0.998
M1	71.45 (7.95)	79.36 (3.32)	74.74 (8.73)	73.48 (12.71)	0.550	**0.028**※	**0.003**※
M2	82.95 (2.57)	84.95 (1.76)	82.26 (2.78)	83.52 (2.42)	0.740	**<0.001**※	0.345
M3	84.91 (1.07)	86.59 (2.67)	83.89 (2.46)	84.59 (2.33)	**0.005**※	**0.004**※	0.217
M4	81.27 (3.34)	84.27 (5.29)	81 (2.92)	80.85 (4.02)	0.069	**0.013**※	**0.006**※
M5	70.86 (6.85)	72.95 (11.03)	69.74 (8.47)	69.93 (9.58)	0.372	0.364	0.446
MF	51.23 (5.94)	51.05 (7.65)	51.59 (6.25)	53.04 (7.52)	0.447	0.615	0.517
HM	48.14 (7.82)	46.59 (6.49)	53.44 (6.80)	51.85 (6)	**0.05**※	0.052	0.976
HL	47.5 (7.34)	46.05 (6.06)	52 (6.33)	50.22 (5.56)	0.100	0.059	0.847
CA							
T1	12.77 (2.94)	13.31 (2.42)	13.87 (2.26)	14.95 (1.94)	0.100	0.065	**0.008**※
T2-5	12.32 (4.23)	11.4 (3.02)	16.3 (3.56)	15.19 (4.9)	**<0.001**※	0.109	0.880
M1	10.76 (2.24)	11.12 (3.03)	13.96 (2.12)	13.67 (1.91)	**<0.001**※	0.929	0.377
M2	10.81 (1.76)	11.1 (1.9)	12.16 (1.43)	12.09 (1.3)	**0.003**※	0.666	0.474
M3	9.75 (1.13)	9.88 (1.39)	10.19 (1.19)	10.36 (1.12)	0.104	0.443	0.924
M4	9.85 (1.42)	9.67 (1.28)	9.56 (1.23)	9.88 (1.44)	0.906	0.756	0.263
M5	7.07 (2.03)	7.06 (2.61)	7.27 (1.53)	7.05 (1.23)	0.820	0.698	0.742
MF	29.9 (7.64)	31.46 (8.74)	29.42 (5.66)	32.97 (3.92)	0.772	**<0.001**※	0.140
HM	15.84 (0.59)	15.71 (0.89)	17.81 (1.51)	18.36 (1.6)	**<0.001**※	0.312	0.113
HL	14.16 (0.7)	13.75 (0.94)	15.37 (1.37)	15.92 (1.46)	**<0.001**※	0.736	**0.021**※

Note: Statistical significance was set to $p < 0.05$. The bold represents significant differences.

4. Discussion

In this study, we focused on investigating the changes in plantar pressure distribution in women with mild HV before and after fatigue intervention, when compared with that of the healthy counterpart. While this study specifically addresses the biomechanical impacts of induced fatigue on plantar pressure distribution in females with mild HV, it is worth noting the condition’s higher prevalence among women compared to men. This gender disparity justifies the female-focused approach of our research; however, incorporating a comparative analysis with male subjects in future studies could offer valuable insights. In line with our initial hypothesis, we observed that individuals with mild HV showed distinct adaptive shifts in plantar pressure distribution compared to healthy participants. Specifically, there was a notable decrease in FM, PP, and impulse in M1 and M2 regions, coupled with an increase in these parameters in the third to fifth metatarsal (M3-M5) regions. On the contrary, the control group displayed a contrasting tendency, with an increased concentration of pressure in the M1 and M2 regions following fatigue and a decrease in M3-M5.

Consistent with previous research [12,26], compared to the healthy participants, the mild HV population showed increased pressure in the hallux and first metatarsal regions and decreased pressure in the remaining metatarsal regions. Meanwhile, SPM results indicated that (**Figure 2**), unlike the healthy group, which exhibited two distinct peak forces in the lateral metatarsal region (M4 and M5)—representative of typical pressure characteristics during the gait cycle (passive and active peaks)—HV patients displayed a more uniform pressure curve lacking a distinct first peak. This difference may be attributed to structural changes in HV feet, leading to decreased transverse arch and stability [27,28]. Such structural changes can lead to uneven force transmission and distribution, particularly concentrated in the T1 and M1 regions, potentially exacerbating the degree of HV. However, as this disease progresses, increase in valgus angle or the onset of pain, there might be adaptive changes in plantar pressure patterns, as indicated by previous studies showing reduced pressure in the T1 and M1 regions and increased pressure in the lateral metatarsal region [7]. Wen [7] suggests that this adaptation likely involves a pain avoidance mechanism, functioning to diminish discomfort in the foot. Therefore, strict categorization is essential in analyzing plantar pressure in HV patients.

