Sensitivity of the foot in the flat and toe off positions

Buso, Alice; Shitoot, Ninad

DOI
10.1016/j.apergo.2018.12.001

Publication date
2019

Document Version
Final published version

Published in
Applied Ergonomics

Applied Ergonomics 76 (2019) 57–63

Contents lists available at ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo

Sensitivity of the foot in the flat and toe off positions

Alice Buso*, Ninad Shitoot

Delft University of Technology, Faculty of Industrial Design Engineering, the Netherlands

ARTICLE INFO

Keywords:
Foot
Sensitivity
Pressure discomfort
Pressure points
Footwear design

ABSTRACT

The purpose of this study is to examine the differences in pressure sensitivity for areas of the foot in a toe-off position and with the feet on the ground. This data could provide a base for adapting the softness of different areas while designing footwear. 21 healthy subjects are asked to participate in a test where a researcher applies pressure with an advanced force gauge in 20 locations on the foot until the subject starts experiencing discomfort. Rigid shells of three sizes have been designed and 3D printed based on 3D foot scans. The test is performed in two positions: standing with load on the plantar surface and toe-off loading only the forefoot. The outcome is a pressure discomfort threshold map of the foot. Interestingly, in 16 locations the sensitivity was similar in both conditions (toe-off and complete foot on the ground). Especially, stretched areas showed increased sensitivity.

1. Introduction

Understanding the foot sensitivity and plantar pressure could contribute to better design of insoles, shoes and could be a guide as well for therapeutic interventions (Machado et al., 2016). The question is whether shoes, insoles or other products touching the foot can be designed in such a way that the prolonged localized peak pressures are reduced. However, in designing shoes or insoles, comfort plays a major role as well. Au and Goonetilleke (2007) studied the comfort and fit of shoes and found that a comfortable shoe does not necessarily have the same perceived fit in every region of a shoe.

Analysis on the fit ratings in the study of Au and Goonetilleke (2007) showed with a Wilcoxon test a significant impact on the fit preferences in the Toe region ($p < 0.0001$), Metatarsophalangeal (MPJ) region ($p < 0.0001$) and Arch region ($p = 0.002$). Therefore in designing comfortable shoes, insoles, products touching the foot or protections, it would be important to know which areas are sensitive. There are studies available on the sensitivity of the foot. For instance, Hennig and Sterzing (2009) found that the areas that bear high loads tend to be less sensitive than areas that bear less load. The heel had the highest detection thresholds for touch and compared to the dorsum, the plantar foot was substantially more sensitive. Xiong et al. (2011) considered the effect of spatial summation related to PDT (pressure discomfort threshold) and showed that a larger stimulus size results in lower PDT and PPT (pressure pain threshold). Nonetheless, no previous studies have looked into the discomfort perception by varying the position of the foot. In daily life use, the position of the foot varies greatly as some foot tissues stretch while other tissues compress. Rodgers (1995) explained how in a toe-off position during walking, the tension across the longitudinal arch increases to provide foot stability. This means that the foot behaves differently in every position of walking to provide adequate support and balance. Therefore, it was important to understand the sensitivity of the foot in different foot positions in order to design footwear products that would be comfortable for daily dynamic use. The aim of this research is to determine foot pressure sensitivity and evaluate whether a different foot position would affect the sensitivity. The research question is: *Does sensitivity of the foot differ in two different positions of the foot and if so, in which regions is it different.* Expected differences could change the way footwear is designed and improve the fit for the users during high performance sport activities.

2. Methods

2.1. Materials

To overcome the large anthropometric variations between individuals, a system of testing the pressure sensitivity was developed. In developing this system, 3D scans of 7 persons were made with EU shoe sizes varying from 37 to 47 (Fig. 1). Based on these 3D scans three foot shells were modeled close to foot size 38, 41 and 45 in Rhinoceros vs.5.0.1 and then printed with a Ultimaker 2+. A surface, 5 mm offset

* Corresponding author. TU Delft, Faculty of Industrial Design Engineering, Landbergstraat 15, 2628 CE, Delft, the Netherlands.
E-mail address: alice.buso@icloud.com (A. Buso).
URL: http://www.io.tudelft.nl (A. Buso).

https://doi.org/10.1016/j.apergo.2018.12.001
Received 21 May 2018; Received in revised form 5 November 2018; Accepted 1 December 2018
Available online 10 December 2018
0003-6870/

Fig. 1. Example of 3D scan in standing position.

