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ORIGINAL ARTICLE

Body Mass and Foot-dominance Disparities in the Foot Plantar Pressure Parameters of Older Women

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Objectives: To examine the effects of foot dominance and body mass on foot plantar pressures in older women of regular, overweight, and obese weights.

Methods: 96 female adults were divided into regular-weight group (68.30 ± 4.19 yr), overweight group (69.88 ± 3.76 yr), and obesity group (68.47 ± 3.67 yr) based on their body mass index scores. Footscan® plantar pressure test system was used to assess the dynamic plantar pressures, and parameters were collected from risk analysis, foot axis analysis, single foot timing

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analysis, and pressure analysis.

Results: (1) The local risks of lateral forefoot and midfoot, the minimum and maximum subtalar joint angles, the flexibility of subtalar joint, foot flat phase, as well as the average pressures on toes, metatarsals,, midfoot, and lateral heel, with the peak pressures on toe 2-5, metatarsal 2, metatarsal 5, midfoot, and lateral heel had significant within-subject differences. (2) The phases of initial contact and foot flat, the average pressures on toe 2-5, metatarsals, midfoot, and heels, with the peak pressures on metatarsal 1-4, midfoot, and heels exhibited significant between-subjects differences. (3) There was an interaction effect of foot dominance and body mass index on the flexibility of subtalar joint.

Conclusions: The non-dominant foot works better for stability, especially when touching on and off the ground. The dominant foot works better for propulsion but is more susceptible to pain, injury, and falls. For obese older women, the forefoot and midfoot are primarily responsible for maintaining stability, but the lateral midfoot and hindfoot are more prone to pain and discomfort.

Keywords: foot plantar pressure; foot dominance; overweight and obesity; older women

1. Introduction

Globally, the aging of population is one of the most important medical and socio-demographic problems. According to the *Decade of Healthy Aging: Baseline Report* released by Word Health Organization (WHO)[1], the worldwide population aged 60 years and over (older adults) surpassed over 1 billion people in 2020, representing 13.5% of the world's population of 7.8 billion. *The Decade of Healthy Aging 2021-2030*[2] was initiated in an effort to improve the health and well-being of an increasing number of older adults. China, the developing country with the largest population of older people in the world[3] and where more than 50% of older people are overweight or obese[4], is sharing the complex challenges faced by other nations and has thus also unveiled some crucial strategies, such as *Healthy China 2030* and *Responding Proactively to Population Aging*. Extending the healthy lifespan of older adults is one of the primary objectives of the implementation of these measures. However, accidents pose a threat to the health and longevity of older adults. The fall is the leading cause of accidents among older adults in China[5] and the greatest number of fatal falls occur among older adults[6]. Moreover, older adults who are overweight or obese are more likely to experience falls due to their substantial body weight, significant lower extremity load, poor stability, and limited flexibility[7]. Therefore, overweight, obesity, and falls, listed as major concerns in public health contemporarily, are negatively affecting the enjoyment of better health and well-being.

The key to healthy aging is optimizing functional capabilities to ensure the well-being of older adults[2]. Regarding mobility and intrinsic capacity, older women demonstrated less functional capacity than their male peers[8,9]. Mobility is one of the important functional abilities highly associated with mortality risk in older adults[10]. Mobility impairment is often measured by walking. Some studies indicate that older women were less able to walk long distances or up stairs than older men[11]. The walking speed decreased with age substantially more rapidly than that of men[12]. The intrinsic capacity refers to all the physical and mental capacities that contribute to functional ability and includes sophisticated duties and leisure activities[2]. A Brazilian Longitudinal Study of Aging revealed that older women tend to have lower intrinsic capacities[13,14]. Begin with the disparity between life and healthy life expectancy at birth and at age 60 grew faster for women than that for men, indicating that older women survive longer with disease than older men, which was noted in the WHO global estimates between 2000 and 2019[15]. Being overweight and obesity is more dangerous for older women than for older men[16]. Consequently, the health issues of older women merit extra consideration for healthy aging.

Examining the distribution patterns of plantar pressures in older adults during walking is important when assessing the physiologic function of the foot, its clinical diagnosis and rehabilitation[17,18]. The distribution of plantar pressure between the foot and support surface provides quantitative information which aids in diagnosing foot problems at an early stage period. This information may be used in injury prevention, risk assessment, and general well-being[19]. Walking is a fundamental functional ability in daily life. During the gait cycle, the ground reactive force is experienced by both feet directly and independently. The feet support the body's musculoskeletal system while providing shock absorption, generating propulsive force and maintaining stability. Changes in plantar pressures as a result of aging are associated with pain and functional changes[20,21].

Previous studies have found that increased plantar pressure is associated with a higher risk of foot aches, injury, and falls among older adults[20-22]. It has been shown that older adults with greater body mass had higher plantar pressures than those of normal weight[23]. Limb dominance could influence the symmetrical behavior of the lower extremities which has a direct affect on the stabilizing influence of each extremity during activities[24]. Among older adults, female gender and obesity emerge as prominent risk factors strongly associated with foot pain. Furthermore, older female adults are significantly more likely to report foot pain compared to older male adults[25]. Foot dominance has also been found to be a solid predictor of right-left asymmetry during ambulation[26,27], and it has been emphasized in studies concerning fall risk[28,29] and posture control in dynamic balance[30,31]. Despite the fact that plantar pressure is regarded as an effective variable for understanding foot problems and fall injuries among older adults, there have been few studies on the effect of the dominant side on plantar pressure among older adults, with the majority of research focusing on young adults[32-34].

Given the apparent gaps in the aforementioned literature, the goal of this study was to examine the effects of foot dominance and body mass on plantar pressures in older women with a normal, overweight, or obese body mass index and its place in functional ability assessment, fall prevention, clinical diagnosis, and biomechanics studies[35,36]. Analyzing the distribution characteristics of plantar pressures among older women with variant body weight and foot dominance could provide significant data and help provide insight into healthy aging whole retaining functional abilities.

