Advanced Foot Pressure Technology for Demonstrating the Influence of Over-weight and Obesity on Ankle Joint

Suhad KR Al-Magsoosi
University of Southern Queensland
West Street, Toowoomba
QLD Australia
+61 46312546
U1052339@umail.usq.edu.au

Albert K. Chong
University of Southern Queensland
West Street, Toowoomba QLD Australia
+61 46312546
Chonga@usq.edu.au

ABSTRACT
Foot pressure technology has been utilized to study the influence of over-weight and obesity on the ankle joint which because of gaining weight lead to change gait characteristics, particularly foot ailments, and has been used in academic teaching in the Medical and Allied Health fields for over 30 years. However, earlier sensors often required an indoor setup as they were not portable. Advanced technology provides the means to take the system outdoors, thus the having the ability to determine the impact of walking-paths terrain on foot pressure and on the ankle joint. Over-weight and obesity cause a number of adverse walking issues for the ankle as extra weight is loaded onto this vital joint component. In addition, footpath terrain may be uneven and thus plays a role in the characteristics of gait and subsequently has an impact on the ankle. In this research, simulated obesity was introduced to study foot pressure and the impact on the ankle of outdoor walking. One aspect was the potential for foot injury, particularly foot ankle rotation. This technology allows researchers and academics to demonstrate the impact of over-weight and obesity in outdoor walking.

CCS Concepts
• Information systems → Database management system engines.

Keywords
Advanced foot pressure sensor; ankle injury; medical and allied health education; outdoor foot path terrain.

1. INTRODUCTION
The increasing number of overweight and obese adults has become a significant public health concern worldwide and is associated with both increasing health care costs and disability [1], [2], [3], [4], [8]. [10]. It has been estimated that more than 1.9 billion adults, 18 years and older, were overweight in 2015. Of these, over 650 million were obese. 41 million children under the age of 5 were overweight or obese and over 340 million children and adolescents aged 5-19 were overweight or obese in same year (WHO, 2016). Healthcare experts and physicians have commonly utilized the body mass index (BMI) scale to define overweight and obesity [3]. Body mass index (kg/m2) is calculated by dividing weight in kilograms (kg) by the square of the height (length) in meters (m) [2], [5].

ICISS 19, March 16–19, 2019, Tokyo, Japan

ACM ISBN 978-1-4503-6103-3/19/03...$15.00
http://doi.org/10.1145/3322645.3322661

Overweight and obese people suffer ankle pain as additional weight over-stretches the joint ligaments which leads to losing their elasticity in relation to the ligaments properties for the arch, thus creating imbalance and injury [11, 12, 14].

We developed an innovative method by marking the medial foot axis (MFA) reference line on every plantar pressure pedobarograph [6], [7]. The MFA reference line was established by connecting the imprint of the conjugate 2nd metatarsal head ($2MH_C$) and the conjugate pternion (PN_C) (Figure 1). The distance between $2MH_C$ and PN_C and along the MFA line is called the marker linear distance (MLD). The x and y coordinates based on the established MFA line was used to derive the spatial, temporal and COP velocity measures. Using these measurements, minute change in the pressure at heel-strike can be determined accurately. This change in pressure could be indexed according to the weight gain (BMI).

Both the developed foot marking technique and advanced insole pressure sensors could detect small pressure change during gait. The change in pressure could be converted to stress at the ankle by calculating the x, y and z rotation [8].

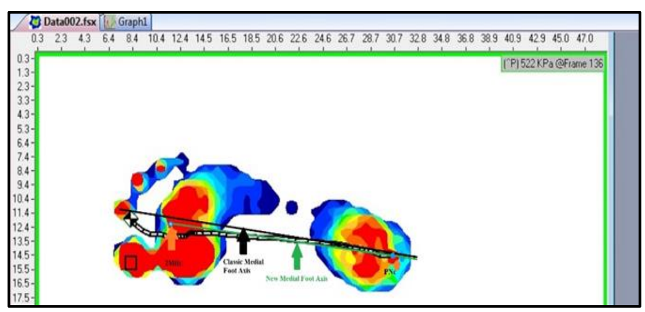

Figure 1. Pre-marked medial foot axis.