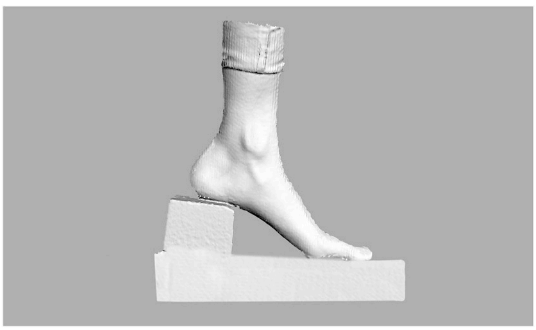

Fig. 2. Example of 3D scan in toe-off position, obtained by placing a block of polystyrene 65 mm high under the participant's heel.

from the 3D scanned foot was traced in 3D and used to develop a shell, which was used in the experiment. The three foot sizes (37-39, 40-43, 44-47) were printed in two positions (in total six foot shells). One position was the flat foot in the normal standing position. The other position was the rear foot bent upwards as the toe-off position during the walking/running gait. In this case, the heel was lifted approximately 65 mm from the ground (see Fig. 2). In the 3D printed models (Fig. 3) 20 holes were made with a diameter of 11 mm (indenter diameter 10 mm + 1 mm clearance) to make comparison with previous studies possible (Dohi et al., 2004; Xiong et al., 2011; Messing and Kilbom, 2001). Although these holes were not precisely in the same location for each participant within the same size group, the difference was negligible. Two rigid tables (Figs. 6–7) were constructed for the researchers to be able to easily reach the holes on the plantar surface of the foot shells and read off the AFG.

2.2. Participants

21 healthy participants (10 males and 11 females) between the age of 20 and 49, were asked to take part in the test (see Table 1). After signing an informed consent, the participants were asked to fill in their information about age, EU shoe size (according to British Standards Institute (2001)), stature, body weight (the last two were used to calculate the BMI). Subjects with any kind of diabetes or diseases that could affect skin sensitivity were excluded, as well as people who had experienced foot pain within the previous 6 months or had foot surgery. Moreover, none of the participants feet had a high amount of callosities as that could have affected the results.

2.3. Equipment

An advanced force gauge (AFG) meter (Mecmesin AFG 500N) connected to a cylindrical 3D printed PLA rod (diameter = 10 mm) was used to apply the pressure (Fig. 4). Two different rods were 3D printed with a Ultimaker 2 + with fillet radius of 3 mm and 5 mm (spherical ending) to test how the fillet radius would affect the perception on skin

Fig. 3. The three pairs of 3D printed foot shells.

Fig. 4. Mecmesin AFG 500N with the 3D printed rod screwed on top.

(Fig. 5). During the pilot test the 3 mm fillet radius rod (enclosed in the black rectangle of Fig. 5) was chosen because the flatter surface better simulates the contact between the inner surface of a shoe and the skin.

2.4. Experimental procedure

1. Participants were informed about the purpose of the research and the procedure. They were asked to sign a consent form.
2. Participants were asked to take off their shoes and the sock from the right foot and wear the provided disposable sock for hygienic reasons.
3. After this, they were asked to step onto the first table and put their right foot inside the first shell (see Fig. 8). The smallest shell was used to fit foot sizes ranging from 37 to 39, the medium shell for foot sizes from 40 to 43 and the largest shell for foot sizes from 44 to 47. Participants were allowed to lean on the wall for support during the measurements since this would not have affected the results.
4. Researcher 1 positioned the AFG in each of the 20 holes of the foot shell, the hole number was called by researcher 2 in a different order each time.[1] Pressure was then slowly increased until participants indicated that they felt uncomfortable, as previously done in the studies by Gonzalez et al. (1999) and Vink and Lips (2017). Researcher 2 noted the output values (N) indicated by the AFG and read aloud by researcher 1. Each point was measured 3 times.

[1] The same person took all the measurements in order to maintain the same indentation speed for all participants, given the influence of the speed on PDT (Xiong et al., 2011). Moreover, the researcher in charge of the indentation also practiced on a pressure mat and during the pilot test before the real measurements.

