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Foot weight bearing variations in sitting postures with respect to trunk angles and thigh lengths on chair – a new proposed protocol for determination of sitting postures in foot measurement studies

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ABSTRACT

Foot weight bearing (FWB) is important in foot-measurement studies. Methods used to estimate the subject's FWB in standing posture were usually not practicable in that sitting postures, and FWB was then usually assumed in previous studies. This study investigated the FWB variations in sitting postures with respect to trunk angle and thigh length on the chair. Thirty-six subjects (18 males and 18 females) were recruited in this study. A four-factor factorial design was conducted, including gender (male, female), trunk angle (0°, 45°, Max), thigh length on the chair (1/3-, 1/2-, 2/3-thigh length), and foot side (left, right). FWB was calculated as the proportion of the subject's own body weight for further analyses. The results showed that both trunk angle and thigh length on the chair had significant effects on FWB. As the trunk angle increased, the mean FWB increased, ranging from 6.57% to 21.91%; as the thigh length on chair decreased, the mean FWB increased, ranging from 12.17% to 17.19%. Overall, the mean FWB ranged from 5.53% and 24.89%. The results provided values of FWB variations in nine sitting postures with respect to three trunk angles and three thigh lengths on chair in both feet of the male and the female subjects (also total population). As a general referential protocol in foot measurement studies, these values can be used by researchers as the predetermined FWB of their studies and then to determine the subject's sitting postures in terms of trunk angle and thigh length accordingly, or vice versa.

Keywords: Foot measurement, Foot weight bearing (FWB), Sitting

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1. INTRODUCTION

Foot weight bearing (FWB) is an important variable or setting in foot measurement studies (Tu, 2014; Varga et al., 2020; Kouchi et al., 2021; Allan et al., 2023; Tu, 2023). Many studies have indicated that different FWB can affect foot measurements (Houston et al., 2006; Xiong et al., 2010; Bjelopetrovich and Barrios, 2016; Takabayashi et al., 2020). Researchers, therefore, usually need to determine the subject's posture, whether in sitting or standing, for foot measurement in according to the predetermined FWB in their studies.

In foot measurement, researchers often asked subject to allocate a specific FWB, in terms of a percentage of their own body weight (% BW), onto the involved foot and investigate its effect on the foot shape. Take studies in which subject adopted standing posture in measurement for example. Pohl and Farr (2010) instructed subjects to allocate 50% BW and 90% BW respectively to the right foot for measurement. William and McClay (2000) instructed subjects to allocate 10% BW and 90% BW respectively to the left foot in a standing posture. McPoil et al. (2008) required subjects to allocate 50% BW to both feet in a standing posture. Houston et al. (2006) instructed participants to allocate 0% BW, 10% BW, 25% BW, 50% BW, and 100% BW respectively to the right foot in a standing posture. Cobb et al. (2011) instructed subjects to allocate 10% BW and 90% BW respectively of their body weight to the left foot in a standing posture. Bjelopetrovich and Barrios (2016) instructed subjects to allocate from 10% BW to 120% BW with 10% BW increment respectively to the right foot (with subjects carrying additional weight when exceeding 100% BW). Takabayashi et al. (2020) instructed subjects to allocate 10% BW, 50% BW, and 90% BW respectively to the right foot in a standing posture. However, subject is usually not easy to maintain their posture stably to distribute the required FWB on the involved foot in standing posture, except 50% BW on both foot (McPoil et al., 2008). Therefore, researchers had used weight scales to instruct subjects to adjust the FWB during foot measurement. For example, researchers could place a weight scale directly under subject's right foot (involved foot) to measure the FWB on it, or when subject put their right foot on a three-dimensional foot scanner platform and a weight scale cannot be placed underneath the right foot, researchers may have the subject's left foot (non-involved foot) step on the weight scale instead, and subtract the weight on the left foot from subject's own body weight to estimate the weight bearing on the right foot. Such method was applicable when subject adopt standing posture in foot measurement, in such condition their own body weight was born only by both feet. When subjects adopt a sitting posture and place the involved foot on the measurement plane of the device for foot measurement, the body weight was not only distributed onto two feet but also by the buttocks and parts of the thighs in contact with the chair they sat on. Consequently, the aforementioned FWB measurement methods used in the standing posture are not applicable in sitting posture.

