

Balance and Pressure Distribution under the Foot during Standing and Walking with no Orthotics Compared to Custom and off the Shelf Orthotics, A Pilot Study

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Rec date: Sep 16, 2014, Acc date: Nov 15, 2014, Pub date: Nov 23, 2014

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Abstract

Objective: Potential pain relief from foot pain can come from a shoe insert foot orthotic. This study assessed foot pressure distribution and balance in off the shelf foot orthotics versus a custom made foot orthotic compared to no orthotic.

Methods: The subjects (8) were both men and women. The average age was 25.1 ± 2.8 years, the average weight was 68.8 ± 13.7 kg, and BMI 24.5 ± 6.4 . Each patient was fit for both off the shelf and custom shoe insert foot orthotics and needed orthotics to reduce pain. Once fit, they were evaluated by standing and then walking 12 meters on a level surface while being monitored by a Tactilus Pressure Mapping system. Balance was also evaluated with a pressure platform during 8 balance tests.

Results: With the subjects accomplishing quiet standing, the average pressure and peak pressure was shifted from the hind foot and forefoot to the mid foot when wearing foot inserts ($p < 0.05$). During walking, the average pressure was significantly shifted from the forefoot and hind foot to the mid foot in both orthotic groups with the greatest reduction in forefoot pressure in the off the shelf orthotic group ($p < 0.05$). This is especially seen when measuring the peak pressures on the foot, where, during standing the peak pressures on the fore foot were 20% higher with no orthotic than seen for the 2 orthotics tested here. Balance was best in the custom orthotic group while both orthotic groups had better balance than the no orthotic studies for the most difficult balance tests. Conclusion: At least in this small group of subjects, off the shelf foot orthotics help gait or balance but custom orthotics are better.

Keywords: Orthotics; Plantar pressure; Arches

Introduction

Foot impairments are a common condition affecting people who have many different levels of activity and can happen at any age [1-3]. Obesity, high muscle activity, old age, and arthritis are some of the leading conditions contributing to foot pain [4]. Foot pathologies include flattened arches, toe deformities from improperly fitted shoes, pronated feet, and inflamed aches are other common disorders [4].

Obesity is growing in America and around the world [5]. A study conducted on adults, shows that both men and women are continuing to shift from overweight to the classification of obesity [6]. Obesity is measured by having a BMI greater than or equal to 30 [6,7]. Obesity can cause posterior tibial tendon dysfunction. This acute condition is more common in women and people over 40 years old. Specifically, a tear or inflammation of the tendon being overused causes the arch of the foot to slowly collapse [8]. Other effects linked to obesity include tendonitis, plantar fasciitis, and osteoarthritis of the foot and ankle [8].

Arthritis, due to age, is another leading cause of foot dysfunction [9]. Arthritis of the tarsometatarsal joint in the elderly has increased tremendously. Common characteristics of arthritis of the tarsometatarsal joint are pain and low-arch alignment, which limit the ability to walk [9].

The onset of disabling foot pain increases with increasing age [10]. The toe region is the most common location of foot pain of older community-dwellers [11]. Common toe deformities are claw or hammer toes. Lump formations from a misaligned big toe joint that makes the big toe turn inward toward the other toes are known as bunions, can often be very swollen and tender. Calluses occur on the soles and sides of feet which is excess growth of hard skin that forms in response to a pressure point. Similarly, corns form over bony areas and on top of toes [4,12].

Problematic foot conditions can occur unilaterally or bilaterally. Foot pain affects activities of daily living, such as shopping, walking, or heavy housework. Pain during walking is associated with high plantar pressures along the bottom of the foot, as well as the second metatarsal head [11]. The average pressure generated beneath the second and third metatarsal heads is associated with higher plantar pressures overall. Considering this, higher planter pressure discomfort, in turn, causes gait and balance impairment [13]. Plantar fasciitis, pes cavus, and pain produced functional limitations are especially seen in older individuals [14].

Burns and colleagues have stated that the pes cavus foot is characterized by an excessively high medial longitudinal arch [15]. It is also known as a high-arched or supinated foot. The foot type is a multi-planar foot deformity that creates a varus rear foot, a plantar flexed first metatarsal, and clawing of the digits. People with cavus feet experience foot pain such as metatarsalgia, sesamoiditis, or plantar heel pain. Interestingly, arch height does not necessarily predict pain

or dysfunction considering many people have natural high arches from birth [16]. The difference in height between the forefoot and the hind foot is often associated with a tight plantar fascia [4].