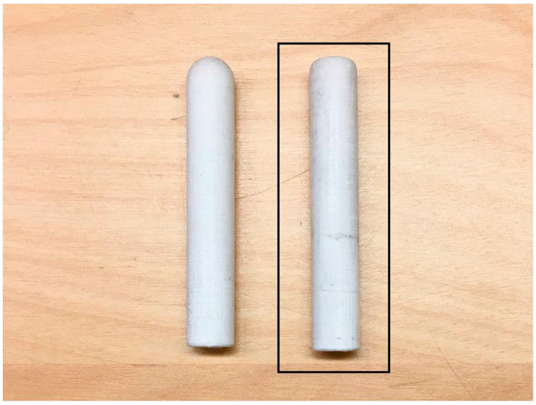

Fig 5. 3D printed rods. The one enclosed in the rectangle is the one used for the measurements.

Fig. 6. Measurements in standing position.

Fig. 7. Measurements in toe-off position.

Results were noted in an Excel sheet. Participants were asked to rest after each set of measurements.

5. After the 3 rounds for the first position (standing/toe-off), participants were asked to take a break for 5 min. Then they were asked to move to the second position and place the feet in the (toe-off/standing) shell. All 20 points were again measured each time in a different order.
6. After each measurement round, participants were able to express some comments about their personal experience during the experiment.

10 subjects started with the shell in standing position and then toe-off position; the remaining did it the other way around. Participants

Table 1
Descriptive statistics of participants (n = 21).

Variables	*Mean*	*SD*	*Maximum*	*Minimum*
Males (n_1 = 10)				
Age *(years)*	26.8	7.69	49	20
Stature *(m)*	1.77	0.11	1.89	1.52
Body weight *(kg)*	72.1	11.88	89	53
BMI *(kg/m²)*	22.81	2.2	26.28	19.81
EU shoe size	42.6	1.85	46	39
Females (n_2 = 11)				
Age *(years)*	25.18	1.85	29	22
Stature *(m)*	1.66	0.03	1.70	1.61
Body weight *(kg)*	59.09	3.29	64	54
BMI *(kg/m²)*	21,52	1,54	24,09	19,36
EU shoe size	38.55	0.99	41	37

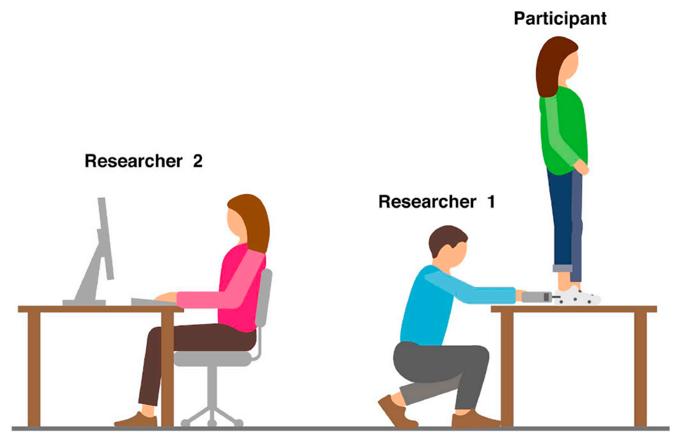

Fig. 8. Test set-up.

were asked to rest between each set of measurements to avoid numbness that could affect the outcomes of the test.

2.5. Data analysis

The values from the first measurement of each subject were discarded because previous studies with this method showed a large variation in the first recording (Vink and Lips, 2017). Probably the person needs to adapt to the procedure and get to understand his level of resistance (Vink and Lips, 2017). The values of the forces at which pressure started to create discomfort were placed in an Excel file (second and third measurement). As the output of the AFG was Force in Newtons, the PDT had to be calculated manually from these values. PDT was the force applied per unit area of indentation (Xiong et al., 2011) and since the size of the indenter was known, the PDT could be calculated as:

$$PDT\ [kPa] = \frac{Force\ [N]}{Area_{Indentation}\ [mm^2]}$$

$$Area_{indentation} = \pi \times (Radius_{Indenter})^2$$

Mean values of pressure threshold and standard deviations among all participants were calculated for each point (Table 2) and displayed in a sensitivity map of the foot in a way similar to Xiong et al. (2011) and Johansson et al. (1999). The gathered data were then transferred into SPSS vs.24. Average values, standard deviations, minimum and maximum values and variance were calculated for each point, in both positions. A *t*-test for paired samples was run for the single measurements from all three trials in order to check if statistically significant differences between standing and toe-off could be observed ($p < 0.05$). The pairs were made comparing the average value between all participants of one foot location in standing position with the same foot location in toe-off position.