2. Methodology

2.1. Participants

In order to minimize the potential impact of each conditions (such as gender, age and the ability of walking independently, etc.) on the relationship between body mass and plantar pressure parameters, this study recruited older adults from three communities in the Haidian

District of Beijing who met the following 5 criteria: (1) female gender; (2) age between 60 and 74 years; (3) body mass index (BMI) greater than 18.5 kg/m^2; (4) a score of 6 or higher on the *Lawton Instrumental Activities of Daily Living (IADL) Scale*[37], indicating clear consciousness, independent walking without the use of aids; (5) no lower extremity joint surgery, no significant bone and joint diseases, and no heart diseases within the past 2 years, which is the average time for individuals to return to sport after surgery or recovery[38,39]. The three communities selected had well-constructed household registration system and two volunteer community employees to assist with recruiting in this study.

Based on the suggested sampling proportion of 20%[40] including the attrition rate of 5%, the sample size was 103 which resulted in the recruitment of 110 females from the pool of 514 female residents aged 60 to 74. Twelve participants who did not meet the selection criteria were removed resulting in a total of 98 females to be included in the testing sample. All participants were required to sign an informed consent and complete a battery of tests. Based on the BMI classification standard from the General Administration of Sport of China[4], the older adults were divided into 3 groups (Table 1). Two people in the OB group were not included in the analytical sample because they didn't complete all the tests. Finally, 28, 30, and 38 people, respectively, were enrolled in the 3 groups, respectively. Figure 1 provides supplementary information.

Table 1 Grouping form based on the BMI classification standard

BMI classification standard	Groups
BMI ≥ 28.0 kg/m^2	obese group (OB group)
24.0 ≤ BMI < 28.0 kg/m^2	overweight (OW group)
18.5 ≤ BMI < 24.0 kg/m^2	regular weight group (RW group)

Note: The BMI classification standard is from the General Administration of Sport of China[4]

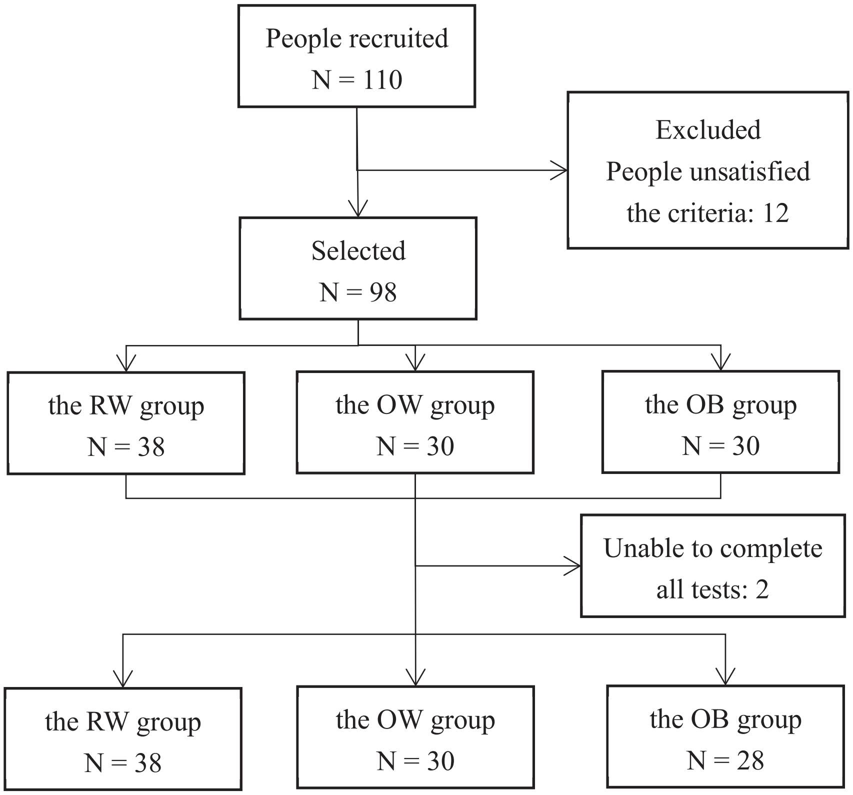


Fig 1. Flowchart explaining assignment of the participants to 3 groups.

2.2. Test Time and Place

This study was conducted at the Innovation Laboratory of the Integration of Sport and Medicine in Peking University from Sep 25th to Oct 12th 2022. To maintain the best performance of the test instruments, especially the accuracy of the data collection by Footscan® pressure measurement system, the temperature and humidity in the lab should meet the machine requirements (operating temperature range of 15°C to 30°C, humidity range of 20% to 80%). Throughout the whole test stage, the average temperature was 21.2°C and the average humidity was 38.5%.

2.3. Instrument and Measures

2.3.1. Measures of Basic Characteristics of Participants

The main parameters of basic characteristics were the age (years), shoe size (EU), height (m), body compositions, and instrumental activity of daily living (IADL) of all participants.

Body compositions: they were tested by In-body 270 which was manufactured by Korea In-body Co. Ltd. (Seoul, Republic of Korea). Standardized, self-serving, national body composition parameters can be detected by means of bio-resistance. In this study, weight (kg), body mass index (kg/m^2), muscle mass of lower extremities (kg), and body fat (%) were the requested parameters.

IADL: it was tested by Lawton Instrumental Activity of Daily Living[37]. It is widely used in the assessment of a person's ability to perform independent living skills including using a telephone, shopping, preparing food, housekeeping, doing laundry, using transportation, handling medications, and handling finances[37,41,42]. The assessment score is range from 0 (low functioning) to 8 (high functioning), with a higher score indicating a better ability to live independently.

First foot when walking: There were two methods employed to determine the dominant limb. In the first method, muscle mass of the individual limbs was analyzed by In-body 270. The side with more muscle mass is considered the dominant side, while the other side is considered the non-dominant side. In the second method, the side on which the participant took the initial step while walking naturally was considered the dominant foot, while the opposite side was considered the non-dominant foot. The Limb with increased muscle mass was considered the dominant limb unless the values of muscle mass on both sides were identical, the second method was the alternation.

2.3.2. Measure of Foot Plantar Pressure

The plantar pressure of each foot was tested by the Footscan® pressure measurement system version 9 (RS Scan Company, Paal, Belgium). This system could perform state-of-the-art dynamic plantar pressure recording and analysis with a 1.5 m entry level plate (length × width × height: 1.61 × 0.47 × 0.02 m, weight: 24 kg, number of sensors: 12288, arranged in a 192 × 64 matrix, sensor dimensions: 0.00762 m × 0.00508 m, active sensor area: 1.46 m × 0.33 m, pressure range: 10000-1270000 Pa, sata acquisition frequency: 200 Hz, resolution: 10 bits) and the Footscan® software (version: 9) for general, clinical, scientific and industrial use.