2. METHODS
We designed our research to allow the independent variable to be body mass index. The dependent variables were measures of foot pressure (pressure time integral, peak pressure, pressure contact area and average pressure) over ten regions of the foot namely: (heel, midfoot (MF), metatarsal head 1 (MH1), metatarsal head 2 (MH2), metatarsal head 3 (MH3), metatarsal head 4 (MH4), metatarsal head 5 (MH5), hallux, second toe(2nd T), and three to five toe (3rd -5th T) (Figure 2) [9]. The utilized portable foot

pressure measurement system was F-Scan insole sensor and F-Scan software (Version 6.70-03, Tekscan, Boston, MA).

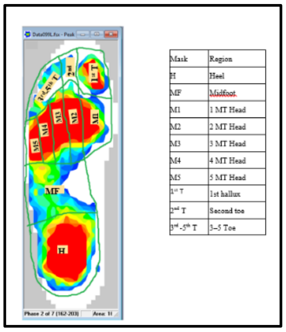

Figure 2. Foot pressure sampling location.

2.1 Test subject

In 2018, the research proposal was accepted by the Research Ethics Committee (proposal number: (H18REA065). All participants signed an informed consent form to participate voluntarily in the study.

Twelve adult males' participants were recruited in this preliminary study; participant demographics are presented in Table 1. The participants were aged between 29-50 years. Each subject's weight was determined using a digital scale and height was determined using stadiometer wall.

Recruits were excluded from participation in the study if they had a history of orthopaedic problems, any disturbance of balance, musculoskeletal dysfunction or any difficulties in independent locomotion neurological and/or musculoskeletal problems likely to affect their gait.

Table 1. Participant Demographics

Parameter	Normal-weight (N=4)		Overweight (N=4)		Obese (N=4)	
	mean	SD	mean	SD	mean	SD
Age (yrs)	36.00	7.16	37.75	6.02	39.50	8.23
Weight (kg)	72.53	3.21	88.50	4.27	112.10	16.78
Height (m)	1.82	0.02	1.78	0.05	1.75	0.05
BMI (Kg/m^2)	21.92	1.45	28.01	0.41	36.67	3.69

2.2 Over-weight and Obesity simulation

For the simulation test, an external weight belt (vest) was worn to simulate all-round obesity (Figure 4). For the data collection, the first walk was without any external load. Then, in the second walk the participant wore a weight of 10 kg; the third walk involved a weight of 20 kg and the last walk entailed a weight of 30 kg. While walking, the plantar pressure pattern of these participants was recorded for further processing. Foot pressure parameters were obtained from 10 areas under the foot: heel, mid-foot, first, second, third, fourth and fifth metatarsal heads, hallux, second toe and third to fifth toes.

Based on the weight added, the participants were divided into three groups: healthy weight, overweight, and obese group.

2.3 Foot pressures

For Protocols for the assessment of plantar pressures in adults previously used in our laboratory were three-step method wearing in-sole sensor (Figure 3). In-sole sensor is becoming increasingly, popular in both research and clinical tools for pressure measurement and force data during dynamic movements, such as evaluating foot plantar pressure of humans worldwide (15, 16).

All participants were asked to walk along a five-meter walkway with foot pressure insole system that was attached to the participants' shoes. Participants were instructed to familiarize themselves with the test using the pressure sensing system, thus ensuring they were comfortable with the procedure. Participants were encouraged to adopt a natural gait pattern and to walk at a self-selected speed. Three trials of the gait were recorded for each participant.

Figure 3. The in-shoe pressure system (Pressure sensor).

Figure 4. The foot pressure sensor system set-up.

2.4 Statistical evaluation of foot pressures

We designed our research to allow the independent variable to be body mass index. The dependent variables were measures of foot pressure (pressure time integral, peak pressure, pressure contact area and average pressure) over ten regions of the foot namely: (heel, midfoot (MF), metatarsal head 1 (MH1), metatarsal head 2 (MH2), metatarsal head 3 (MH3), metatarsal head 4 (MH4), metatarsal head 5 (MH5), hallux, second toe(2^{nd} T), and three to five toe (3^{rd} -5^{th} T) (Figure 2). The utilized portable foot pressure measurement system was F-Scan insole sensor and F-Scan software (Version 6.70-03, Tekscan, Boston, MA).