Table 2
Average values (in N) with standard deviations and pressure discomfort threshold (PDT) (in kPa) for the 20 locations of the foot in the standing and toe-off positions. Significant difference between standing and toe-off positions values are highlighted in bold.

	Standing				Toe-off			
Locations	Force	SD	PDT	SD	Force	SD	PDT	SD
1	10.64	8.28	135.49	105.49	9.83	5.73	125.24	73.00
2	12.04	9.09	153.35	115.76	11.35	8.00	144.56	101.86
3	10.32	8.28	131.45	105.48	10.26	6.97	130.72	88.73
4	11.96	11.47	140.89	146.09	11.40	8.96	145.19	114.18
5	**6.89**	**5.73**	**87.72**	**73.01**	**5.68**	**4.26**	**72.31**	**54.24**
6	9.36	7.64	119.26	97.3	7.94	5.02	101.09	63.91
7	**12.07**	**11.58**	**153.78**	**147.48**	**9.32**	**8.04**	**118.68**	**102.46**
8	13.60	10.79	173.31	137.39	15.33	10.85	195.27	138.28
9	6.72	4.23	85.56	53.85	7.86	6.67	100.12	84.93
10	5.69	4.00	72.46	51.00	6.44	4.07	82.04	51.85
11	6.05	5.12	77.10	65.37	5.67	3.50	72.19	44.62
12	5.73	4.37	73.04	55.69	6.57	5.22	83.65	66.44
13	7.45	7.17	94.97	91.33	6.79	5.44	86.47	69.36
14	7.76	7.23	98.85	92.15	7.22	5.03	91.96	64.11
15	7.47	6.53	95.18	83.20	6.70	4.81	85.32	61.30
16	**5.75**	**4.39**	**73.25**	**55.88**	**4.81**	**3.02**	**61.24**	**38.53**
17	5.35	4.39	68.12	54.38	4.80	3.11	61.21	39.60
18	**7.10**	**5.13**	**90.42**	**65.38**	**5.87**	**4.35**	**74.80**	**55.40**
19	6.19	5.03	78.86	64.09	6.29	5.14	80.16	65.42
20	6.66	6.59	84.87	83.96	5.76	5.38	73.43	68.52

Another *t*-test for paired samples was run between the average value of all participants of one foot location during the second trial and the average value of the same foot location during the third trial. Correlations between BMI and sensitivity were calculated to study the connection between body fat and decreased sensitivity. ANOVA between male and female participants was performed to check whether their foot sensitivity difference was statistically significant ($p < 0.05$).

3. Results

A sensitivity map of the standing and toe-off positions can be found in Fig. 9.

- Large foot points variations

The measurements showed that some areas are more pressure sensitive than others (Table 2). In both positions the plantar surface of the foot resulted being less sensitive than the rest of the foot. Nevertheless, there is no significant difference between the forefoot and the hind foot sensitivity.

- Variations between trials

The measurements from the first trial were ignored because the subjects needed to get used to the procedure. There is no significant difference between the second and third trial, in both standing and toe-off positions (Fig. 11 and Fig. 12).

- Variations between standing and toe-off positions

From the results of the *t*-test most points on the feet did not show a significant difference (Table 2 and Fig. 10). A significant difference was found for only 4 out of the 20 points: point 5 ($p = 0.010$), point 7 ($p = 0.003$), point 16 ($p = 0.022$), point 18 ($p = 0.011$).

- Large inter-individual variations

Measurements and their variance showed that especially in some areas of the foot, large differences in grade of sensitivity were recorded. For example, point 4, 7, 8 in standing position and point 9 in toe-off position (Table 2). It needs to be pointed out that one participant showed approximately 1/10 of average force values of the other participants. Therefore it can be said that his sensitivity was 10 times higher than the rest of subjects and he was excluded from the analysis.

- Pressure sensitivity and gender

From the results of ANOVA, there was no significant difference in foot sensitivity between female and male participants ($p > 0.05$).