The 1.5 m entry level plate measures plantar pressures of both feet using an X-Y matrix of resistive pressure sensitive sensors that are scanned sequentially. The Footscan® software registers pressure data when the participant walks over the plate and processes the data to provide the normalized foot plantar pressure analysis of the complete gait cycle because those sensors in the plate could capture the pressure and force under the participant's feet over the full duration of a step from initial contact until the end of the foot roll-off (See Fig 2A). The Footscan® software recognizes left and right feet automatically when recording the dynamic measurement. Its reliability and repeatability have been well validated previously[43,44].

Test requirements: The 1.5 m entry level plate should be plated on the floor and connected to the computer. All participants should remove their shoes and socks. Due to shod conditions that could lead to the attenuation on plantar pressure parameters, barefoot assessments were performed to obtain more accurate results from plantar pressure measurements[45,46]. After a two-time practices to acclimate to the plate, participant was instructed to walk across the plate six times in the natural gait pattern and the average of the six trails was recorded.

Observed parameters:

During feet detection, the location of 10 anatomical zones could be determined, including the heel, middle foot, 5 metatarsal bones, and 5 toes. As shown in Fig 2B, all the partitions are as follows: toe 1 (T1), toe 2 to toe 5 (T2-5), metatarsal 1 (M1), metatarsal 2 (M2) and metatarsal 3 (M3), metatarsal 4 (M4), metatarsal 5 (M5), midfoot (MF), medial heel (MH), and lateral heel (LH). All analyses need these zones to compute parameters, including the risk analysis, foot axis analysis, single foot timing analysis, and pressure analysis of both feet.

Risk analysis: the risk analysis gives local risks of both feet, which are predictive percentage values calculated based on the footscan risk analysis algorithm by using the D3D design wizards with a dynamic measurement method given per foot zone[47]. The foot zone risks of (1) medial forefoot, (2) lateral forefoot, (3) medial midfoot, and (4) hindfoot were calculated.

Foot axis analysis: the foot axis analysis gives the roll-offs of both feet based on the 2D analysis. (1) The foot axis exorotation in degrees, (2) the minimum subtalar joint angle in degrees, (3) the maximum subtalar joint angle in degrees, and (4) the flexibility of subtalar joint in degrees were calculated. In Fig 2B, the long pink line shows the foot axis connecting the middle of MH and LH with the middle of M2 and M3; the brown lines show the minimum and maximum subtalar joint angle.

Single foot timing analysis: The single foot timing analysis records the different phases during a foot roll off for both feet. The phases are displayed as a percentage of seconds. The following phases are shown: Initial Contact Phase (ICP), Forefoot Contact Phase (FCP), Foot Flat Phase (FFP), and Forefoot Push Off Phase (FPOP). Every phase was calculated on the basis of the following 5 events (5 distinct instants): Initial Foot Contact (IFC), Initial Metatarsal Contact (IMC), Initial Forefoot Contact (IFFC), Heel Off (HO), and Last Foot Contact (LFC). Thus, the relations of 5 events and 4 phases are ICP = IMC - IFC, FCP = IFFC - IMC, FFP = HO - IFFC, FPOP = LFC - HO (Fig 2C).

Plantar pressure analysis: The plantar pressure analysis displays the pressure applied to ten user-defined rectangular areas of both feet. (1) average pressure (Pa), and (2) peak pressure (Pa) in 10 plantar pressure zones of both feet were calculated.

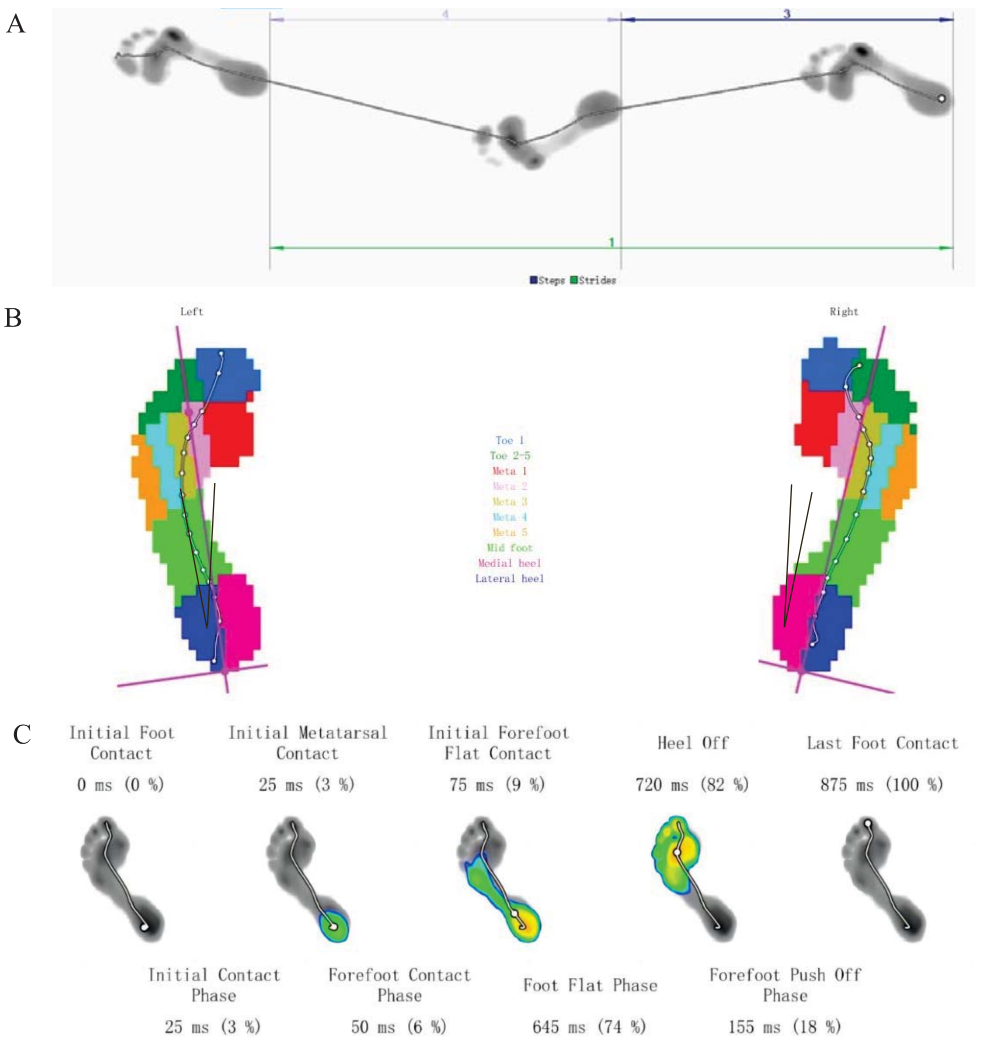


Fig 2. A: One gait cycle; B: Foot axis angle and anatomical zones; C: The phases of single foot timing