3. RESULTS

Twelve adult males' sample were tested in this preliminary research; participants were grouped according to BMI and there were three groups: healthy weight, overweight and obese. The test results were provided as mean values from three sets measured for both foot in Table 2. There were noticeable differences in x-location and y-location pressure between the three BMI categories. Change in pressure along the x-location (green highlight) were more prominent for healthy weight subjects for the left and right foot, while such change for obese subjects are less obvious. However, change in pressure along the y-location (yellow highlight) are clear for all subjects for both feet.

Table 2. Results of the preliminary test as mean values and standard deviations for left and right foot (x and y locational pressure

Left foot x locational pressure-change reading									
Simulated weight gain: Mean of three trials									
Participant	0 kg		10kg		20kg		30 kg		Description
	Mean x	std.	Mean x	std.	Mean x	std.	Mean x	std.	
A	3.33	0.06	3.53	0.55	4.30	0.17	4.47	0.35	healthy
B	4.67	0.35	4.53	0.06	4.53	0.40	5.30	0.30	
C	4.57	0.84	5.07	0.06	5.00	0.00	4.53	0.60	
D	4.87	0.40	5.27	0.25	5.27	0.23	5.20	0.26	
E	4.80	0.17	4.97	0.40	5.57	0.29	4.60	0.36	overweight
F	4.90	0.26	5.20	0.53	5.17	0.29	5.07	0.06	
G	5.30	0.26	5.63	0.32	5.83	0.21	6.03	0.06	
H	4.47	0.12	4.70	0.26	4.57	0.06	4.17	1.14	
I	4.53	0.55	4.17	0.58	4.13	1.50	4.87	0.21	obese
J	3.50	0.44	3.47	0.51	4.13	0.32	3.97	0.06	
K	4.83	1.02	4.03	2.20	5.33	0.29	5.43	0.29	
L	5.53	0.06	5.83	0.06	5.27	0.32	5.53	0.81	

Left foot y locational pressure-change reading									
Simulated weight gain: Mean of three trials									
Participant	0 kg		10kg		20kg		30 kg		Description
	Mean y	std.	Mean y	std.	Mean y	std.	Mean y	std.	
A	3.73	0.23	4.07	0.81	5.13	0.71	5.50	0.78	healthy
B	5.83	0.74	5.57	0.06	5.57	0.51	6.63	0.25	
C	5.1	0.61	5.43	0.06	5.53	0.06	5.20	0.52	
D	6.00	0.00	5.90	0.26	5.70	0.17	5.60	0.10	
E	5.60	0.10	5.60	0.00	6.03	0.06	5.73	0.15	overweight
F	5.73	0.25	5.93	0.21	5.57	0.06	6.07	0.40	
G	6.43	0.29	6.57	0.12	6.60	0.87	7.10	0.00	
H	4.93	0.75	6.20	0.82	6.37	0.06	5.57	1.07	
I	5.73	0.71	5.30	0.79	5.37	1.27	6.20	0.61	obese
J	3.73	0.49	4.23	0.74	5.07	0.46	5.43	0.64	
K	5.87	1.48	5.67	2.05	6.43	0.45	6.80	0.44	
L	6.80	0.52	7.53	0.32	6.67	0.49	6.43	1.24	

