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Effect of arch type and Body Mass Index on plantar pressure distribution during stance phase of gait

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Several factors have been associated with the presence of abnormally high plantar foot pressure including: (i) increased body weight, (ii) foot structure and (iii) walking strategy. It is predicted that the biomechanics of the foot is influenced by the structure of the foot, primarily the Medial Longitudinal Arch. The objective of this study was to examine if Body Mass Index and the foot arch have a direct effect on dynamic peak plantar pressure for healthy subjects. Following a clinical lower limb examination, the Tekscan HR mat was utilised for this study, plantar pressure was profiled at specific events during stance phase of gait including heel strike, midstance and toe off. Results indicated to the preferable normal arch as this produced a low plantar pressure distribution in all cases. The 2nd and 3rd metatarsal head region recorded the highest pressure for all arch types during dynamic analysis. The lowest pressure for the normal and overweight BMI was at toe-off. While the obese BMI group showed highest pressure during toe-off. The obese BMI flat arch sub-category indicated to functional ambulation differences. Future work involves comparing this healthy database to a demographically matched diabetic group.

Key words: *Body Mass Index, foot arch type, gait, plantar pressure distribution*

1. Introduction

Foot structure has a long established connection to foot function within the research field. Foot structure is described and categorised according to foot type, which encompasses foot arch type. When discussing arch type it is specifically in relation to the Medial Longitudinal Arch (MLA). Previous studies believe that the diverging structure of the MLA influences dynamic function of foot [1]. MLA is simply categorised between high (*pes cavus*), normal and flat (*pes planus*) [2]. A high arched foot is denoted by an evidently large gap between the MLA and the ground surface. The majority of cases of high arch are imagined to be idiopathic. A normal arch pertains to the MLA set in a neutral position. Normal arches are not as common as the label normal perceives, it dose however imply that there should be no adverse influences to dynamic foot motion. Plantar pressure in a normal arched foot is generally distributed evenly with no major peak regions resulting in a stable, smooth movement though the gait cycle. Structurally, a flat arch is observed by the lack of space between the inner arch and the flat ground surface. During ambulation it is a frequent occurrence for a subject to experience a inward foot tilt [3]. A flat arch is the most unnatural arch during progression of the gait cycle. The flat arch is caused by the collapse of the MLA and/or the lack of support and strength to the arch.

The architecture of the foot ankle complex is inclusive of bone, muscle and ligaments which support the MLA giving it its shape, strength and stability. Variations to the arch structure lead to the high and flat arches as described. Deviation from the normal arch can be due to an ordinary variant, hereditary and/or neurological problem [3]. These biomechanical differences not always interfere with foot function.

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The relationship is ambiguous and research has not clearly defined a link as the inputs are numerous. Plantar pressure analysis is considered a reliable evaluation of foot function. This study collaborates the effect of Body Mass Index (BMI) on foot function and foot structure, investigating any trends within the acquired results.

BMI is a method of expressing and analysing a person body fat utilising the measurements of height and weight. BMI is applied to evaluate a patient's body weight in relation to what is considered normal for a person of the specified height. BMI is calculated by dividing an individual's body weight by the individual's square height. This formula computes a unit of Kg/m^2. BMI is categorised as underweight (<18.5 Kg/m^2), normal (18.5–24.9 Kg/m^2), overweight (25–29.9 Kg/m^2) and obese (>30 Kg/m^2) [4]. Classification of BMI is utilised in a clinical aspect as a quick and easy method of classifying physically inactive persons with an average body composition [5].

For this study three areas of specific interest were investigated on the plantar surface of the foot, these were (i) hallux, (ii) 2nd and 3rd metatarsal head region and (iii) heel (Figure 1). These three areas are described throughout literature as the commonly increased pressure areas. Armstrong et al. [6] and Ctercteko et al. [7] along with others have concluded that the aforementioned plantar areas are the most inclined to develop calluses and ulcerations as a direct consequence of elevated pressure. These regions are also associated with the highest incidence of ulceration in neuropathic patients [8], [9].

The effect of MLA and also BMI on plantar pressure has not been clarified by present literature. Cavanagh et al. [10] investigated the structural and function characteristics of the foot during walking. Similar to this study plantar pressure profiling was employed to assess functionality. It was found that 35% of the variance in plantar pressure was due to foot structure. This is an inconclusive result but it was concluded by the authors that plantar pressure is influenced by gait pattern and not the foot structure [10]. Cornwall et al. [11] reported poor predictability among arch type and foot function. It was observed that high arched feet exhibited delayed loading of the hallux, while low arched feet showed premature loading of the 5th metatarsal area. Following the aforementioned studies, Van Schie et al. [12] set out to examine the effect of arch index and body mass on plantar pressure for diabetics and non-diabetics subjects. The correlation of body mass and plantar pressure was responsible for 16% of the variance of peak pressure under the foot. A review of previous literature lead to the conclusion that the effect of foot arch on plantar pressure is an area of research which has led to inconclusive trends among varying studies [2], [10], [12], [13]. Therefore, the aim of this study is to further investigate the effect of BMI and foot arch type on common peak plantar pressure areas for healthy subjects.