- Pressure sensitivity and BMI

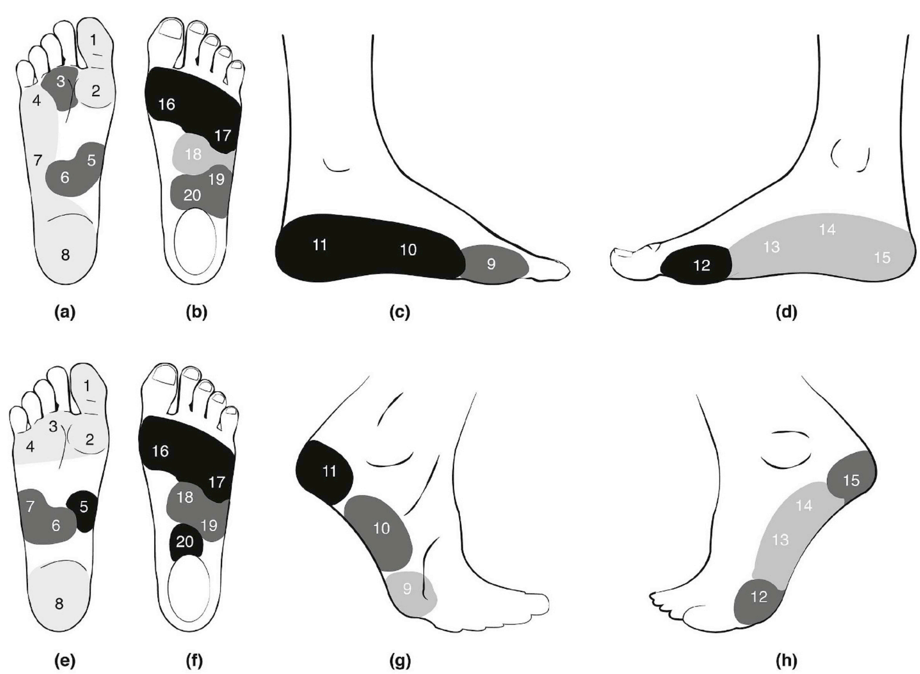

Fig. 9. Sensitivity map of the standing (a–d) and toe-off positions (e–h). A darker color means a more sensitive foot point, tolerating lower amount of pressure (lower PDT value).

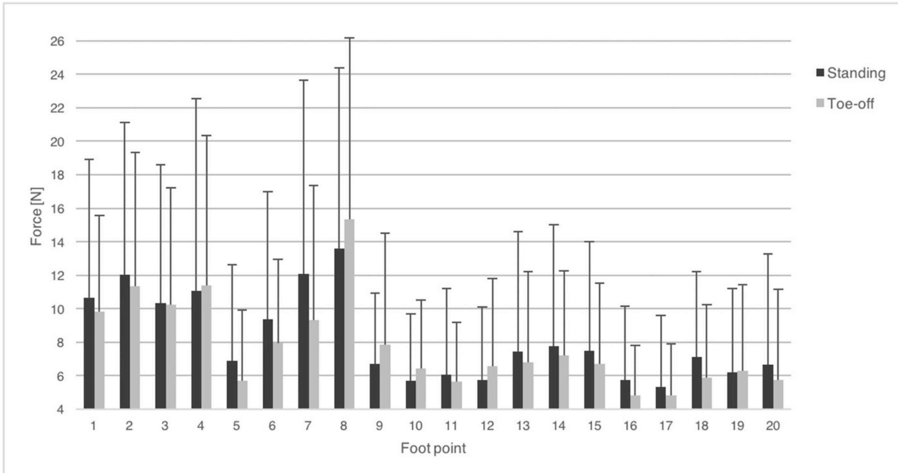

Fig. 10. Comparison of average force between standing and toe-off positions, with relative standard deviations. A higher force means less sensitive foot point.