Right foot x locational pressure-change reading									
Simulated weight gain: Mean of three trials									
Participant	0 kg		10kg		20kg		30 kg		Description
	Mean x	std.	Mean x	std.	Mean x	std.	Mean x	std.	
A	4.83	0.29	4.67	0.21	4.83	0.31	5.13	0.25	healthy
B	4.40	0.82	4.80	0.26	4.43	0.06	4.83	0.06	
C	4.3	0.35	4.10	0.72	4.77	0.40	4.57	0.45	
D	4.13	0.25	4.77	0.29	4.37	0.40	4.43	0.29	
E	4.40	0.20	4.97	0.51	5.17	0.21	4.50	0.50	overweight
F	4.90	0.10	5.07	0.76	4.70	0.26	5.27	0.60	
G	5.4	0.26	6.03	0.06	6.10	0.00	6.10	0.00	
H	4.30	1.22	4.20	0.26	4.17	0.21	4.17	0.21	
I	3.93	0.90	4.83	0.65	5.03	0.15	3.70	0.52	obese
J	3.57	0.21	2.63	0.21	3.37	0.65	3.43	0.06	
K	4.93	0.58	5.70	0.44	5.53	0.40	5.37	0.25	
L	5.50	0.10	5.60	0.00	5.57	0.06	5.77	0.29	

Right foot y locational pressure-change reading									
Simulated weight gain: Mean of three trials									
Participant	0 kg		10kg		20kg		30 kg		Description
	Mean y	std.	Mean y	std.	Mean y	std.	Mean y	std.	
A	5.90	0.52	5.97	0.06	6.27	0.23	6.23	0.29	healthy
B	4.83	0.83	5.40	0.35	5.63	0.40	5.83	0.12	
C	5.00	0.50	4.27	1.03	5.40	0.35	5.17	0.12	
D	4.80	0.26	5.47	0.32	5.57	0.31	5.60	0.10	
E	5.20	0.53	5.87	0.68	6.23	0.25	5.90	0.87	overweight
F	6.20	0.26	6.17	0.67	6.13	0.23	6.47	0.15	
G	7.57	0.42	7.43	0.21	7.60	0.10	7.43	0.25	
H	5.20	1.39	5.40	0.26	5.13	0.55	5.87	0.23	
I	4.90	0.82	5.20	0.53	6.10	0.10	4.17	0.67	obese
J	5.20	0.96	3.60	0.17	4.27	1.31	4.60	0.26	
K	6.03	0.55	6.60	0.26	6.70	0.17	6.80	0.36	
L	5.87	0.32	6.00	0.10	6.33	0.21	6.73	0.47	

4. DISCUSSION

In evaluation of the **(17) targeted** pressure values in the normal foot. Fifty-three healthy subjects (17 females and 36 males) aged between 19–52 years were recruited. The authors divided the foot plantar area into ten regions. Six of the most clinically relevant parameters which were peak pressure (PP), contact area (CA), contact time (CT), pressure-time integral (PTI), force-time integral (FTI) and instant of peak pressure (IPP). They established that the highest areas of PP were found under the second and third metatarsal heads, with mean equal to 361 kPa and 330 kPa, respectively, followed by the hallux 321 kPa and heel 313 kPa. CA was highest under the heel strike at 35 cm^2. The percentage CT was in the range 75-85% under the metatarsal heads, and 70% under the hallux. Additionally, PTI was highest under metatarsal heads one to three and hallux 87 kPa s, 107 kPa s, (104 kPa s, and 87 kPa s respectively. FTI was highest under the heel 105. The ranges of the parameters documented can be applied in orthopaedic clinics as part of the assessment of pathological conditions.

Authors of (18) have investigated foot pressure differences between two differences racial group of thirty-six participants {twelve Caucasians (19–52 years and twenty-one person from India 21-46 years) using the in-shoe pressure (Pedar ®system). The authors divided the foot into 10 regions. They concluded that the Caucasian group is higher than the Indian group in two pattern parameters which were PP and PTI; Particularly the PP under the heel 293 kPa vs. 251 kPa; $P < 0.001$), 1^{st} (294 kPa vs. 233 kPa; $P = 0.01$), 2^{nd} (266 kPa vs. 236 kPa; $P = 0.03$), 3^{rd} (254 kPa vs. 223 kPa; $P = 0.04$), and 5^{th} (168 kPa vs. 133 kPa; $P = 0.04$) metatarsal heads and the PTI under the 1^{st} (79 kPa s vs. 62 kPa s; $P = 0.03$) and 5^{th} (58 kPa s vs. 44 kPa s; $P = 0.03$) metatarsal heads in the Caucasian group was higher than in Indian group. There were no significant differences in the CA. CT, FTI, IPP, MaxF and MeanF variables among two groups.