2. Materials and methods

2.1. Subjects

Ethics Committee approval for this study was received from the Cork Institute of Technology Ethical Review Board. All subjects were fully informed of the study to be performed and all enrolled subjects signed written consent form.

Recruitment was communicated through the mediums of email and word of mouth. All of those whom expressed interest were encouraged to attend the gait laboratory for a foot exam and to complete a lifestyle questionnaire. The purpose of the Foot exam was to ensure no participants had lower limb ailments. Inclusion criteria required that all subjects were in good general health prior to and during assessment, where within the age category of 18–70, had no history of previous lower limb surgery or ulceration and demonstrated no other neurological or orthopedic impairments such as severe knee deformations (genu valgum/genu varum) or severe foot deformities that would adversely affect their gait.

A group of 33 healthy subjects were enrolled for this study (Table 1). The mean age, body mass and height were 35 years (20–70 years), 84 kg (range 50–131 kg) and 168.83 ± 10.696 cm.

2.2. Research design

The clinical assessment consisted of performing a visual exam of the foot and ankle complex, noting appearance of symmetry, deformities and the skin discoloration and roughness. Simple examinations of sensation and range of motion were also completed. Foot assessment was based on the SIGNS guidelines [14] and a localised Diabetic foot risk assessment tool.

BMI was calculated based on the recorded participants' height and weight. The findings were then categorised between normal, overweight and obese according to the WHO standards [4].

MLA type was classified as flat (FT), normal (NL) and high (HH) through performance of the aforementioned clinical foot assessment. Handheld callipers were utilised to get appropriated measurement in order to ascertain Arch Height Index in accordance with McCrory et al. [15]. In addition digital photography was used to backed up classification of arch type by the Arch Index. Tekscan HR Mat[tm] pressure mapping system (Tekscan, Inc., US), with sensor spatial resolution of 4 sensels/cm^2 and recording at 80 Hz was used to capture barefoot plantar pressure distribution and analyse foot function. Equipment was calibrated to each subject's body mass prior to assessment. Data was collected from five dynamic trials while subjects ambulated down a 5 meter walkway. Participants were allowed to practice walking, so as to strike the pressure mat at a comfortable position during their gait cycle. The peak pressure was analysed under hallux, head of 2nd and 3rd metatarsal (M_2M_3) and the heel as these areas are more susceptible to formation of calluses and pressure ulcers (Fig. 1). Only footprints which occurred after initiation of walking (second or third step) were utilised for profiling. Also trials were eliminated if the subject did not strike the mat correctly or if the subject seemed to adapt their gait to aim for the mat.

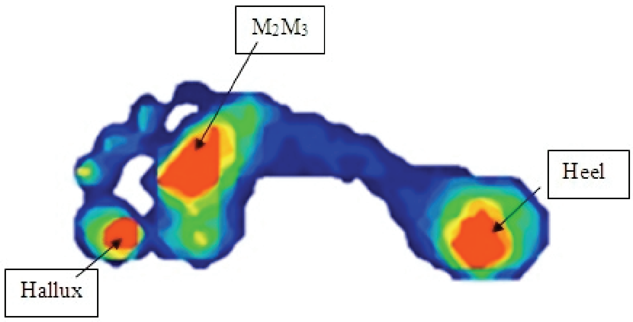

Fig. 1. Plantar areas of interest

2.3. Data and statistical analysis

All data recorded was scrutinised in order to eliminate unsuitable trials. Appropriate trials were then collected and analysed. The Research Foot 6.33 analysis software (Tekscan, Inc., US), was utilised to create any masks needed and also the isolated the plantar regions of the foot in question. Peak pressure was documented for the three areas throughout the phases of stance.

Statistical analysis was performed using the OriginPro 8.1 (OriginLabCorporation, US). Data distribution *n* was assessed with Shapiro–Wilk and histogram tests. Normally distributed continuous variables were subjected to two tailed *t*-tests. Mann–Whitney test was used on skewed data. Pearson Chi-squared test was performed on categorical data. A *p*-value of less than 0.05 was considered statistically significant.

3. Results

Participants' information is reported in Table 1.