As a result of persistent pain, people may compensate for the pain by walking on the lateral border of the foot and reduce rear foot and forefoot loading by shifting their weight bearing pattern [17, 18]. To reduce pain, shoe insert orthotics is commonly used.

Early foot orthotic designs were made by innkeepers from matted animal hair retrieved from barns, which today we know as felt. But, the functional foot orthotic boom began in the late 1960's when increased knowledge in pathology and anatomy helped improve the effectiveness of foot orthotics [19]. These new functional foot orthotics encouraged joint stability, pressure distribution and overall pain reduction [20].

Today, shoe inserts can be easily purchased at stores or corrective inserts can be custom fabricated by certified orthotists [19]. While both types of inserts feel good, functional testing for pressure distribution during gait and balance has not been assessed. Balance can be impaired in people with foot impairments including flat feet [21]. Balance by dynamic posturography has been shown to improve after wearing custom orthotics [21]. However, no study has examined the pressure profiles under the foot with off the shelf vs. custom orthotics as well as balance. This was the purpose of this investigation.

Subjects

The subjects (8) were both men (2) and women (6). The general characteristics of the subjects are shown in Table 1 below. Basic medical and familial history was taken to make sure inclusion and exclusion factors were accessed. Foot evaluation for inclusion and exclusion conditions and pathologies were examined by a certified pedorthist or competent orthotics student. Once the subject was considered eligible for the study, a consent form was fully completed and signed by the participant. They had no current lower extremity amputations, ulcers, bunions or other foot deformities. The subjects presented with no diabetes, morbid obesity, gait or musculature altering pathologies, or any neuropathies or myopathies of the lower extremities. None of the subjects had any lower extremity surgeries or injuries within the last 12 months. The subjects had full range of motion in both lower extremities. Both lower extremities had no congenital deformities or defects. Subjects had all worn foot orthotics due to flat feet. Subjects were informed about all procedures and signed a consent form for participation. This study was approved by the Institutional Review Board of Loma Linda University.

	Age	Height	Weight	BMI
Mean	25.1	167.6	68.8	24.5
Standard deviation	2.8	12.3	13.7	6.4

Table 1: General characteristics of subjects.

Methods

Assessment for custom orthotic

Subjects were digitally assessed using a FootMaxx (Roanoke, Virginia) for a custom foot orthoses. FootMaxx testing was administered and assessed by a qualified pedorthist. Based on FootMaxx results and the recommendation of the pedorthist, a custom foot orthotic was created for each subject

Assessment for commercial orthotics

Subjects were fitted for off the shelf foot orthosis by utilizing a Dr. Scholl's foot evaluation fitting machine. After evaluation from the Dr. Scholl's machine, subjects were recommended the proper orthosis for them.

Assessment of foot pressures

A Tactilus foot pressure map was used to determine pressure distribution of custom and off the shelf-inserts as subjects stood and ambulated. Sensors were placed in between the bottom of the foot and insert. Subjects walked 12 meters two consecutive times wearing each type of insert. The Tactilus Pressure Mapping System is manufactured by Sensor Product Inc. (Madison, NJ). It has 250 sensors under the feet and samples 10 times per second.

Measurement of postural sway

The displacement of the subject's center of gravity during normal standing was measured using a balance platform of 1 m by 1 m in size and 0.1 m in height [22]. Four stainless steel bars, each with four strain gauges, were mounted at the four corners under the platform (TML Strain Gauge FLA-6, 350-17, Tokyo, Japan). The output of the 4 Wheatstone strain gauge bridges was amplified with BioPac 100C low-level bio-potential amplifiers and recorded on a BioPac MP-150 system through a 24-bit A/D converter. The sampling rate was 2000 samples per second [22].