Therefore, many researchers conducting foot measurement studies with subjects in sitting posture often made assumptions about FWB rather than directly measuring it. Saghazadeh et al. (2015) and Akambase et al. (2019) assumed 0% BW as FWB in a sitting posture (non-weight bearing). Schuster et al. (2021) referred to FWB in a sitting posture as minimum weight bearing in their study. More often, many researchers simply assumed 10% BW as FWB in a sitting posture. Such assumptions were adopted by Richards et al. (2003), Zifchock et al. (2006), Pohl and Farr (2010), Bjelopetrovich and Barrios (2016), Zifchock et al. (2017), and Takabayashi et al. (2020). Zifchock et al. (2006) and Zifchock et al. (2017) referred to Dempster and Gaughran (1967) as the primary reference for their assumption, while other studies did not provide their reference for the assumption. Chaffin et al. (2006) had compiled relevant studies and provided weights estimation of each body segments from cadavers. According to their report, the weight of a single leg accounted for approximately 15.7% BW to 20.9% BW, which were inconsistent, however, with the assumption of 0% BW or 10% BW as FWB in sitting posture as mentioned in the previous studies. Of course, while the subject is in sitting posture, some part of the thigh is supported by the chair, this would reduce the corresponding certain weight from FWB. How much weight is reduced or effected is therefore worth investigating. Additionally, Houston et al. (2006) mentioned that when sitting with hands placed ipsilaterally on the knee, a forward lean of the trunk may result in an increase of FWB of up to 25% BW, but Houston et al. (2006) did not provide detailed information about the posture or the effect of body forward lean on FWB. From a biomechanical perspective, the forward inclination of trunk affects the subject's center of gravity in sitting posture, thereby influencing the FWB. The detail of this influence is also worthy to be investigated. Kouchi et al. (2021), in their conclusion for an IEEE white paper, has mentioned that "not all sources specify how each measurement is taken-non-weight bearing (in air), partial weight bearing (sitting position), half weight bearing (on both feet, bilateral stance), or full weight bearing (standing on one foot)". Meanwhile, Allan et al. (2023) in their scoping review also suggested that researchers should have clear definition of FWB conditions when conducting foot shape measurements. The actual relationship of sitting posture and FWB was still unknown as well as the lack of protocols as sitting posture standardization in literature.

Based on the research gap identified above, the present study aims to investigate the FWB variations in sitting postures with respect to trunk angle and thigh length on chair.

2. MATERIALS AND METHODS

Thirty-six subjects were recruited in this study. With Wii Fit® and self-assembled device, a four-factor factorial design was conducted, including gender (male, female), trunk angle (0°, 45°, Max), thigh length on chair (1/3-, 1/2-, 2/3-thigh length), and foot side (left, right). FWB was calculated as portion of body weight before further analyses.

2.1 Participants

Eighteen males and eighteen females were recruited in this study. They are aged in 18–25 years old. All subjects had no reported history of foot surgery, trauma, or deformity. This study complied with the Declaration of Helsinki and was approved by the Institutional Review Board at Chaoyang University of Technology, Taichung City, Taiwan (code: CYUTIRB-111-001). Informed consent was obtained and signed by each subject before the measure was performed.

2.2 Apparatus

2.2.1 Wii Fit® force plate

This study utilized two Wii Fit® force plates (Fig. 1), produced by Nintendo® company in Kyoto, Japan, to measure the FWBs of subject's both feet. According to the specifications provided, the Wii Fit® force plate has a measurement accuracy as ± 0.5 kg and a sampling rate as

120 samples per second. The use of the Wii Fit® force plate as a weight measurement instrument has also been validated by Deans (2011). A self-developed software was used to record the measurement data from the Wii Fit® force plate.

Fig. 1. Wii Fit® force plate

2.2.2 Laser angle aligner

A laser angle aligner, consisting of a laser level meter and a tripod, was used in this study for aligning the subject's trunk angle (Fig. 2). The laser level meter, model GLL 3-60 XG Professional of Robert Bosch GmBH®, Germany, can emit laser beams simultaneously in three different planes: the horizontal plane, sagittal plane, and coronal plane. The tripod was model 3036, Bogen Manfrotto®, Italy. With the sagittal plane aligned vertically to the ground as the 0-degree reference, the laser beam on sagittal plane could be adjusted within the range of -30 to 90 degrees by using a control handle of the tripod. The adjustment was made in 15 degrees as each increment (Fig. 3), allowing the experimenter to guide the position of the subject's trunk inclination angle according to the experiment setting. The center of the laser angle aligner was 270 cm away from the center of the hydraulic adjustable chair on which the subject sat.

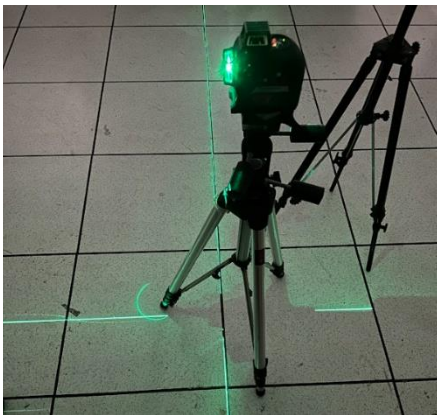

Fig. 2. Laser angle aligner consisted of a laser level meter and a tripod

Fig. 3. Each increment is 15 degrees with adjustment range in -30 to 90 degrees.