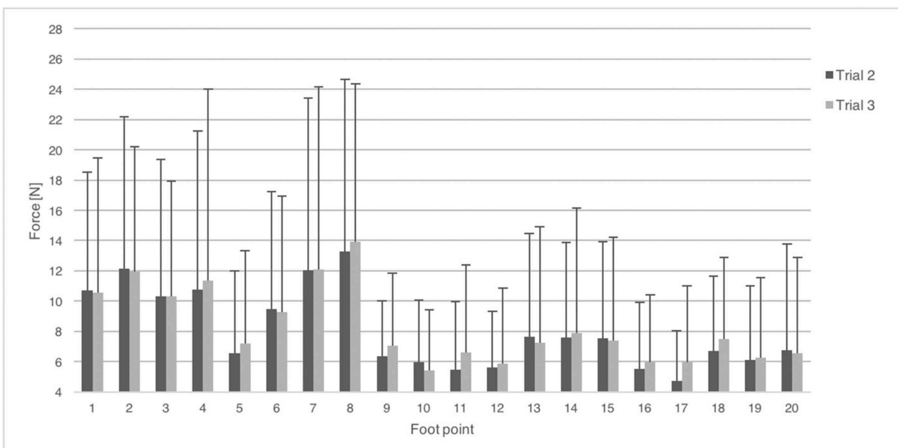

Fig. 11. Comparison of average force between second and third trial for standing position, with relative standard deviations.

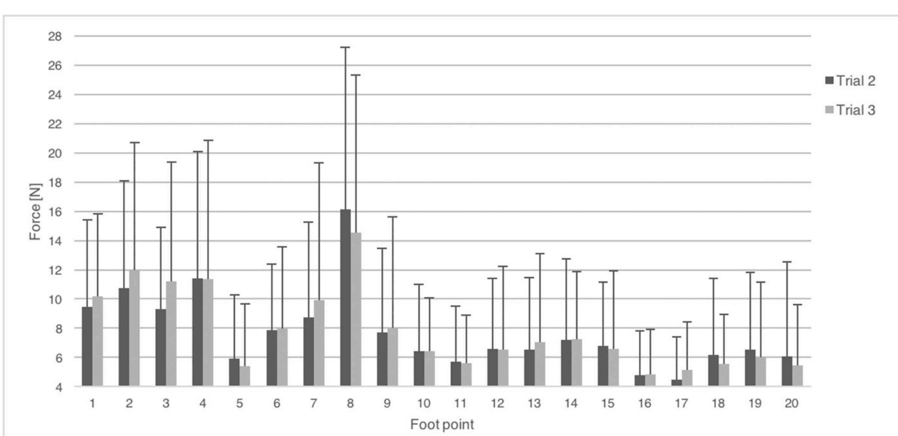

Fig. 12. Comparison of average force between second and third trial for toe-off position, with relative standard deviations.

Table 3
Pearson correlation coefficients between subjects BMI and three foot locations.

Locations	BMI
9	0.370
10	0.399
11	0.334

Correlations between pressure sensitivity and BMI were statistically significant for points 9 (p = 0.016), 10 (p = 0.09) and 11 (p = 0.031) in the toe-off position only (Table 3).

A comment received in various ways after the experiment was that sometimes subjects had difficulties in deciding whether it was discomfort or already pain. They also mentioned that it was hard to report "Now it is discomfort" every time the exact moment of discomfort. Finally, they claimed to feel in a state of higher discomfort during the last sets of measurements due to the effect of fatigue.

4. Discussion

The PDT values obtained in this experiment support previous findings in the literature (Hennig and Sterzing, 2009), stating that research areas which can bear higher loads are less sensitive. Indeed Metatarsophalangeal, external midfoot and heel regions resulted in higher PDT values, which means lower sensitivity in these areas. Even if there is difference in numeric values between the recent study of Weerasinghe et al. (2017) and the current one, the PDT distribution in their cluster maps matches in many cases with the sensitivity map in Fig. 9.

It is interesting to note that there are differences in sensitivity between the standing and toe-off position for only 4 locations of the foot (point 5 and 7 on the plantar surface and point 16 and 18 on the dorsal surface). This could be related to the fact that in those locations, muscles are respectively relaxed in the standing position and tensed in the toe-off. Alternatively, it could be that the tissue is more stretched and therefore less pressure is needed to create discomfort. Other studies also showed that stretching tissues results in more discomfort (Hiemstra-van Mastrigt et al., 2016). The current study is the first to assess foot sensitivity in two different positions. In addition, it goes in line with the results of Alfuth and Rosenbaum (2011) that proved that foot sole sensitivity was not altered by long-distance running. Instead, Messing and Kilbom (2001) demonstrated lowered PPT in subjects after prolonged standing.