2.4. Statistical Analysis

In this study, Microsoft Office version 2020 was used for data input and cleaning. Statistical

Package for Social Sciences (SPSS) version 26.0 (American IBM, Chicago, IL. USA) was used for data analysis. The statistical analysis includes 3 sections.

Initially, the normal distribution test was performed. Kolmogorov-Smirnov test (K-S test) was used as the judgment method to test the normal distribution of the data. If the data was not normally distributed, logarithmic transformation was performed. The formula is as follows: (1) $Z_{\chi_i} = \log_{10}(\chi_i)$ ($i = 1, 2, \ldots, p$) or (2) $Z_{\chi_i} = \log_{10}(\chi_i + 1)$ ($i = 1, 2, \ldots, p$)

where Z_{χ_i} is the transformed value, χ_i is the original value. If $\chi_i \neq 0$, formula (1) was selected; if $\chi_i = 0$, formula (2) was selected.

Second, then the descriptive statistical analysis was applied. If the data was normally distributed, the data was described as the means and standard deviation (M ± SD); if not, the data was described as medium and interquartile ranges, that is Md (P_{25}, P_{75}).

Finally, the Mixed-design Factorial ANOVA was conducted in data analysis. In this study, the independent variables were a within-subject factor (foot dominance) and between-subjects factor (BMI), and the dependent variables were plantar pressure parameters. Mauchly's Test of Sphericity was performed. If the significance (P) of the approximate chi-square value was > 0.05, the spherical hypothesis was satisfied. If not, the Greenhouse & Geisser or Huynh-Feldt methods can be used for correction. In the case of multiple comparisons, the Scheffe test or the Games-Howell test, which are commonly used and relatively free, were used for post-hoc comparison due to the inconsistency of sample sizes in each group. The confidence interval (CI) was 95%, $p < 0.05$ was considered a significant difference, and $P < 0.01$ was considered a very significant difference.

3. Results

3.1. Descriptive Statistics

A total of 96 female older women completed all tests, with 38 in the RW group, 30 in the OW group, and 28 in the OB group. Table 2 shows the basic descriptive information and the comparison results between the 3 groups. Except for weight, BMI, body fat, and muscle mass, which were the parameters related to the basis of grouping, other parameters of the 3 groups had no significant differences ($p > 0.05$) (Table 2).

Table 2 Basic characteristics of participants (N = 96)

Group	N	Year (yr)	Shoe Size (EU)	Height (m)	Weight (kg)	BMI (kg/m^2)	Body Fat (%)	IADL	Muscle mass (kg)	
									D	ND
RW group	38	68.30 ± 4.19	37.88 ± 1.40	1.58 ± 0.05	52.89 ± 6.06	21.10 ± 1.78	0.35 ± 0.03	7.00 (8.00, 8.00)	6.05 ± 0.61	5.92 ± 0.59
OW group	30	69.88 ± 3.76	38.04 ± 1.82	1.57 ± 0.08	61.37 ± 7.04	24.94 ± 1.24	0.38 ± 0.05	8.00 (8.00, 8.00)	6.67 ± 0.66	6.44 ± 0.60
OB group	28	68.47 ± 3.67	38.46 ± 1.48	1.58 ± 0.04	74.97 ± 7.81	30.34 ± 2.83	0.44 ± 0.04	7.00 (8.00, 8.00)	7.20 ± 0.63	7.07 ± 0.63
F		1.462	1.096	0.493	79.403**	163.239**	23.565**	1.393	15.564**	16.953**
P		0.237	0.339	0.613	0.000	0.000	0.000	0.257	0.000	0.000

** $p < 0.01$, compared basic variables between 3 groups
Abbreviations: BMI = body mass index, D = Dominant, ND = Non-Dominant, IADL = Instrumental activity of daily living, OB group = obesity group, OW group = overweight group, RW group = regular weight group.

3.2. Foot Plantar Pressure

3.2.1. Local Risk

Table 3 shows the comparison results of local risk percentage between the RW group, OW group, and OB group. It was shown by the tests of within-subject effects that the local risks of lateral forefoot and midfoot had significant within-subject differences, which means that the local risks of lateral forefoot and midfoot in the dominant side are significantly higher than those in the non-dominant side ($p < 0.05$, $p < 0.01$). There was no interaction effect of foot dominance and BMI on the local risks of medial forefoot, lateral forefoot, midfoot, and hindfoot ($p > 0.05$). It was shown by the tests of between-subjects effects that the local risks of medial forefoot, lateral forefoot, midfoot and hindfoot had no significant between-subjects differences ($p > 0.05$).