2.3 Measurement Procedure

The experimental setup is shown in Fig. 4. In front of the hydraulic adjustable chair, there are two Wii Fit balance boards. During the experiment, the subjects sat on the hydraulic chair with their feet placed on the two Wii Fit® force plate and posed their postures according to the experimenter's instructions. The measurement procedure consisted of preparation phase, positioning phase, and FWB measuring phase.

In preparation phase, subject's body height and body weight were measured first. For body weight measurement, the subject adopted a static natural standing posture and each of their feet stood on one Wii Fit® force plate respectively. The summation of the FWB data measured by each Wii Fit® force plate was considered as the subject's own body weight. The process was about 10 seconds. After the body weight was measured, the subject was asked to sit on the hydraulic adjustable chair, and the experimenter manually adjusted the height of the chair to ensure the subject positioning their knee joints and ankle joints both at a 90-degree angle. After the adjustment, the experimenter measured the subject's total seated thigh length (as shown in Fig. 5), from posterior of buttocks to anterior of knee, as the calculation basis of the level of thigh length on chair. There were three levels of thigh length on chair: 1/3 of the total seated thigh length, 1/2 of the total seated thigh length, and 2/3 of the total seated thigh length. When the level of thigh length on chair was 1/3, there was 1/3 of the subject's total seated thigh segment resting on the chair. Next, the experimenter attached two reflective markers with 3-cm diameter on the surface positions of the subject's C7 cervical vertebra and L5 lumbar vertebra respectively. The angle between the line connecting these two reflective markers and the horizontal plane was the subject's trunk angle. Fig. 6 shows the subject in sitting posture with 2/3 thigh length on chair and three levels of trunk angle.

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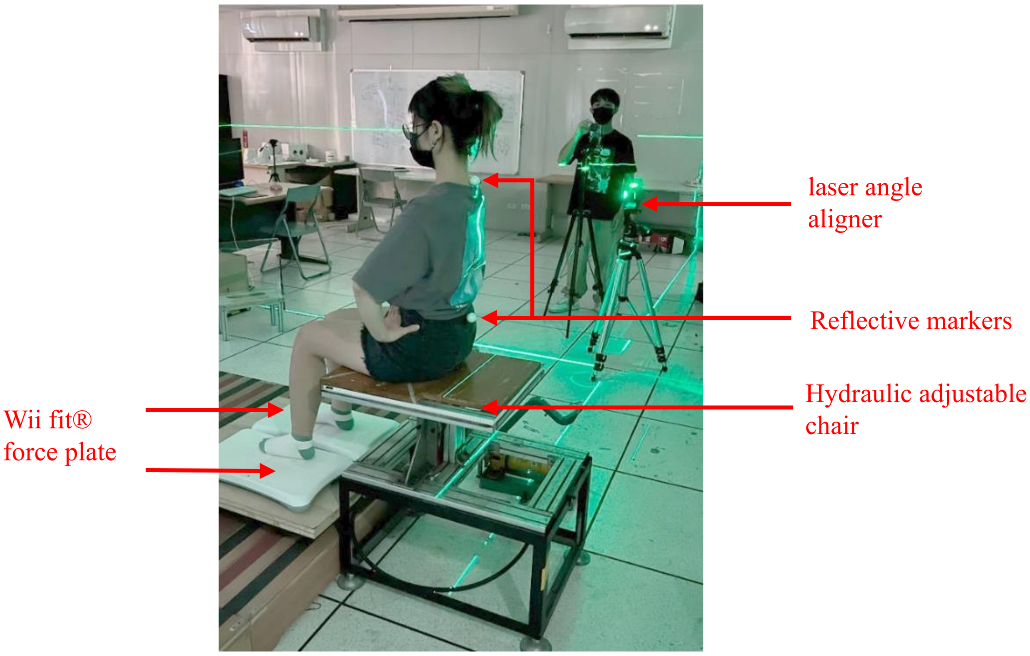