Inter-individual difference in sensitivity could have affected the results of this study (Hennig and Sterzing, 2009). The elevated variance can be justified by the subjectivity of the test. Although the participants were being explained about the protocol, some subjects at the end of the test spontaneously pointed out the difficulty to understand whether they just felt uncomfortable or painful. However, this method was adopted because it has already been used by Vink and Lips (2017) and Gonzalez et al. (1999). Many participants expressed to feel more discomfort during the second and third measurement even though they were allowed to rest after each set. One participant in particular resulted to be extremely more sensitive compared to the other subjects. Nevertheless, no significant difference between trials was observed.

Contrary to Putti et al. (2010), Vink and Lips (2017) and Weerasinghe et al. (2017) this study does not show significant differences in foot sensitivity between male and female participants and the result is therefore in line with Dohi et al. (2004). A possible explanation for this could be that the foot area does not contain much muscle or fat. Therefore, this observation is different from other areas of the body like the back, which was evaluated by Vink and Lips (2017). The difference in foot anatomy between genders is less than the difference in back anatomy, leading to no significant foot sensitivity difference between genders.

Another possible reason for this could be that the BMI values of the participants are not very different. The correlation of BMI and foot sensitivity was found for only 3 foot locations in the toe-off position. This finding should be interpreted with care because there was not enough variation in BMI between participants: all of them were close to normal weight or slightly overweight but not obese. In future studies this experiment could be repeated with larger sample size with more variation in BMI to study the effect.

4.1. Limitations

The research may have three limitations. Xiong et al. (2011) demonstrated the effects of indentation speed on PDT. Even though the same researcher was taking the measurements and he was trained to indent always with the same speed, it is not certain (and it was not checked in this study) that the speed was always the same. Also, a small delay in reading the force value on the gauge meter could have altered the numeric value with a tolerance of 0.5 N, which is around 6% of the values recorded in this study. The above stated concern about the indentation speed was also encountered by Vink and Lips (2017). The use of shells to test the sensitivity proved to be successful in minimizing the risk of edge effect of the head of the probe on the skin. Several 3D scans of feet were overlapped and used to design the shells taking into account anatomical differences between participants as much as possible. On the other side, minor differences between subjects with the same shoe size may have affected the accuracy of the locations of measurement. Hence, a more reliable testing method should be developed. For instance, Xiong et al. (2011) created an automated indentation apparatus for their experiment.

Another improvement could be following the approach of the 95-point matrix from the study of Weerasinghe et al. (2017) in order to be able to systemically compare the results, in future studies too. Nevertheless, they demonstrated that the plantar surface has areas with similar sensitivity that can be clustered together, so a grid with that amount of test points is probably not necessary. Placing the probe in locations very close to each other could increase the risk of influencing the sensitivity of adjacent areas.

A useful suggestion for future research would be 3D scanning the feet of each participant in a previous session in order to develop and 3D print custom shells that perfectly match the subjects anatomy. A disadvantage of this method is that comparison between subjects might be more difficult. The third limitation is that the research is done in a static situation. In daily life situations humans move and Qi et al. (2015) showed much variation in the dynamics of the foot, which could potentially influence the sensitivity in different areas.

5. Conclusions

This study is the first step towards enhancing the understanding of foot sensitivity in different positions of the foot. There were 4 out of the 20 positions with a significant difference in foot sensitivity between standing and toe-off position showing that the majority is comparable. This implies that even though some skin and tissue areas in the foot are stretched in the toe-off position and relaxed in the standing position, the sensitivity of the area does not depend on the foot position. Therefore, footwear companies designing new products using foot sensitivity can assume that the sensitivity in one foot position has similarities with sensitivity in other foot positions. However, manufacturers could consider avoiding presence of hard surfaces or stitches in some of the areas that showed significant sensitivity difference in the standing and toe-off position, because their effect on the foot would be different in dynamically changing foot positions (e.g. during running and cycling activities). PDT values are useful parameters in product design (Goonetilleke, 2001); specifically in this case, they can be used to study the footwear stitching elements and internal inserts to provide better fit comfort and minimizing the creation of friction between the shoe and the skin in areas with higher sensitivity. More research is advised in dynamic positions as it is unknown how sensitivity is influenced in the constantly changing situations of daily life.