Table 3 Comparison of local risk percentage between 3 groups (N = 96)

Local risk (%)	FD	RW group	OW group	OB group	F_{FD}	P_{FD}	F_{FD*BMI}	P_{FD*BMI}	F_{BMI}	P_{BMI}	Post-hoc
Medial forefoot	D	80.20 ± 12.52	77.57 ± 13.38	76.33 ± 11.15	0.136	0.713	1.272	0.285	0.692	0.503	n.s.
	ND	80.15 ± 13.28	82.32 ± 13.04	77.39 ± 15.97							
Lateral forefoot	D	76.16 ± 12.16	78.82 ± 13.09	79.86 ± 10.80	4.161 *	0.045	1.271	0.286	0.661	0.519	n.s.
	ND	76.19 ± 12.85	74.21 ± 12.91	78.84 ± 15.48							
Midfoot	D	80.04 ± 8.44	77.41 ± 6.12	79.19 ± 8.26	8.185 **	0.005	2.095	0.129	0.103	0.902	n.s.
	ND	78.57 ± 9.01	79.78 ± 7.01	78.01 ± 10.10							
Hindfoot	D	83.54 ± 8.40	81.38 ± 5.71	80.63 ± 8.80	3.089	0.082	0.484	0.618	1.985	0.144	n.s.
	ND	84.83 ± 6.33	82.70 ± 6.06	81.68 ± 6.84							

* $p < 0.05$, ** $p < 0.01$, compared local risk between dominant and non-dominant foot

Abbreviations: BMI = body mass index, D = Dominant, FD = foot dominance, ND = Non-Dominant, OB group = obesity group, OW group = overweight group, RW group = regular weight group.

3.2.2. Foot Axis Parameters

Table 4 shows the comparison results of foot axis between the RW group, OW group and OB group. It was shown by the tests of within-subject effects that the foot axis exorotation, the flexibility of subtalar joint, the minimum and maximum subtalar joint angles had significant within-subject differences, which means that all variables in dominant side are significantly higher than those in non-dominant side ($p < 0.01$, $p < 0.05$). There was an interaction effect of foot dominance and BMI on the flexibility of subtalar joint ($p < 0.05$). From the results of the tests of between-subjects effects, all variables had no significant between-subjects differences ($p > 0.05$).

Table 4 Comparison of foot axis between 3 groups (N = 96)

Foot axis (°)	FD	RW group	OW group	OB group	F_{FD}	P_{FD}	F_{FD*BMI}	P_{FD*BMI}	F_{BMI}	P_{BMI}	Post-hoc
ExR	D	11.79 ± 6.87	9.88 ± 5.19	12.76 ± 7.70	19.162**	0.000	3.023	0.054	0.495	0.611	n.s.
	ND	10.53 ± 5.81	13.48 ± 9.27	12.44 ± 5.73							
MaxSJA	D	7.69 ± 5.40	5.46 ± 5.97	6.28 ± 5.62	35.306 **	0.000	2.183	0.119	1.351	0.264	n.s.
	ND	7.00 ± 5.41	7.79 ± 5.70	4.60 ± 5.40							
MinSJA	D	-6.08 ± 3.41	-7.07 ± 4.17	-7.80 ± 5.77	38.955**	0.000	0.670	0.514	1.362	0.262	n.s.
	ND	-6.06 ± 4.43	-7.57 ± 3.82	-6.80 ± 3.51							
SJF	D	8.25 (13.00, 19.00)	7.25 (11.50, 18.00)	8.00 (13.00, 18.00)	5.893*	0.017	3.175▲	0.047	0.375	0.689	n.s.
	ND	8.00 (12.50, 15.75)	11.00 (13.50, 16.75)	7.00 (11.00, 13.00)							

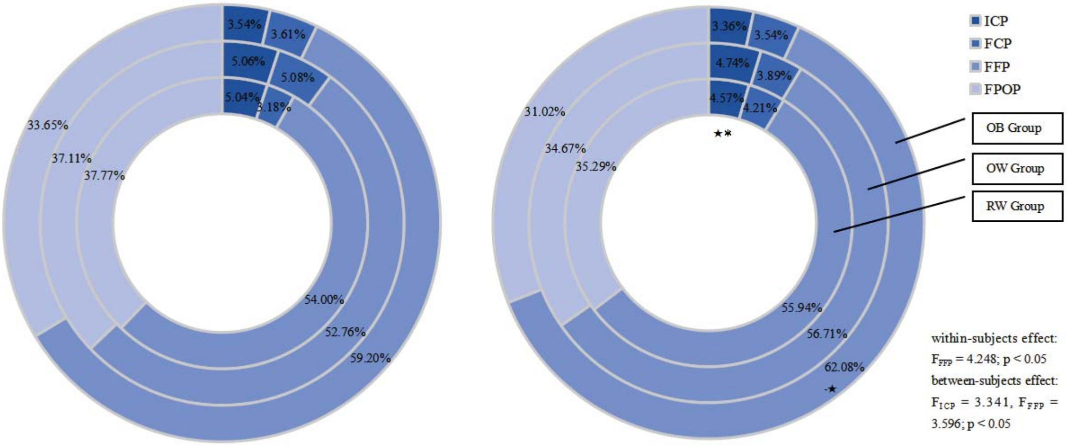
* $p < 0.05$, ** $p < 0.01$, compared foot axis between dominant and non-dominant foot; ▲ $p < 0.05$, significant interaction effect

Abbreviations: BMI = body mass index, D = Dominant, ExR = Exorotation, FD = foot dominance, MaxSJA = Maximum subtalar joint angle, MinSJA = Minimum subtalar joint angle, ND = Non-Dominant, OB group = obesity group, OW group = overweight group, RW group = regular weight group, SJF = flexibility of subtalar joint.

3.2.3. Single Foot Timing

Figure 3 shows the comparison results of single foot timing percentage between the RW group, OW group and OB group. It was shown by the tests of within-subject effects that the phase of FFP had significant within-subject differences, which means that the phase of FFP in the non-dominant side was significantly longer than it in the dominant side ($p < 0.05$). There was no interaction effect of foot dominance and BMI on all of the phases ($p < 0.05$).

From the results of the tests of between-subjects effects, the phases of ICP and FFP had significant between-subjects differences ($p < 0.05$), respectively. After the post-hoc test, it was found that the phase of ICP in the RW and OW groups were both longer than those in the OB group ($p < 0.05$); the phase of FFP in the OB group was longer than it in the RW group ($p < 0.05$).



★: Single Foot Timing in OB group was significantly shorter than RW group; *: Single Foot Timing in OB group was significantly shorter than OW group; -★: Single Foot Timing in OB group was significantly longer than RW group.