Fig. 4. Experiment setup

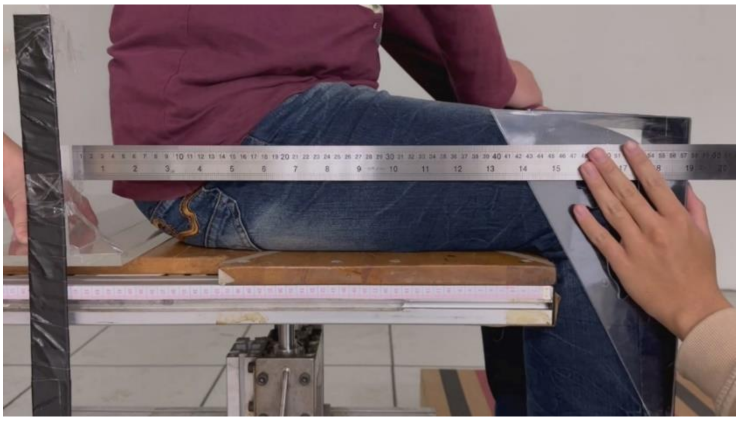
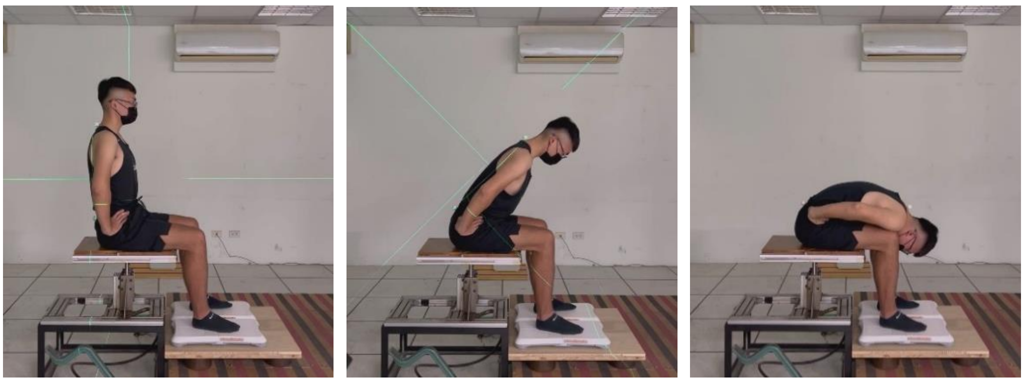


Fig. 5. Measurement of total seated thigh length of subject



(a) (b) (c)

Fig. 6. Subject with two reflective markers attached on C7 and L5 in sitting posture of 2/3 thigh length on chair and (a) 0-degree, (b) 45-degree, and (c) maximum degree as trunk angle

In positioning phase, the subject moved their sitting position for complying with the level of thigh length on chair by experimenter's instruction, say, 2/3, and the experimenter then adjusted the height of the hydraulic chair to ensure that the subject's knee joints and ankle joints remain at 90-degree angles. Once the subject's sitting position was determined, the experimenter instructed the subject to incline their trunk forward to a predetermined angle, including 0-degree (trunk erected), 45-degree, and maximum forward inclination angle (self-awareness). 0-degree and 45-degree inclinations were achieved when the projected laser beam with the same angle passed through the reflective markers on the subject's C7 and L5; maximum forward inclination was achieved according to subject's self-awareness (see also Fig. 6).

In FWB measuring phase, the subject was asked to maintain their posture for 8 sec. In these 8 sec, FWB data of the Wii Fit® force plates under each the subject's feet were recorded. The total measurement time for each subject is approximately 15 min, including the device adjustment time for different measurement settings (e.g., adjusting the height of the adjustable chair, thigh length on chair, laser angle settings, etc.). During the measurement, for 1 min in every 5 min, the subject was asked to leave the adjustable chair, rested, and move freely for 1 min to prevent the accumulation of blood or body fluid in the lower limbs due to prolonged sitting, which might affect the FWB.

2.4 Data Analysis

Data analysis consisted two stages in this study. The first stage was to analyze the FWB values recorded by the Wii Fit® force plates. For FWB values of each subject's two feet, each measurement of the feet lasted for 8 sec. The average value of the recorded FWB values during the middle 4 sec (with a sampling frequency of 120 samples per second, resulting in approximately 480 samples) was taken as the resultant FWB raw value for this measurement of the foot. The resultant FWB raw value was then divided by the subject's own body weight, as portion of body weight (% BW), which was then used in the second stage analysis and further demonstration. The second stage was to conducting ANOVA analysis with a four-factorial design model and post-hoc analysis with Tukey's honestly significant difference (HSD) test in trunk angle and thigh length on chair.

3. RESULTS

3.1 Demographic Data of Subjects

Means and standard deviations (S.D.) of the ages, heights and weights as well as the thigh length in sitting posture of the subjects recruited as male, female, and total population were shown in Table 1.

Table 1. Demographic data of subjects

Item	Male		Female		Total	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
Age (yr)	18.78	0.43	19.83	1.76	19.31	1.37
Stature (cm)	172.28	5.46	161.08	6.60	166.68	8.24
Weight (kgw)	69.29	10.43	56.22	13.89	62.76	13.80
Seated thigh length (cm)	59.28	1.73	57.72	2.23	58.50	2.12