Authors of (19) studied a comparison in-shoe foot pressure parameters in males and females in 10 different regions of the foot for all the important pressure measurement characteristics. Twenty-eight subjects [sixteen females aged between (19-52) and twelve males aged between (21-52)] were recruited. The authors observed that contact area in male was significantly larger in all regions of the foot compared with females ($P < 0.001$). They found a higher value within heel region (44.1 cm^2 male and 34.1 cm^2 females). Furthermore, force–time integral was also significantly higher in males than females under the 1^{st}, 3^{rd}, and 4^{th} metatarsal heads (58, 35, 26 N s) while in females it was (41, 21, 13 N s) respectively. Also, maximum force was also significantly higher in males under the heel compare to females (701 N and 525 N), 1^{st} (216 N and 168 N) and 3^{rd} (115 N and 77 N) metatarsal heads. And, mean force was greater in males under the 1^{st}, 3^{rd}, and 4^{th} metatarsal head. The authors found that there were no significant differences between genders in contact time, peak pressure, pressure–time integral and instant of peak pressure in the foot

The authors of (20) predestined pressure value in normal foot by Emed1 ST2 system. Twenty-three (fourteen females and nine males) participated, mean aged (36.0 ±11.6 years). The authors divided the foot for 10 regions to recoded seven-foot pressure variables which were beginning of contact (BC), end of contact (EC), contact time (CT), peak pressure (PP), instant of peak pressure (IPP), contact area (CA) and pressure–time integral (PTI). The highest areas of PP were found under the hallux and second metatarsal heads, with mean equal to 435 kPa and 407 kPa, respectively, followed by the third metatarsal head 345 kPa and the hindfoot 332 kPa. The CT (range of pressure, %) was in the range 74–85% under the metatarsal heads, and 71% under the great toe. CA was highest under the heel at 33.8 cm^2.

Based on our literature review, there is no research which studies simulated body weight to evaluate the x-locational and y- location pressure changes. Founded on the limited data for x-locational change, the healthy weight subjects' foot pressure compressed the soft plantar tissues more than the over-weight and obese subjects when a load was applied, with mean (4.39) of the control (0 kg) compared to mean (4.81) of (30 kg) conditions.The rational of such occurrence was that the soft tissue of over-weight and obese subjects were subjected to heavier weight constantly, thus having a small change in the weight was no longer having a greater impact.

The mean for y-locational with (0kg) and (30 kg) were 5.15 and 5.72, respectively.

As the data were normalized according to the total time taken for the loading phase of the gait, the y-locational change was due partly to the extra-weight which could increase the time of lifting the foot.

Therefore, the results showed that the x-locate and y-locate change can be to calculate the change in the rotation of ankle joint.

The techniques could be used to demonstrate the effect of walking along hilly walkways.

(Notes: in our discussion section, the x and y-locational means for the left and rights side were comparable and combined values are presented the relationship between dynamic foot alignment and foot pressure patterns in participants with different load).

5. CONCLUSIONS

The utilization of an innovative pre-marked medial foot reference and the advanced insole foot pressure sensor have made the demonstration of the effect of overweight on the ankle motion possible. Preliminary tests showed that the technique is practical for clinical study and clinical demonstration. Further testing will be needed to demonstrate the suitability of the techniques for developing an indexing scheme for the study of ankle injury of obese people.

6. REFERENCES

[1] Anandacoomarasamy, A., Caterson, I., Sambrook, P., Fransen, M. and March, L., 2008. The impact of obesity on the musculoskeletal system. International journal of obesity, 32(2), p.211.

[2] Jegede, J.A., Adegoke, B.O. and Olagbegi, O.M., 2017. Effects of a Twelve-Week Weight Reduction Exercise Programme on Selected Spatiotemporal Gait Parameters of Obese Individuals. Journal of Obesity, 2017.