To calculate the load and the center of the pressure of the force on the platform, the output of the four sensors was used to measure the X and Y coordinates of the center of gravity of the subject. To calculate the movement of the center of pressure from the center of the platform, a series of equations were solved in real time from raw platform data. The load cells were labeled as (Rf) right front, (Lf) left front, (Rr) right rear, (Lr) left rear. Assuming then, that the subject is placed initially so that the center of mass provides equal weight distribution to all four sensors, the direction weight varies from the center of the platform and the angle can be calculated as follows. First, assuming that the subject starts with the center of gravity in the center of the platform, the center of the platform can be represented as the origin of a four quadrant diagram as follows in Figure 1:

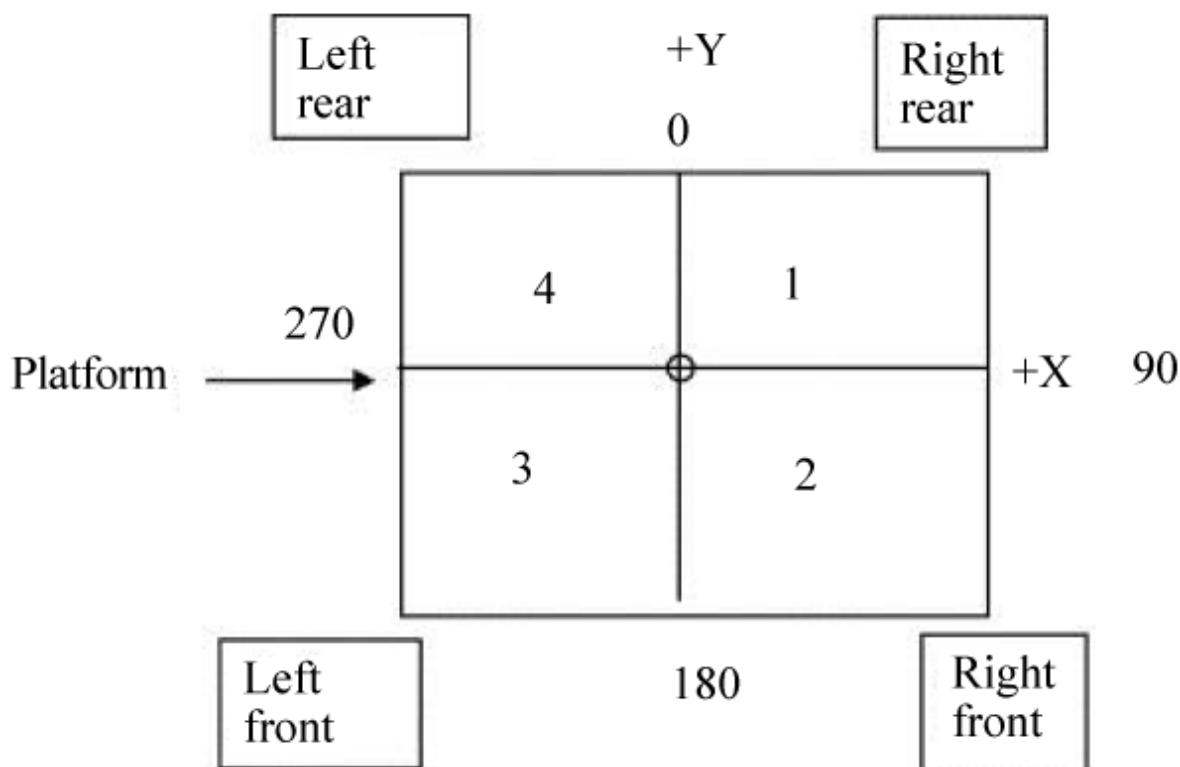


Figure 1: Diagram of the balance platform.

Diagonal movement toward the right rear of the platform would be movement in the first quadrant, movement to the right front of the platform, the second quadrant, movement to the left front of the platform would be to the third quadrant, and movement to the left rear of the platform would be to the fourth quadrant. Movement directly toward the direct back of the platform is in the +Y direction and movement to the right is in the +X direction. If the person was standing with their center of gravity exactly above the center of the platform, they would be at the origin and not leaning to any angle. In a four quadrant system, angles start at the top and in a clockwise direction go from 0° to 360°. For example, leaning toward the front of the platform would cause a vector at an angle of 180° with a magnitude proportional to the extent of the lean. In this manner, then, by using a diagrammatic representation of the platform with the center of the platform being the origin of the graph, to calculate the X and Y coordinates of the movement of the center of pressure from the center of the platform, the following equations are used.

For the Y co-ordinate of the center of pressure

Equation (1)

$$Y = (0.26/BW)[(Rr+Lr)-(Rf+Lf)]$$

where Rr=right rear, Lr=left rear, Rf=right front, Lf=left front. BW=total body weight of the subject. 0.26=the perpendicular distance from the center of the platform in m.