3.2 Data of Foot Weight Bearing

The detail results of FWB values for the male, the female, and the total (two genders combined) are shown in Table 2. For the total population, the range of means of FWB ratios on subjects' one foot (right or left foot) is between 0.71% and 31.86%. In different levels of thigh lengths, the range of means of FWB ratios is between 12.17% and 17.19%. In the case of thigh length on chair as 2/3, there is a minimum mean ratio of 12.79% (S.D. 6.41%); whereas in the case of thigh length on chair as 1/3, there is a maximum mean ratio of 17.19% (S.D. 7.39%). The results of the study indicated that as subject's thigh length on chair became shorter, the mean of FWB ratios on each foot increased. In different levels of trunk angles, the range of means of FWB ratios is between 6.57% and 21.91%. At a trunk angle as 0-degree, there is a minimum mean ratio as 6.57% (S.D. 2.34%), while at the maximum flexed trunk angle, there is a maximum mean ratio of 21.91% (S.D. 3.92%). The results showed that as subject's trunk angle increased, the mean of FWB ratios on each foot also increased. When considering both different levels of thigh length on chair and trunk angles, the range of means of FWB ratios is between 5.53% and 24.89%. In the condition of thigh length on chair as 2/3 and trunk angle as 0-degrees, the minimum value ratio is 5.55% (S.D. 2.49%), while in the case of thigh length on chair as 1/3 and the maximum trunk angle flexed, the maximum mean ratio is 24.89% (S.D. 3.16%). The conditions under which the minimum and maximum mean ratios of each foot (right and left) occurred in both the male and the female populations are consistent with the total population.

Table 2. Data of foot weight bearing (Unit: %)

Gender	Thigh length on chair	Foot	Trunk angle												Sub-total			
			0°				45°				Max							
			Mean	S.D.	Min	Max	Mean	S.D.	Min	Max	Mean	S.D.	Min	Max	Mean	S.D.	Min	Max
Male	1/3	R	8.19	1.29	6.40	11.05	18.56	1.46	15.98	21.49	24.77	2.92	19.90	30.20	17.17	7.19	6.40	30.20
		L	7.29	1.13	5.23	9.42	18.33	1.71	15.87	21.55	24.58	3.34	17.84	30.42	16.73	7.55	5.23	30.42
		Sub-total	7.74	1.28	5.23	11.05	18.44	1.57	15.87	21.55	24.68	3.09	17.84	30.42	16.95	7.34	5.23	30.42
	1/2	R	6.30	1.63	3.50	9.19	15.36	2.23	10.84	18.41	21.62	2.22	18.13	25.12	14.42	6.66	3.50	25.12
		L	5.33	1.48	2.40	7.82	15.27	1.92	11.81	19.26	21.11	3.03	16.60	27.71	13.90	6.93	2.40	27.71
		Sub-total	5.82	1.61	2.40	9.19	15.31	2.05	10.84	19.26	21.36	2.63	16.60	27.71	14.16	6.77	2.40	27.71
	2/3	R	6.07	2.96	2.98	16.01	13.32	3.26	6.81	19.07	19.59	2.75	13.87	24.40	12.99	6.30	2.98	24.40
		L	4.94	1.85	1.60	7.97	13.75	2.48	7.75	17.37	19.31	3.05	13.39	25.46	12.67	6.46	1.60	25.46
		Sub-total	5.50	2.50	1.60	16.01	13.53	2.86	6.81	19.07	19.45	2.86	13.39	25.46	12.83	6.35	1.60	25.46
	Sub-Total		6.35	2.10	1.60	16.01	15.76	3.00	6.81	21.55	21.83	3.57	13.39	30.42	14.65	7.03	1.60	30.42
Female	1/3	R	8.43	1.71	6.26	11.66	19.12	3.14	15.73	26.07	25.56	2.76	21.60	31.13	17.71	7.57	6.26	31.13
		L	8.44	1.99	4.56	11.05	18.37	3.61	14.49	29.08	24.66	3.71	16.86	31.86	17.16	7.44	4.56	31.86
		Sub-total	8.43	1.83	4.56	11.66	18.75	3.36	14.49	29.08	25.11	3.25	16.86	31.86	17.43	7.48	4.56	31.86
	1/2	R	6.57	2.37	2.75	11.92	15.78	2.58	12.56	22.38	22.12	2.86	17.59	27.73	14.83	6.93	2.75	27.73
		L	6.08	2.44	2.82	10.87	15.14	4.05	8.79	23.43	21.13	4.06	11.26	28.21	14.12	7.17	2.82	28.21
		Sub-total	6.32	2.39	2.75	11.92	15.46	3.36	8.79	23.43	21.63	3.49	11.26	28.21	14.47	7.03	2.75	28.21
	2/3	R	5.55	2.47	0.71	10.44	13.78	3.23	6.41	20.32	19.66	3.46	11.07	26.25	13.00	6.58	0.71	26.25
		L	5.64	2.64	1.18	11.00	13.09	3.62	6.56	20.46	18.83	4.15	8.61	25.25	12.52	6.46	1.18	25.25
		Sub-total	5.60	2.52	0.71	11.00	13.43	3.40	6.41	20.46	19.25	3.79	8.61	26.25	12.76	6.49	0.71	26.25
	Sub-Total		6.35	2.10	1.60	16.01	15.76	3.00	6.81	21.55	21.83	3.57	13.39	30.42	14.65	7.03	1.60	30.42
Total	1/3	R	8.31	1.50	6.26	11.66	18.84	2.43	15.73	26.07	25.16	2.83	19.90	31.13	17.44	7.35	6.26	31.13
		L	7.86	1.70	4.56	11.05	18.35	2.79	14.49	29.08	24.62	3.48	16.86	31.86	16.94	7.46	4.56	31.86
		Sub-total	8.09	1.61	4.56	11.66	18.60	2.61	14.49	29.08	24.89	3.16	16.86	31.86	17.19	7.39	4.56	31.86
	1/2	R	6.44	2.01	2.75	11.92	15.57	2.38	10.84	22.38	21.87	2.53	17.59	27.73	14.62	6.77	2.75	27.73
		L	5.70	2.03	2.40	10.87	15.20	3.12	8.79	23.43	21.12	3.53	11.26	28.21	14.01	7.02	2.40	28.21
		Sub-total	6.07	2.04	2.40	11.92	15.39	2.77	8.79	23.43	21.49	3.07	11.26	28.21	14.32	6.89	2.40	28.21
	2/3	R	5.81	2.70	0.71	16.01	13.55	3.21	6.41	20.32	19.63	3.08	11.07	26.25	13.00	6.41	0.71	26.25
		L	5.29	2.28	1.18	11.00	13.42	3.08	6.56	20.46	19.07	3.60	8.61	25.46	12.59	6.43	1.18	25.46
		Sub-total	5.55	2.49	0.71	16.01	13.48	3.12	6.41	20.46	19.35	3.34	8.61	26.25	12.79	6.41	0.71	26.25
	Sub-Total		6.57	2.34	0.71	16.01	15.82	3.53	6.41	29.08	21.91	3.92	8.61	31.86	14.77	7.14	0.71	31.86