[3] Rossouw, H.A., Grant, C.C. and Viljoen, M., 2012. Overweight and obesity in children and adolescents: The South African problem. South African Journal of Science, 108(5-6), pp.1-7.

[4] Tavel, Sheffler, L.R., Bailey, S.N., Gunzler, D. and Chae, J., 2014. Effect of body mass index on hemiparetic gait. PM&R, 6(10), pp.908-913.

[5] Vijaya kumar, K., Senthil kumar, S., Ramesh kumar Subramanian 2016. A Study on relationship between BMI And prevalence of flat foot among the adults using foot print parameters. International Journal of Advanced Research.Volume 4, Issue 5, 1428-1431.

[6] Chong AK, Milburn P. Push-off apparent time delay based on COP trajectory of gait. Footwear Science 9(sup 1) (2017) S54-S56.

[7] Pataky, TC, Caravaggi, P, Savage, R, Parker, D., Goulermas, JY, Sellers, WI, Crompton, RH. New insights into the plantar pressure correlates of walking speed using pedobarographic statistical parametric mapping (pSPM). Journal of Biomechanics 41 (2008) 1987–1994.

[8] Hills, A.P., Hennig, E.M., Byrne, N.M. and Steele, J.R., 2002. The biomechanics of adiposity–structural and functional limitations of obesity and implications for movement. Obesity reviews, 3(1), pp.35-43..

[9] Birtane, M. and Tuna, H., 2004. The evaluation of plantar pressure distribution in obese and non-obese adults. *Clinical Biomechanics*, *19*(10), pp.1055-1059.

[10] Vela, S.A., Lavery, L.A., Armstrong, D.G. and Anaim, A.A., 1998. The effect of increased weight on peak pressures: implications for obesity and diabetic foot pathology. *The* Journal of foot and ankle surgery, 37(5), pp.416-420.

[11] Butterworth, P.A., Landorf, K.B., Smith, S.E. and Menz, H.B., 2012. The association between body mass index and musculoskeletal foot disorders: a systematic review. Obesity reviews, 13(7), pp.630-642.

[12] Dowling, A.M., Steele, J.R. and Baur, L.A., 2001. Does obesity influence foot structure and plantar pressure patterns in prepubescent children? International journal of obesity, 25(6), p.845.

[13] [13] Browning, R.C. and Kram, R., 2007. Effects of obesity on the biomechanics of walking at different speeds. Medicine & Science in Sports & Exercise, 39(9), pp.1632-1641.

[14] Yan, S.H., Zhang, K., Tan, G.Q., Yang, J. and Liu, Z.C., 2013. Effects of obesity on dynamic plantar pressure distribution in Chinese prepubescent children during walking. *Gait & posture*, *37*(1), pp.37-42.

[15] Waaijman, R & Bus, S 2012, 'The interdependency of peak pressure and pressure–time integral in pressure studies on diabetic footwear: no need to report both parameters', Gait & posture, vol. 35, no. 1, pp. 1-5.

[16] Chong, A.K., Alrikabi, R. and Milburn, P., 2017, July. Gait COP trajectory of left side hip-dislocation and scoliotic patient using ankle-foot orthoses. In *Ninth International Conference on Digital Image Processing (ICDIP 2017)* (Vol. 10420, p. 104204S). International Society for Optics and Photonics.

[17] Putti AB, Arnold GP, Cochrane LA, Abboud RJ (2008) Normal pressure values and repeatability of the Emed (R) ST4 system. *Gait Posture.* 27: 501-505

[18] Putti, A.B., Arnold, G.P. and Abboud, R.J., 2010. Differences in foot pressures between Caucasians and Indians. *Foot and Ankle Surgery*, *16*(4), pp.195-198.

[19] Putti, A.B., Arnold, G.P. and Abboud, R.J., 2010. Foot pressure differences in men and women. *Foot and ankle surgery*, *16*(1), pp.21-24.

[20] Maetzler M, Bochdansky T, Abboud RJ. Normal pressure values and repeatability of the Emed® ST2 system. Gait & Posture. 2010 Jul 1;32(3):391-4.