The X coordinate of the weight is calculated as

Equation (2)

$$X = (0.26/BW)[(Rf+Rr)-(Lf+Lr)]$$

where Rr=right rear, Lr=left rear, Rf=right front, Lf=left front. BW=total body weight of the subject. 0.26=the perpendicular distance from the center of the platform in m.

To calculate the polar coordinates of the weight displacement, the following equation is used:

Equation (2)

$$\text{Vector magnitude} = (x^2 + y^2)^{0.5}$$

where x and y are the x and y displacement calculated above in Eqs. (1) and (2). The units here are m. Finally, to calculate the angle that the person leaned, phi, arctangent function is used as shown in Eq. (4).

Equation (4)

$$\Phi = \arctan y/x$$

To convert the angle to a circle, the following conditionals were used as shown below. (1) If X and Y are both positive, then the subject is leaning into the first quadrant and therefore the final angle=90-Φ. (2) If X is positive and y is negative than the subject is leaning into the second quadrant and the angle is 90+Φ. Since phi is a negative angle in this case, by adding the angle will fall between 90° and 180°. (3) If x and y are both negative, then the subject is leaning into the third quadrant and the angle is 270-Φ. (4). Finally, if X is negative and Y is positive, the subject is leaning into the fourth quadrant, the final angle is derived as 270+Φ. The equations and the conditionals accomplished here were solved in real time for each A/D conversion. The equations

were solved 2000 times per second for a continuous presentation of the angle and magnitude of the vector associated with any sway linked to either tremor or movement in the body [23-25]. By averaging the vector magnitude over 6 seconds, mean and standard deviation (SD) were obtained for this measure. The Coefficient of Variation (CV) of movement was calculated (SD/Mean ×100) as a measure of the postural sway [22]. The average CV of each task was then determined by averaging the CVs of the 3 separate trials. The balance platform was validated in previous studies [23-25].

Balance tasks

Eight quiet standing balance tasks, each lasting for 6 seconds were included in this study [26]. To challenge the somatosensory input, 2 different foot positions (feet apart and tandem), and 2 different surface compliances (firm surface and foam) were used. To challenge the visual input, 2 levels of vision (eyes open and closed) were used in the balance tasks. An Aeromat balance block (16×19×2.5 inches) (AGM Group, Aeromat Fitness Product, Fremont, CA) was placed on top of the balance platform and was used as the foam surface. The eight balance tasks are listed below;

- Standing with feet apart on a firm surface with eyes open (FAEO-FIRM) and eyes closed (FAEC-FIRM).
- Standing with feet in tandem on a firm surface with eyes open (TEO-FIRM) and eyes closed (TEC-FIRM).
- Standing with feet apart on a foam surface with eyes open (FAEO-FOAM) and eyes closed (FAEC-FOAM).
- Standing with feet in tandem on a foam surface with eyes open (TEO-FOAM) and eyes closed (TEC-FOAM).

Procedures

Evaluation and comparison of custom and off the shelf orthotics was conducted with the same shoes. The participants were required to provide any running or walking shoes of their choice, with the exception if the sole has high damage or tears. Each participant walked a distance of 12 meters, two consecutive times, at their normal pace, on a flat linoleum surface with no orthotics, custom or off the shelf orthotics. The Tacilus Pressure Mapping System collected all gait data. Each subject then stood in 8 different positions in a random order for ten seconds each while wearing custom orthotics, off the shelf orthotics and no orthotics.

Data analysis

Data analysis involved the calculation of means and standard deviations. To compare means, non-parametric statistics were used. First data was tested and shown to be a normal distribution by a Kolmogorov-Smirnov test. Next mean comparisons were made by Kruskal-Wallis non parametric one way Anova. The significance was $p < 0.05$.

Results

The pressure measured under the foot with no insert is illustrated in Figure 2A. As can be seen here, for the no orthotics condition, the average pressure, which was significantly lower when standing on the forefoot than the mid foot and hind foot ($p < 0.05$), was significantly greater in the fore foot than the mid foot and hind foot when walking ($p < 0.01$). The peak pressures, also shown in this figure, had the same

trends with significantly lower peak pressures on the fore foot during standing ($p < 0.01$) and higher when walking on the forefoot ($p < 0.01$ compared to mid foot and hind foot).