Table 3. ANOVA of FWB

Source	Type III Sum of squares	df	Mean square	F	Sig.	Partial eta square
Gender	0.001	1	0.001	1.192	0.275	0.002
Thigh length on chair	0.215	2	0.108	139.762	< 0.001	0.314
Trunk angle	2.579	2	1.289	1673.020	< 0.001	0.845
Foot side	0.004	1	0.004	5.326	0.021	0.009
Gender * thigh length on chair	0.001	2	0.000	0.550	0.577	0.002
Gender * trunk angle	0.000	2	0.000	0.203	0.816	0.001
Gender * foot side	0.000	1	0.000	0.120	0.729	0.000
Thigh length on chair * trunk angle	0.019	4	0.005	6.195	< 0.001	0.039
Thigh length on chair * foot side	0.000	2	< 0.001	0.080	0.923	0.000
Trunk angle * foot side	0.000	2	0.000	0.165	0.848	0.001
Gender * thigh length on chair * trunk angle	0.000	4	0.000	0.011	1.000	0.000
Gender * thigh length on chair * foot side	0.000	2	0.000	0.003	0.997	0.000
Gender * trunk angle * foot side	0.002	2	0.001	1.363	0.257	0.004
Thigh length on chair * trunk angle * foot side	0.000	4	0.000	0.040	0.997	0.000
Gender * thigh length on chair * trunk angle * foot side	0.000	4	0.000	0.078	0.989	0.001
Error	0.472	612	0.001			
Total	17.426	648				
Corrected total	3.294	647				

3.3 ANOVA Analyses

The ANOVA analyses are shown in Table 3. The results showed that there is no significant effect in gender, while thighs length on chair, trunk angle, and foot side have significant effects on FWB ratio respectively with a level as 0.05. Thigh length on chair and trunk angle have a two-way interaction effect. Furthermore, based on the partial eta squared values, it can be observed that trunk angle has greater impact on FWB ratio than thigh length on chair. Additionally, post hoc analysis using Tukey's honestly significant difference (HSD) test reveals significant differences among the three levels of sitting leg positions (as shown in Table 4) and among the three levels of trunk angles (as shown in Table 5).

Table 4. Post hoc analysis of significance of three levels of thigh length on chair by Tukey's HSD test

(I) Thigh length on chair	(J) Thigh length on chair	Average difference (I-J)	Standard error	Sig.	95% Confidence interval	
					Lower bound	Upper bound
1/2	1/3	-0.029	0.003	< 0.001	-0.035	-0.022
	2/3	0.015	0.003	< 0.001	0.009	0.022
1/3	1/2	0.029	0.003	< 0.001	0.022	0.035
	2/3	0.044	0.003	< 0.001	0.038	0.050
2/3	1/2	-0.015	0.003	< 0.001	-0.022	-0.009
	1/3	-0.044	0.003	< 0.001	-0.050	-0.038

Table 5. Post hoc analysis of significance of three levels of trunk angle by Tukey's HSD test