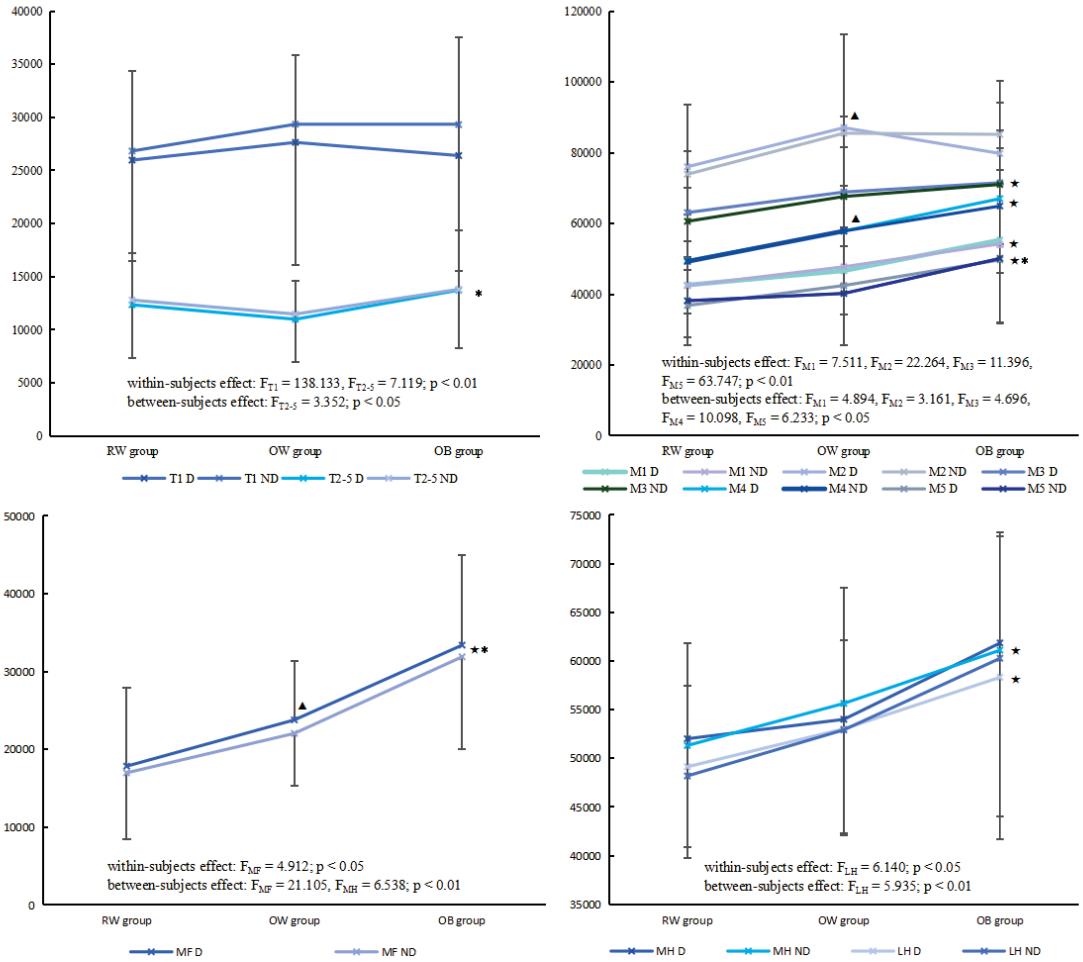
Abbreviations: D = Dominant, FCP = forefoot contact phase, FFP = foot flat phase, FPOP = forefoot push-off phase, ICP = initial contact phase, ND = Non-Dominant, OB group = obesity group, OW group = overweight group, RW group = regular weight group.

Fig 3 Comparison of single foot timing between 3 groups (N = 96)

3.2.4. Average Pressure and Peak Pressure Parameters

Figure 4 shows the comparison results of average pressure between the RW group, OW group and OB group. It was shown by the tests of within-subject effects that the average pressures on T1, T2-5, M1, M2, M3, M5, MF, and LH had significant within-subject differences ($p < 0.01$, $p < 0.05$). There was no interaction effect of foot dominance and BMI on the average pressure ($p > 0.05$). From the results of the tests of between-subjects effects, the average pressures on T2-5, M1, M2, M3, M4, M5, MF, MH and LH had significant between-subjects differences ($p < 0.01$). After the post-hoc test, it was found that the average pressures on M4, M5 and MF in RW group and OW group were all lower than those in the OB group ($p < 0.01$); the average pressures on M1, M3, MH and LH in the RW group were all lower than those in the OB group ($p < 0.05$, $p < 0.01$); the average pressure of T2-5 in the OW group was lower than it in the OB group ($p < 0.05$); the average pressure of M2 in the RW group was lower than it in the OW group ($p < 0.05$).