Participants were instructed to walk the platform with a self-selected ambulation pace, Table 1 indicates the average walking characteristics. Group walking speed was 1.23 ± 0.5 m/s.

All subjects' results were classified between arch type and BMI and are summarised in Table 2. There was no significant difference between averaged BMI when related to arch type classifications. This specific group showed those that fell with the normal BMI classification had either a high of normal arch. The overweight category indicated all three arch types, while the obese grouping classified the normal and flat arch.

Table 1. Participants' demographic and walking characteristics

	Participants (n = 32)
Male	81.25%
Age (years)*	35 (20–70)
Weight (Kg)*	84 (50–131)
Height (cm)**	168.83 ± 10.696
BMI (Kg/m^2)*	25.865 (19–37)
Temporal parameters	
Cadence (steps/min)*	112.167 (88.7–127.8)
Stride time (seconds)*	1.071 (0.85–1.353)
Step time (seconds)*	0.525 (0.475–0.685)
Walking speed (m/s)**	1.23 ± 0.5
* Median(Range) ** Mean ± standard Deviation	

Table 2. Subjects correlated to arch type and BMI

	BMI category		
Arch type	Normal	Overweight	Obese
Flat	0	5	4
Normal	5	6	1
High	7	5	0

Peak pressures at the commonly increased plantar pressure regions are represented in Fig. 2 for the three BMI categories and the respective arch type groups. A non-significant trend emerged, the NL arch group indicated to the lowest pressure at the hallux in the three BMI groups. In addition, the average combined peak pressure per arch type, elevated with increasing BMI (Fig. 3). Statistical differences were noted between the obese BMI category and both other categories ($p < 0.05$).

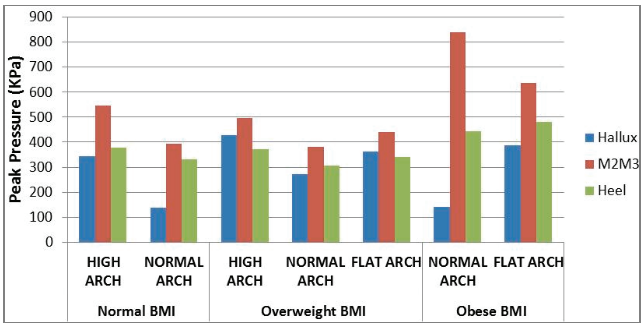

Fig. 2. Peak plantar pressure areas correlated to BMI and arch type

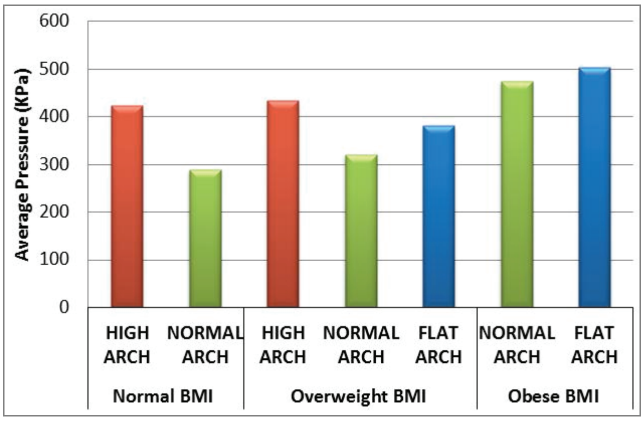

Fig. 3. Average peak pressures correlated to arch type and BMI

Figure 4 visualises peak plantar forces for the three BMI groups during the specified phases of dynamic stance; heel strike, midstance and toe off. Heel strike indicated the highest plantar pressure in the normal and overweight categories. The obese BMI shows toe-off to have highest plantar pressure.

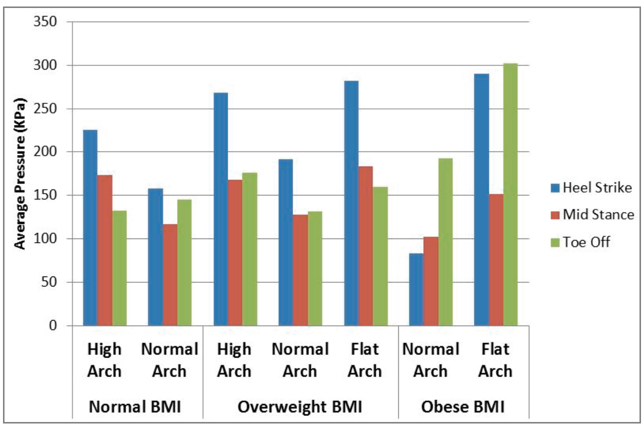

Fig. 4. Peak pressures during dynamic phases of stance correlated to arch type and BMI

4. Discussion

This study set out to investigate if a relationship exists between BMI, arch type and peak plantar pressure. Peak pressure was examined in dynamic component. Results indicated to interesting trends.