(I) Trunk angle	(J) Trunk angle	Average difference (I-J)	Standard error	Sig.	95% Confidence interval	
					Lower bound	Upper bound
0°	45°	-0.093	0.003	< 0.001	-0.099	-0.086
	MAX	-0.153	0.003	< 0.001	-0.160	-0.147
45°	0°	0.093	0.003	< 0.001	0.086	0.099
	MAX	-0.061	0.003	< 0.001	-0.067	-0.055
MAX	0°	0.153	0.003	< 0.001	0.147	0.160
	45°	0.061	0.003	< 0.001	0.055	0.067

4. DISCUSSION

The results showed that thigh length on chair and trunk angle effected FWB significantly. Factors contributing to the impact of sitting position (thigh length on chair) and trunk angles on FWB might result from the actual weight of the lower limb without supported by chair and the change of the position of subject's center of gravity. As descriptions in the introduction section, body weight of subject in sitting posture would be distributed onto two feet and body parts on the chair (the buttocks and thighs in contact with the chair), the more the body weight was supported by the chair, the less the body weight was by each foot (that is FWB in this study). Different level of thigh length on the chair (1/3, 1/2, 2/3) would determine the body weight supported directly by the chair, and therefore will affect the FWB. On the other hand, the larger the trunk angle was, the more the subject's center of gravity move forward to his/her foot position in pivot of the ischial tuberosity. The change of the position of center of gravity would then introduce more body weight distributed onto the feet.

Overall, for the total population, as the thigh length on chair decreases, the mean ratio of FWB increases, ranging from 12.17% to 17.19%; as the trunk angle increases, the mean ratio of FWB increases, ranging from 6.57% to 21.91%. Both thigh length and trunk angle have significant effects on the FWB ratio (see also Table 3), and there is a two-way interaction between them. Furthermore, trunk angle has a greater impact on FWB than thigh length on chair. ANOVA analysis also shows that gender does not have a significant effect on FWB, and although there is a significant difference between the left and right feet, their performance is consistent. Discussions thereafter mainly focus on the measurement results of the total population.

The range of the mean FWB ratios measured in this study does not comply with the frequently assumed 0% BW (Saghazadeh et al., 2015; Akambase et al., 2019) or 10% BW (Richards et al., 2003; Zifchock et al., 2006; Pohl and Farr, 2010; Bjelopetrovich and Barrios, 2016; Zifchock et al., 2017; Takabayashi et al., 2020) in previous studies. As mentioned earlier, changes in thigh length on chair resulted in a range of mean ratios between 12.17% to 17.19%, while changes in trunk angle resulted in a range of mean ratios between 6.57% to 21.91%. It is evident that the FWB ratios in sitting postures in this study is not 0% BW nor non-weight bearing. In fact, when mean ratios measured under all sitting postures in this study are compared with 10% BW (assumption) using t-tests, given the same number of subjects (N = 36) and standard deviations, the results were significantly different ($p < 0.0001$). In other words, the mean FWB ratios under all sitting postures in this study are not consistent with the assumption of 10% WB in the literature. However, it is worth noting that the range of mean FWB ratio for the total population in this study is between 5.53% to 24.89%, which still includes 10% BW. Therefore, further investigation is needed to determine in which sitting posture conditions the mean FWB ratio will approximate to 10% BW. The results of this study are partially consistent with the data reported in Chaffin (2006). The range of mean FWB ratios for the total population is 5.53% to 24.89%, which covers the range reported in Chaffin (2006) as 15.7% to 20.9% of whole leg weight relative to total body weight. This suggests that data relying solely on cadavers is insufficient to be used to evaluate FWB ratio, and loadings induced from biomechanical factors, such as thigh length on chair or trunk angle, and tissue fluid as well as blood are also needed considering. Additionally, Houston et al. (2006) reported that the FWB in sitting posture with an erect upper trunk is approximately 10% BW, while the one can reach 25% BW when the sitting posture leaning forward with hands ipsilaterally placed on the knees. Although Houston et al. (2006) did not specify the sitting conditions of their subjects, comparing the results of this study indicates that, regardless of the difference of the hand placement, the thigh length on chair in the sitting posture adopted in Houston et al. (2006) might be 1/3. In this condition, when the trunk angle is 0-degree, the mean FWB ratio is 8.09% (close to 10%), and when the trunk angle reaches the maximum, the mean FWB ratio 24.89% (basically 25% rounded). However, such sitting posture is not easy to be maintain in stability. Furthermore, Schuster et al. (2021) claimed the FWB in their study as minimum weight bearing. From the figures provided in Schuster et al. (2021), the sitting posture of their subjects is similar to the one with 2/3 thigh length on chair and 0-degree trunk angle used in this study. Therefore, according to the results of this study, the average value of this so-called minimum weight bearing should be around 5.55%.