Pressure Mapping Data

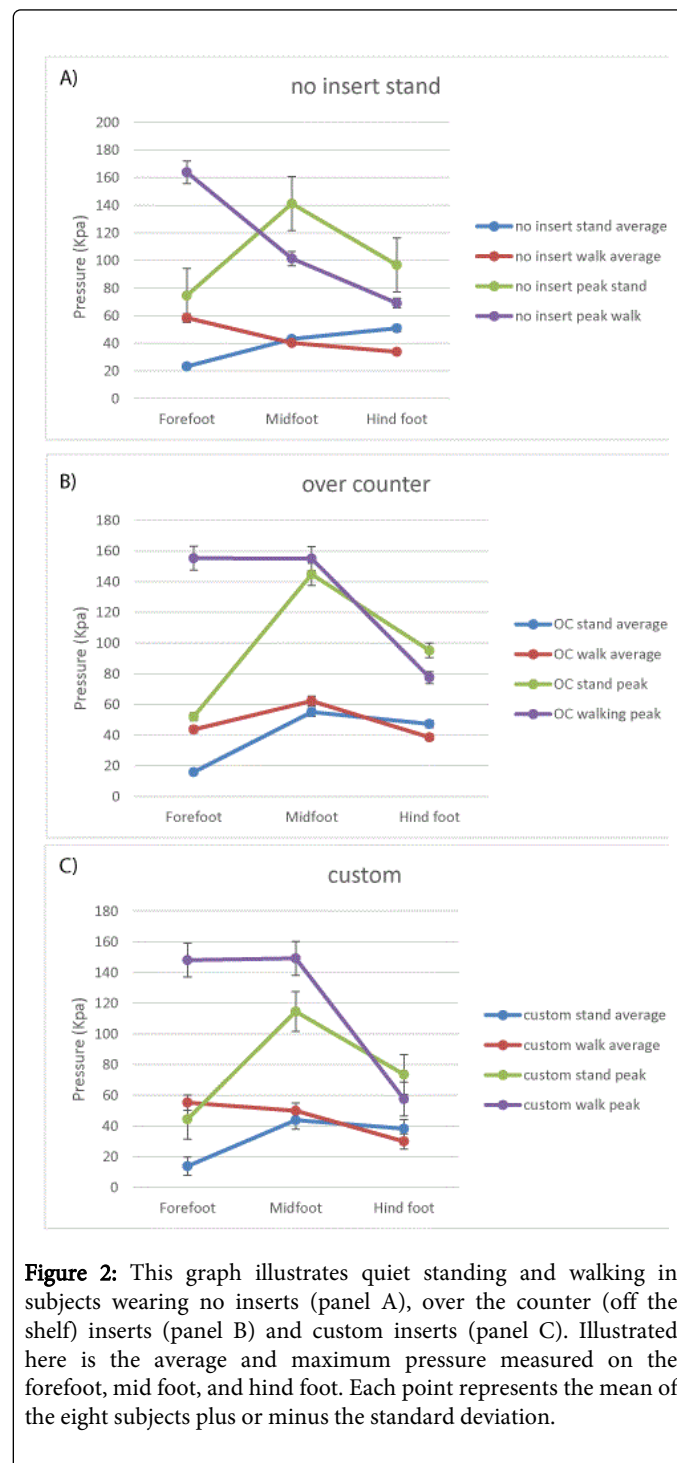


Figure 2: This graph illustrates quiet standing and walking in subjects wearing no inserts (panel A), over the counter (off the shelf) inserts (panel B) and custom inserts (panel C). Illustrated here is the average and maximum pressure measured on the forefoot, mid foot, and hind foot. Each point represents the mean of the eight subjects plus or minus the standard deviation.

The pressure measured under the foot with off the shelf foot orthotics is illustrated in Figure 2B. As can be seen here, the average pressure, which was significantly lower when standing on the forefoot than the mid foot and hind foot ($p < 0.05$), was not significantly

different in the forefoot than the mid foot and hind foot when walking ($p>0.01$). The peak pressures, also shown in this figure, showed significantly lower peak pressures in the forefoot standing ($p<0.01$) but when walking the forefoot and mid foot had the same peak pressures ($p>0.05$). The peak pressures in the hind foot was significantly less than the mid foot and hind foot when walking ($p<0.01$).