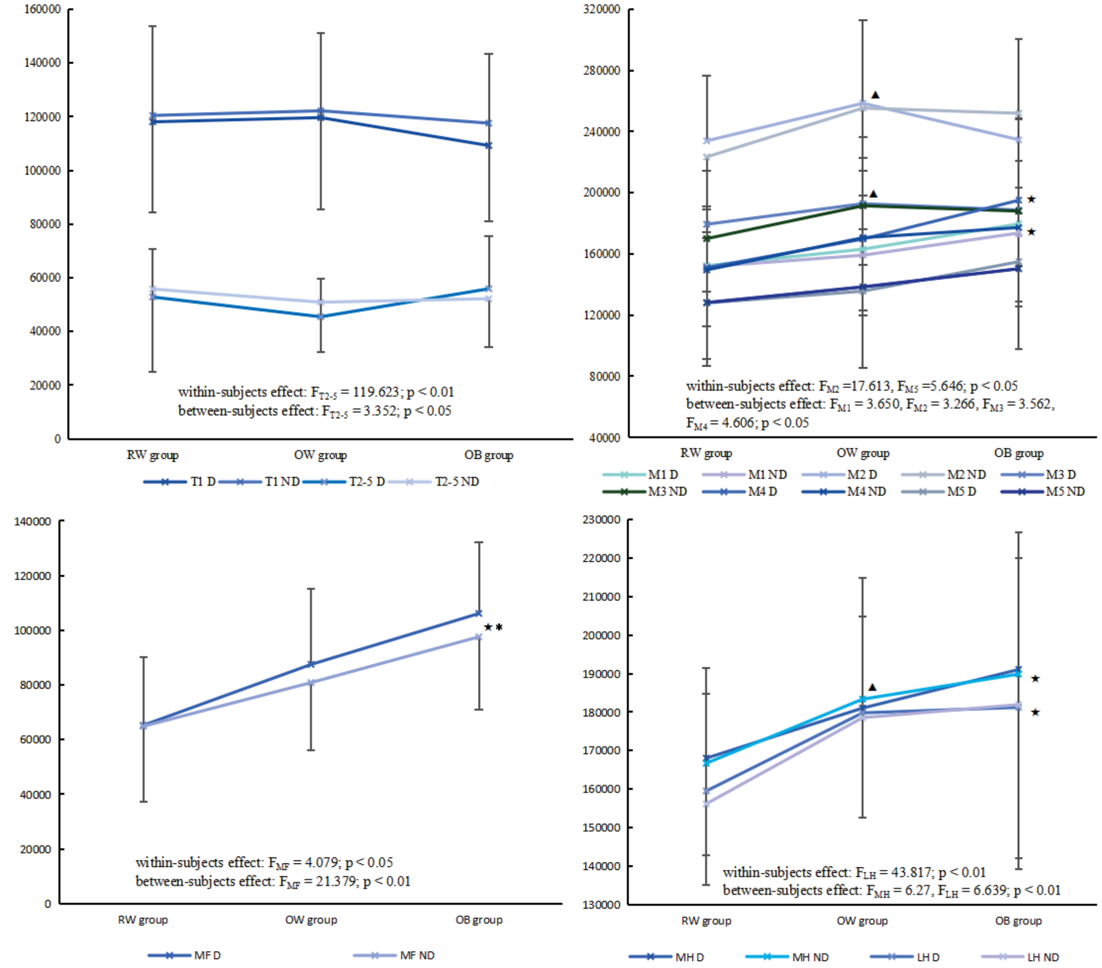
Figure 5 shows the comparison results of peak pressure between the RW group, OW group, and OB group. It was shown by the tests of within-subject effects that the peak pressures on T2-5, M2, M5, MF, and LH had significant within-subject differences ($p < 0.01$, $p < 0.05$). There was no interaction effect of foot dominance and BMI on the peak pressure ($p < 0.05$). From the results of the tests of between-subjects effects, the peak pressures on M1, M2, M3, M4, MF, MH and LH had significant between-subjects differences ($p < 0.01$, $p < 0.05$). After the post-hoc test, it was found that the peak pressures of MF and LH in the RW group and OW group were all lower than those in the OB group ($p < 0.01$); the peak pressures on M1, M4, and MH in the RW group were all lower than those in the OB group ($p < 0.05$, $p < 0.01$); the peak pressures on M2 and M3 in the RW group were both lower than it in the OW group ($p < 0.05$).



★: average pressure in OB group was significantly higher than RW group; ✱: average pressure in OB group was significantly higher than OW group; ▲: average pressure in OW group was significantly higher than RW group.

Abbreviations: D = Dominant, ND = Non-dominant, LH = lateral heel, M1 = metatarsal 1, M2 = metatarsal 2, M3 = metatarsal 3, M4 = metatarsal 4, M5 = metatarsal 5, MF = midfoot, MH = medial heel, ND = Non-Dominant, OB group = obesity group, OW group = overweight group, RW group = regular weight group, T1 = toe 1, T2-5 = toe 2 to toe 5.

Fig 4 Comparison of average pressure between 3 groups (N = 96)



★: peak pressure in OB group was significantly higher than RW group; *: peak pressure in OB group was significantly higher than OW group; ▲: peak pressure in OW group was significantly higher than RW group.

Abbreviations: D = Dominant, FD = foot dominance, LH = lateral heel, M1 = metatarsal 1, M2 = metatarsal 2, M3 = metatarsal 3, M4 = metatarsal 4, M5 = metatarsal 5, MF = midfoot, MH = medial heel, ND = Non-Dominant, OB group = obesity group, OW group = overweight group, RW group = regular weight group, T1 = toe 1, T2-5 = toe 2 to toe 5.

Fig 5 Comparison of peak pressure between 3 groups (N = 96)

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4. Discussion

In this study, the following findings were noted: (1) The local risks of the lateral forefoot and midfoot, the minimum and maximum subtalar joint angles, the flexibility of subtalar joint, the phase of FFP, along with the average pressures on T1, T2-5, M1-3, M5, MF, and LH, and the peak pressures on T2-5, M2, M5, MF, and LH had significant within-subject differences. (2) There were significant between-subjects differences in ICP and FFP, the average pressures on T2-5, M1-5, MF, MH, and LH, and the peak pressures on M1-4, MF, MH, and LH. (3) There was an interaction effect between foot dominance and BMI on the flexibility of the subtalar joint.

In the case of local risk, which is a straightforward interpretation of risk that could provide possible percentages for each foot zone, it is calculated with the footscan risk analysis algorithm to evaluate the pain and injury risks for the dominant and non-dominant lower limb and foot. A prospective cohort study firtstly revealed the risk assessment by footscan software can predict injury in a military population[47] and another study of military new entry trainees also found that subjects who had higher local risk percentages experienced more injuries[48]. Although foot injury and pain in civilians are not as severe as in militaries, the daily lives can still be hindered. A prior review addressed foot injury and pain are associated with falls which are very common among older adults[49]. The evaluation of local risk may provide risk prediction of pain and/or injury, insight into a strategy for injury prevention as well as mitigation of risk through orthotic intervention in the at risk population[50]. It has been noted that the higher degrees of asymmetry among female runners render them more prone to higher injury risk[51] and Bredewig[52] also emphasized that asymmetry was a causative factor for injuries. Despite the subjects were community-dwelling older females in this study, not athletes like the above studies[51,52], asymmetry was also seen and noted in the significantly higher local risk of the lateral forefoot and midfoot of dominant side when compared to the non-dominant side. This suggests for older women, the risk of injury or pain is higher on the lateral forefoot and midfoot on the dominant side than on the non-dominant side. Similarly, in a study by Niu, Wang, and He, et al.[24], a greater injury risk was found in the dominant side during drop landing, the moment the foot hits the ground, compared with the non-dominant side, although the ankle joint was taken as the objective, not the foot. Thus, risk assessment of pain and injury on the dominant side should be taken seriously, especially on the lateral forefoot and midfoot.