References

Alfuth, M., Rosenbaum, D., 2011. Long distance running and acute effects on plantar foot sensitivity and plantar foot loading. Neurosci. Lett. 503 (1), 58–62. https://doi.org/10.1016/j.neulet.2011.08.010.

Au, E.Y.L., Goonetilleke, R.S., 2007. A qualitative study on the comfort and fit of ladies dress shoes. Appl. Ergon. 38 (6), 687–696. https://doi.org/10.1016/j.apergo.2006.12.002.

British Standards Institute, 2001. Size Designation of Clothes - Part 1: Terms, Definitions and Body Measurement Procedure.

Dohi, M., Mochimaru, M., Kouchi, M., 2004. Distribution of tactile sensitivity and elasticity in Japanese foot sole. KANSEI Eng. Int. 5 (2), 9–14. https://doi.org/10.5057/kei.5.2_9.

Gonzalez, J., Garcıa, A., Vivas, M., Ferrus, E., Alcantara, E., Forner, A., 1999. A new portable method for the measurement of pressure discomfort threshold (ptd) on the foot plant. In: Proceedings of the 4th Symposium on Footwear Biomechanics, pp. 48–49.

Goonetilleke, R.S., 2001. The comfort-discomfort phase change. In: Karwowski, W. (Ed.), International Encyclopedia of Ergonomics and Human Factors. Taylor Francis, pp. 399–402.

Hennig, E.M., Sterzing, T., 2009. Sensitivity mapping of the human foot: thresholds at 30 skin locations. Foot Ankle Int. 30 (10), 986–991. https://doi.org/10.3113/FAI.2009.0986.

Hiemstra-van Mastrigt, S., Groenesteijn, L., Vink, P., Kuijt-Evers, L., 2016. Predicting passenger seat comfort and discomfort on the basis of human, context and seat characteristics: a literature review. Ergonomics 60, 1–44. 09. https://doi.org/10.1080/00140139.2016.1233356.

Johansson, L.L., Kjellberg, A., Kilbom, A., Hagg, G.M., 1999. Perception of surface pressure applied to the hand. Ergonomics 42 (10), 1274–1282. https://doi.org/10.1080/001401399184947.

Machado, A.S., Bombach, G.D., Duysens, J., Carpes, F.P., 2016. Differences in foot sensitivity and plantar pressure between young adults and elderly. Arch. Gerontol. Geriatr. 63, 67–71. https://doi.org/10.1016/j.archger.2015.11.005.

Messing, K., Kilbom, A., 2001. Standing and very slow walking: foot pain-pressure threshold, subjective pain experience and work activity. Appl. Ergon. 32 (1), 81–90. https://doi.org/10.1016/S0003-6870(00)00030-2.

Putti, A., Arnold, G., Abboud, R., 2010. Foot pressure differences in men and women. Foot Ankle Surg. 16 (1), 21–24. https://doi.org/10.1016/j.fas.2009.03.005.

Qi, Y., Soh, C.B., Gunawan, E., Low, K.-S., 2015. Ambulatory measurement of three-dimensional foot displacement during treadmill walking using wearable wireless ultrasonic sensor network. IEEE J. Biomed. Health Inform. 19 (2), 446–452. https://doi.org/10.1109/JBHI.2014.2316998.

Rodgers, M.M., 1995. Dynamic foot biomechanics. J. Orthop. Sports Phys. Ther. 21 (6), 306–316.

Vink, P., Lips, D., 2017. Sensitivity of the human back and buttocks: the missing link in comfort seat design. Appl. Ergon. 58, 287–292. ISSN 0003-6870. https://doi.org/10.1016/j.apergo.2016.07.004.

Weerasinghe, T.W., Goonetilleke, R.S., Reischl, U., 2017. Pressure thresholds and stiffness on the plantar surface of the human foot. Ergonomics 60 (7), 985–996. https://doi.org/10.1080/00140139.2016.1229042. https://doi.org/10.1080/00140139.2016.1229042 PMID: 27609429.

Xiong, S., Goonetilleke, R.S., Jiang, Z., 2011. Pressure thresholds of the human foot: measurement reliability and effects of stimulus characteristics. Ergonomics 54 (3), 282–293. https://doi.org/10.1080/00140139.2011.552736.