The pressure measured under the foot with custom foot orthotics is illustrated in Figure 2C. As can be seen here, the average pressure, which was significantly lower when standing on the forefoot than the mid foot and hind foot ($p<0.05$), was not significantly different for the fore foot than the mid foot and hind foot when walking ($p>0.01$). The peak pressures, also shown in this figure, were significantly lower in the forefoot standing ($p<0.01$) but when walking the forefoot and mid foot had the same peak pressures ($p>0.05$). The peak pressures in the hind foot were significantly less than the mid foot and hind foot when walking ($p<0.01$).

Comparison of the 2 foot inserts with no insert

Comparing data illustrated in the 3 panels of Figures 2, with the subjects accomplishing quiet standing, the average pressure was shifted from the hind foot and forefoot to the mid foot when wearing foot inserts when subjects were standing ($p<0.05$). For the custom orthotic, pressure was significantly less on the fore foot than the off the shelf orthotic ($P<0.05$). During walking, the average pressure was significantly shifted from the forefoot and hind foot to the mid foot in both orthotic groups with the greatest reduction in forefoot pressure in the off the shelf orthotic group ($p<0.05$). This is especially seen when measuring the peak pressures on the foot, where, during standing the peak pressures on the fore foot were 20% higher with no orthotic than seen for the 2 orthotics tested here. During walking, forefoot peak pressures were unchanged between the orthotic and no orthotic experiments but mid foot pressures were significantly elevated in the 2 orthotic groups ($p<0.01$).

Balance Data

Data in this study was plotted in the same manner as in a previous experiment by increasing order of difficulty [27]. Thus when examining Figure 3, data was plotted for sway against increased sensory challenge on the X axis.

In this study, sway increased as the level of difficulty of the standing tasks increased. For each task, e.g. eyes open vs. eyes closed, the sway increased. For example, when comparing the sway for the first two positions, standing feet apart eyes open vs. eyes closed, sway increased from Feet Apart Eyes Open to almost doubling in Feet Apart Eyes Closed. This increase was significant ($p<0.01$). Subjects were challenged even further when they stood on a foam pad. In the last 2 positions sway was increased further. For the least difficult 5 positions, there was no statistical difference between the no orthotic, off the shelf and custom orthotic groups ($p>0.05$). But for the most difficult 3 positions tested for balance sway was significantly less in the foot orthotic groups than the no orthotic group ($p<0.05$). For the 2 most difficult positions, the custom orthotics group has less sway than the off the shelf orthotics group ($p<0.05$).

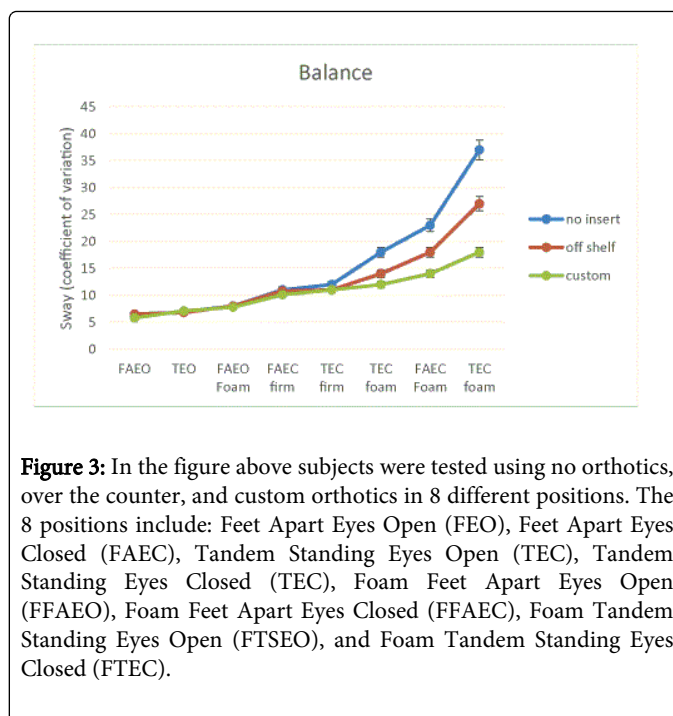


Figure 3: In the figure above subjects were tested using no orthotics, over the counter, and custom orthotics in 8 different positions. The 8 positions include: Feet Apart Eyes Open (FEO), Feet Apart Eyes Closed (FAEC), Tandem Standing Eyes Open (TEO), Tandem Standing Eyes Closed (TEC), Foam Feet Apart Eyes Open (FFAEO), Foam Feet Apart Eyes Closed (FFAEC), Foam Tandem Standing Eyes Open (FTSEO), and Foam Tandem Standing Eyes Closed (FTEC).