The results provided values of FWB variations in nine sitting postures with respect to three trunk angles and three thigh lengths on chair in both feet of the male, the female, and the total (see Table 2). In Table 2, researchers can find FWB value matching their study setting with its corresponding subject's sitting postures in terms of trunk angle and thigh length on chair, or vice versa. These values can fulfill the appeal and requirements of Allan et al. (2023) and Kouchi et al. (2021) that clear definition of FWB conditions were needed as a general referential protocol in foot measurement studies. For researchers who will have foot measurement studies related to estimating the FWB of subject in sitting posture, with no weight scalar needed, researchers can select the subject's sitting posture in terms of thigh length on chair and trunk angle, and refer to Table 2 in this manuscript, and the FWB could then be estimated. For example, a male with sitting posture in 1/2 thigh length on chair and 0-degree trunk angle might have FWB on his right foot as 6.3% of his own body weight. For researchers who will have the specific FWB as control variable in foot measurement studies with subject's in sitting posture, researchers can also refer to Table 2, and select the most approximating value to that very FWB, and the corresponding condition as needed sitting posture can then be determined. For example, a research wants to conduct a study to investigate the foot measurements of right foot with 5% BW as FWB. The research can search the most approximating value of 5% in Table 2, say 4.94% for the male one or 5.55% for the female one, and then the corresponding condition of the sitting posture with 2/3 thigh length on chair and 0-degree trunk angle can be used as the sitting posture in that study.

Foot side had significant effect on FWB in this study. Bilateral allometry in human body had been studies and found, especially in upper and lower limbs (Tomkinson and Olds, 2000; Pierre et al., 2010), as well as perfusion and plantar pressure asymmetries on foot (Rogers et al., 2020; Rodrigues et al., 2022). In ANOVA analysis as shown in Table 3 in manuscript, foot side as a significant factor on FWB in this study seemed consistent to the asymmetry principle reported in these previous studies. However, partial eta squared of foot side, as 0.009, had shown its effect size much smaller than that of thigh length on the chair (0.314) or that of trunk angle (0.845). This phenomenon could also be observed from the FWB differences between different foot sides shown in Table 2, that FWB difference ranging from 0.32% to 0.71% for the total population, with respect to the range of thigh length on chair as 12.17% to 17.19%, and that of trunk angle as 6.57% to 21.91%. Despite foot side as a significant factor on FWB but with small effect size, it was always designated in the foot measurement studies, it was considered by the author that foot side needed not to be suggested or included in the general referential protocol proposed in this study.

There are limitations in this study. First, the small number of subjects limits the strength of this study. Second, the subjects were not asked to be unified in their clothing. The weather when this study was conducted is summer in Taiwan, and the room temperature in the lab was controlled between 25 degrees to 27 degrees Celsius, the subject's clothing, therefore, is about 0.4 clo (see also Fig. 6), with short pants mainly whose weight was about 400–500 g. The "clo" is a common unit of clothing insulation. If a nude person has a thermal insulation of 0 clo, a person wearing a business suit has 1 clo (Parsons, 1991). With respect to subject's body weight and considering the sitting posture, weight of subject's clothing including pants was considered with least effect on FWB. Thirdly, when subject was measured in sitting posture, tissue fluid as well as blood might be accumulated in leg and increased the FWB. To reduce the effect of such accumulation, subject was asked to leave the hydraulic chair every 5 min during the measuring procedure in this study. Therefore, the effect of the tissue fluid accumulation might be as minimum as possible in consideration. Fourth, the mean age of subject population in this study was 18.78 years old, who were assumed with good control capabilities on bending and maintain the angle of trunk. For the studies with senior population as subjects, who might have less control capabilities on their upper trunk, the results of this study might be considered with further investigations.

5. CONCLUSIONS

This study investigated the foot weight bearing of 36 subjects in sitting postures under different thigh length on chair and trunk angles. The results showed that both thigh length on chair and trunk angle had significant effects on the FWB on their both feet, with a two-way interaction. Trunk angle has a greater impact on foot load than thigh length on chair. In general, as the thigh length on chair decreases, the mean FWB ratio increases, ranging from 12.17% to 17.19%; the trunk angle increases, the mean FWB ratio increases, with a range of 6.57% to 21.91%. Considering both thigh length on chair and trunk angle, the range of the mean FWB ratio is 5.53% to 24.89%. In sitting posture with 2/3 thigh length on chair and 0-degree trunk angle, the minimum mean FWB ratio is 5.55% (S.D. 2.49%), while in the sitting posture with 2/3 thigh length on chair and maximum trunk angle, the maximum mean FWB ratio is 24.89% (S.D. of 3.16%). Foot side (right and left) also had significant effect on FWB, their performance with respect to FWB, however, was consistent in combinations of thigh length on chair and trunk angles. Gender had no significant effect on FWB. The performance of the minimum and maximum FWB ratio on both male and female populations are the same as those for the entire population. This study provides the FWB ratio for both left and right feet of male and female subjects (the total population) in nine different sitting postures (3 levels of thigh length on chair × 3 levels of trunk angles). Researchers can ask subjects to adopt the corresponding sitting posture based on predetermined FWB condition of their studies. This study provides clear definition of sitting postures and can be an important FWB protocols in foot measurement studies.

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