The foot axis exorotation is the positive degree of rotation of the foot away from the foot axis line in relation to the gait direction. A prospective study by Menz, Morris, and Lord[53] clarified that the larger foot rotation of older people is associated with the reduction of balance and functional abilities. It has been validated that older adults with greater foot rotation have a higher risk of falling[54]. The foot axis exorotation was found to be increased in the dominant foot of older women. This result is consistent with the findings of Gao, Mei, and Xiang, et al.[34], despite their participants were young adults. Therefore we can conclude that the older adults whose dominant foot has greater foot rotation are more likely to fall, which may be related to increased external rotation of the foot and limb[26,55]. The subtalar joint angle provides an indication of the amount of frontal plane rearfoot motion in relation to the ground, that is the vertical axis of the foot, during the initial contact phase[56]. The maximum value refers to the maximal pronation position of the rearfoot in relationship to the ground during the initial contact phase and the minimum value refers to the maximal supination position. In this study, the higher minimum and maximum subtalar joint angles in the dominant side were both significantly observed. An increse in the maximum subtalar joint angle indicates that a more pronated rearfoot results in more difficulties in supporting the arch, thereby increasing the likelihood of injury. An increased minimum subtalar joint angle indicates that the rearfoot is locked and the connective tissues cannot fully utilize elasticities to absorb shock, resulting in the direct impulsion of these instantaneous loads on the lower extremity and pedal joints resulting in an increased likelihood of joint injury[23]. Therefore, older women are more likely to experience joint injury and pain in their dominant foot. The flexibility of the subtalar joint is demonstrated through the difference between the minimum and maximum subtalar joint angle. This study reveals an interactive effect of foot dominance and BMI, but no within-subject effects of BMI, confirming the previous finding[23]. These findings demonstrate that although body weight is regarded as a key parameter correlated to the supination of the rearfoot[57], the influence of body weight on the flexibility of subtalar joint is not independent, and the differences in the flexibility of subtalar joint among older adults are simultaneously influenced by foot dominance.

In review of single foot timing, the percentage of each phase during total foot contact in the process of walking forward is accurately calculated. In this study, the non-dominant side had a significantly longer FFP which is the longest duration in the total contact time. It indicates that the stabilizing effect of the non-dominant side during walking is greater than that of the dominant side. Likewise, it is noteworthy that multiple studies of older adults have reported similar findings. Sadeghi, Allard, and Prince, et al.[58] found that the non-dominant lower extremity worked better in posture stabilizing, as well as Young, Whitall, and Bair, et al.[59] clarified the non-dominant leg was less active than the dominant leg, resulting in greater balance asymmetry. The effects of BMI on ICP and FFP were also noted in this study. Obese older women had a shorter duration between IFC and IMC than regular-weight and overweight older women but they had a longer duration between IFFC and HO. A study of postmenopausal women (average age > 57 yrs)[60] had consistent results with our findings. That is, in obese older women, the duration of the heel contacting ground is shorter but the duration of the forefoot and midfoot is longer, so the stability is mainly maintained by the forefoot and midfoot.

Regarding plantar pressure, this study shows there were significant effects of foot dominance on plantar pressure, verifying the existence of the asymmetry in plantar pressure[34]. More specifically, through the research results, we mainly found that the average pressures on M2, LH, and T1 in the non-dominant side were higher than those in the dominant side, in contrast, the peak pressures on M2, M5, MF, and LH, as well as the average pressures on M1, M3, M5, and MF in the dominant side were higher than those in non-dominant side. In the previous studies of young adults, the values of plantar pressure on M3 and LH[33], and the variability of peak force beneath the lateral forefoot[61] were also asymmetrical. These results indicate that the non-dominant side plays a greater stabilizing role when touching on and off the ground, and the dominant side plays a role in propulsion. The study of Seeley, Umberger, and Shapiro[32] is in line with this study. This was completed by comparing bilateral ground reaction force impulses of each limb in young adults. In addition to the effect of foot dominance, this study also reports the effect of body mass on plantar pressure, which was in line with the prior studies[62-64]. Importantly, obese older women were noted to have the highest peak pressures in the midfoot and lateral heel which are associated with foot pain and/or injury[21]. This study reveals that each limb provides a different role in older women during walking. This study also suggests that lateral midfoot and hindfoot of obese older women have an increased risk of pain/or injury which may result in decreased functional ability.

Above all, the significance of this study is that we not merely further revealed the effect of body mass on plantar pressures, but also discovered the existence of asymmetry on plantar pressures and the instability during walking in the elderly women by analyzing the effect of foot dominance on plantar pressures. These findings may indicate that the development of symmetry and stability of lower limb in older females, especially in overweight and obese women, should be paid more attention, which could assist in the prevention of foot injury and falls, the treatment of painful symptoms, and the improvements in orthotic interventions.

The study has the following limitations. Firstly, as the causes of the dominant influence on asymmetry and instability are too complex, including but not limited to diversity in muscle recruitment[65], difference of joint kinetics[58], limb length inequality[66], gait pathology[58], etc., it was impossible to demonstrate the mechanism of the dominant influence. Secondly, because this study focuses on older women, the results may not be applicable to older men. Thus, in the future, we will consider recruiting more older males to participate in the study and adding additional tests, such as measurements of muscle strength, joint angle range, and pains assessment, to investigate the effects on different genders and illustrate the reasons for the existence of dominant influence.

5. Conclusions

In summary, this study yields 3 major findings. The first finding notes the non-dominant foot has a lower foot axis exorotation, a smaller range of subtalar joint angle, a larger FFP, and higher average pressures on toes and lateral heel, undertaking better stability, especially when touching on and off the ground during walking. In contrast, the dominant foot, which experiences greater average pressures on the metatarsal and midfoot, plays a better role in propulsion but is more prone to pains, injuries, and even falls during walking. In the second finding, obese older women have the shortest ICP, the highest FFP, and the highest peak pressures, especially on the midfoot and lateral heel, indicating that the forefoot and midfoot are primarily responsible for maintaining stability, whereas the lateral of the midfoot and hindfoot are more likely to experience pain and discomfort. The third and final finding notes the flexibility of the subtalar joint is simultaneously influenced by foot dominance and body mass.

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Informed Consent Statement: Informed consent was obtained from all participants involved in this study.

Data Availability Statement: The data presented in this study are available on request from the corresponding authors. Because of privacy concerns, not all data are available.

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