Discussion

Due to the rising incidence of obesity and other foot pathologies, the need for foot comfort has become increasingly important [6, 7]. There are multiple options for individuals looking for shoe inserts including off the shelf and custom made orthotics [8]. The basic purpose of shoe inserts is to change the pressure distribution across the foot and relieve overall pain [21,28]. A secondary consideration is balance since somatosensory information from the ankle and feet is important in the postural control [29-31]. Off the shelf inserts are cheaper and often initially more comfortable than custom orthotics but may not provide the same kind of support that would come from an orthotic made specifically for the wearer[32]. Such off the shelf or custom shoe inserts can change the pressure distribution and pain in the foot during standing and gait [33].

In a previous study, a difference in insert length was analyzed to examine the potential improvement in mid foot arthritis. The pressure distributed over the mid foot with both a full length and quarter length custom shoe insert changed the pressure in the mid foot by 20% [9]. This finding suggests that an insert can help to distribute pressure more evenly under the foot and it can provide relief in problem areas. This was also true in the present investigation. Similar changes in pressure were seen. What that study did not show, however, was if a common off the shelf shoe insert can accomplish the same pressure distribution. It also did not show whether or not this change in pressure distribution has an effect on the wearer's balance.

In another study, using a survey of the effect of in shoe foot orthotics on user satisfaction, 96% of the people surveyed stated that they received pain relief when wearing custom inserts made for them and 70% of the surveyed reported that they returned to a full functional activity level after wearing the prescribed inserts [28]. This survey shows that custom orthotics provide pain relief in multiple pathologies but, again, did not evaluate whether or not an off the shelf

insert would be able to provide the same pain relief or how balance might be altered.

Rather than examine pain, in the present study we looked at pressure distribution on the foot in the same subjects when wearing no orthotic compared to off the shelf and custom orthotics. Of functional significance was the assessment of balance. Here, during stranding, the foot inserts shifted significant pressure from the forefoot to the mid foot when standing. This was also true of peak pressures when standing or walking. This then agrees with a study on custom and off the shelf orthotics on cadavers examining stress and strain in the bones of the foot [34].

Somatosensory information from the ankle and foot was reported to be important in the postural control [29-31]. Here, as in a previous study, sway was worse in the most difficult balance tasks [27]. For simple balance tests, the inserts offered no better balance during balance testing than did the no insert testing. But for the most difficult balance tasks when vision and feeling on the feet was removed as inputs from balance, the custom orthotic was significantly better for balance than the off the shelf orthotic than the no orthotic condition. There have only been a few studies on orthotics and balance. For example, when using an AFO vs. taping, subjects with an ankle foot orthosis had better balance [21]. While these were custom ankle braces, even off the shelf orthotics foot orthotics altered the muscle activity in the vastus lateralis and gluteus medius during exercise [35]. This same type of increased muscle activity was seen in women wearing high heels where foot stability was maintained by increased muscle co-contraction [36]. The increased muscle activity and co-contraction would aid to stiffen the foot and ankle and lower leg and should increase postural stability at the expense of increased muscle activity. While maintaining balance involves the integration of the sensory systems (vestibular, visual and somatosensory systems) in the CNS, the motor system is also imperative in postural control [37]. The musculoskeletal system can add to stability by using activation of both agonist and antagonist activity to stabilize the body [38]. Laughton and colleagues [39] have shown a correlation of muscle activity at the ankles with the short-term postural sway. Lord and colleagues [40] also reported an association of the increase in body sway with weakness at lower legs especially the ankle dorsiflexors [41]. This also can be said of the orthotic itself. By reducing flexibility of the foot and shifting weight to the center of the foot in line with the center of gravity of the body, it should increase postural stability. Postural stability was better in custom orthotics probably due to better fitting since the off the shelf orthotics also increased balance.

This study was limited to one foot pathology on younger people. Further research needs to look at other pathologies and subject groups to further explore the differences in these orthotics.

Conclusion

In the present investigation, custom made shoe inserts made a significant difference in the amount of pressure distribution and balance during gait. The subjects however, only consisted of people with little to no foot pathologies or pain during gait. These studies should be expanded to both older subjects and subjects with foot pathologies and repeated on larger numbers of subjects.

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