Table 1 indicates to participant demographic. 81.25% of the cohort were male, which corresponds with WHO information that majority of overweight population are older males [4]. In addition, the median BMI was 25.865 Kg/m^2 with a range of 19–37 Kg/m^2. The participants were encouraged to ambulate at a speed comfortable and normal to them, the median cadence was 112.67steps/min (88.7–127.8 steps/min). A mean walking speed of 1.23±0.5m/s was recorded for the group. Cadence and walking speed were not significantly difference across the group ($p > 0.05$).

Some results from this study correlate with topics also investigated by Van Schie et al. [12]. It is agreed that trends emerged throughout analysis but not enough statistical significance was generated. This was an anticipated consequence of examining an assorted group of subjects. It is obvious from everyday observation of ambulation that people adopt unique walking strategies, which in turn effects the plantar pressure distribution.

This study along with previous literature [12], [16] noted an association between a higher BMI classification and a FT arch. The obese BMI category did not incorporate HH arch participants (Table 2). In addition, the normal BMI group did not have any FT arch subjects. It is the opinion of the authors that there is an association between a higher BMI and attaining a FT arch. It was not the intention of the authors for the data to spread in this manner. Contrasting the arch type data (Fig. 3), averaging peak pressures, the NL arch recorded lower pressures although not significantly difference. When mean NL arch values are compared to those of the HH and FT arch, it is apparent that a deviation for a NL arch type can leave a person susceptible to elevated pressures under the foot. However, the obese BMI category NL arch did indicated elevated average plantar pressure.

It can also be comprehended that the M_2M_3 region experiences the highest pressures, for all arch types, when contrasted to hallux and heel areas (Fig. 2). Are metatarsal region in the obese BMI category is extremely elevated ($p < 0.05$). The participants within this grouping performed toe-off from this region, without progression to the hallux in majority of cases. The pressure increase at the M_2M_3 region is due to the elongated period that pressure is in the region, due to toe-off, in a majority of cases. This is irritated by the reduced pressure at the hallux. This indicates an adapted walking strategy in order to redistribute pressure on the plantar surface.

Analysis of plantar pressure results in relation to phases of stance produced novel findings. The toe-off section of stance shows the lowest pressure under the foot for the normal and overweight BMI (Fig. 4). On further examination this is an explainable result and could be due to the fact the foot sequence is heading into pre swing. Heel strike illustrates the highest pressure for normal and overweight BMI groups. The obese BMI grouping again indicated significantly different pressure resutls ($p < 0.05$). Toe-off showed to highest pressures, 300 KPa for the FT arch. It is the opinion of the aurthors that this is due to the aforementioned ambulation strategy, specifically that toe-off is taking place at the metatarsal region and not the hallux. Also, the FT arch obese category have elevated heel strike and toe-off in comparison to mid stance pressure. The walking strategy of this group consisted of a heavy slow heel strike, rapid progession though mid foot and a prolonged toe-off. This is reflected in the pressure results.

At heel strike the FT and HH arch subjects hit pressure recordings within the range of (225–290 KPa) This suggests the heel is a major area for concern especially at heel strike particularly for those with HH or FT arch types as the NL arch did not excede 200 KPa.

Examining the phases of gait was a new approach to investigation of the plantar pressure distribution. Again it is possible to draw the conclusion that a NL arch is a preferable arch type as it produced lower plantar forces at all instances analysed. This is an important research finding, although is it not possible to alter arch type. In some cases a flat arch is acquired due to various symptoms such as increased body weight, therfore in this type of situation it is possible to apply avoidance methods.

This study is not with out its limitations. A major disadvantage is the sample size. With a more diverse and increased sample size the normal BMI FT arch, the obese BMI HH arch and NL arch would be well represented. In addition, a future study is on going comparing this cohort to a match diabetic population.

5. Conclusion

To date the relationship between foot functionality and foot structure is ambiguous. Therefore, this study collaborated the effect of arch type and BMI on plantar pressure during barefoot ambulation. This study also integrated these effects on the functional aspects of the stance phase. It is evident on analysis of results that there is a connection between arch type and foot functionality. The obese BMI FT arch grouping showed to have adapted ambulation and reduced functionally within the mid foot. To conclude a normal arch has the least possibility of injury, and problems with functionality due to its even plantar pressure distribution. Also, as BMI and average plantar pressure increased proportionally. It is prevalent that a high BMI and low arch are predictors for elevated plantar pressure.

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