We observed that the T2-5 and MF regions were particularly sensitive to fatigue (**Table 2**). Upon fatigue induction, FM, PP, and impulse in these areas significantly decreased, aligning with prior studies [29]. However, unlike previous research, our study noted changes in pressure post-fatigue in the hallux and metatarsal regions, possibly due to different methods of fatigue induction and structural differences in the feet.

In analyzing the interactions, we noted distinct adaptive mechanisms to fatigue between the HV and healthy groups due to structural differences in their feet. These differences were not only evident in changes in FM, PP, and Impulse but also in the dynamic variations of CD and CA (**Table 3**). Specifically, once the fatigue was induced, HV patients showed a decrease in these parameters in the T1, M1, and M2 regions, while the control group exhibited an increase (**Table 2**). Additionally, in the lateral foot regions (M4, M5), the HV group showed an increase in FM, PP, and impulse during post-fatigue, while the control group showed a decrease. These findings further demonstrating significant differences in fatigue management mechanisms between the groups, with the HV group redistributes pressure to alleviate stress on vulnerable areas, while the control group leverages the foot’s structural strengths to maintain stability.

Due to its unique structure, the medial foot joints in HV patients bear excessive pressure during prolonged walking or standing. This persistent overload, especially under fatigue situation, might weak the foot arch's ability to distribute pressure, possibly explaining the frequent occurrence of arch collapse in HV patients [30]. As an adaptive adjustment, the load during walking might shift more towards the lateral side of the foot, as indicated by the Foot balance graph, particularly during 26%–74% (**Figure 2**) of the gait cycle, to alleviate pressure in the medial fatigued regions. This load transfer can be seen as a biomechanical self-protection mechanism to lessen the impact of fatigue on foot structure. In contrast, normal feet, due to the integrity of the arch structure and function, can more effectively disperse the pressures generated during walking, thus avoiding overloading in any specific area. This balanced pressure distribution helps maintain the stability and functionality of the foot, especially during extended periods of walking or standing.

The findings from this study significantly enhance our understanding of the biomechanical adaptations in plantar pressure distribution due to fatigue in females with mild HV. By observing shifts from higher pressure in the medial metatarsal regions to increased pressures in the lateral metatarsal areas, we can infer a potential biomechanical compensation mechanism aimed at minimizing pain and discomfort in the affected regions. Clinically, these insights could guide the development of targeted therapeutic strategies, such as customized orthotic supports designed to redistribute plantar loads and alleviate stress on critical areas during fatigue. While this study represents an initial exploration of the biomechanical mechanisms of fatigue on plantar load of women with mild HV, it is important to acknowledge its inherent limitations. Firstly, the fatigue induction in this study was conducted on a treadmill, which might differ from fatigue-induced plantar pressure changes in real-world environments. Moreover, this study solely collected plantar pressure data, with future research planning to incorporate kinematic and kinetic parameters for a more comprehensive insight into the foot function and movement patterns of HV patients under fatigue. Lastly, the small sample size of this study may limit the generalizability of these findings, and further studies with larger sample sizes are warranted for additional verification [29,30].

5. Conclusion

This study revealed that women with mild HV exhibit distinct adaptive changes in plantar pressure following fatigue, compared to healthy individuals. Notably, post-fatigue pressure in HV patients tends to shift towards the lateral aspect of the foot, with significant reductions in maximum force, peak pressure, and impulse in the M1 and M2 areas, whereas increases are observed in the M3-M5 areas. While the control group exhibits an opposite pattern, the pressure is concentrated in the M1 and M2 areas, with decreases in maximum force, peak pressure, and impulse observed in the M3-M5 areas. This shift likely represents a biomechanical adaptation due to altered foot structure, aimed at preventing over-fatigue in certain foot regions. The results can guide the development of targeted treatment strategies, such as clinically customized orthotic supports, or designing specialized footwear for patients with mild HV to redistribute plantar loads and alleviate pressure on key areas during fatigue.

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Ethics approval: Written informed consent was obtained from each participant after familiarization with the testing requirements and procedures. This study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of Research Academy of Grand Health at Ningbo University (RAGH2023071701211.8).

Conflict of interest: The authors declare no conflict of interest.

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