RELATIONSHIP BETWEEN STRETCH AND PRESSURE OF KNITTED FABRIC FOR SHOE UPPERS FOR FEMALE DIABETIC PATIENTS

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RELATIONSHIP BETWEEN STRETCH AND PRESSURE OF KNITTED FABRIC FOR SHOE UPPERS FOR FEMALE DIABETIC PATIENTS

ABSTRACT. Materials for producing shoes for diabetic patients must provide high comfort and protect the feet, preventing foot damage and ensuring aesthetics. The objective of this study was to analyze the impact of a knitted fabric on the pressure on the instep of female diabetic patients. In this study, three shoe samples with similar designs were explored, the shoe uppers were made from two type of space knit fabrics and one type of three layers fabric sample with polyester composition. The knit fabric structure has a top layer (single jersey, raschel) and a bottom layer (interlock, single jersey, and atlas). A Flexiforce A301 sensor was used to measure the pressure. Research was conducted on 45 female diabetics with the same foot length and were categorized into three groups based on the toe joint circumference size, with each group having a difference in the circumference size of 8 mm. Pressure was measured at two positions on the foot. Results show that when the shoe upper is elongated, the compression level increases, leading to an increase in the pressure on the foot. Furthermore, in different walking positions, the pressure value of the shoe upper on the foot varies. M2 presented the smallest pressure value among all three experimental groups, where the largest pressure of 98.66 ± 2.03 mmHg was observed at Posture 2 in Group 3. M1 had the largest pressure values at all stretch levels, where the pressure reached 120.65 ± 2.50 mmHg at Posture 2 in Group 3. With the shoe samples tested here, peak pressure measured on the different areas of the foot reached a maximum of 182 kPa, which is within the recommended limit of 200 kPa. In addition, pressure was determined on three types of knitted fabrics, when used in shoe uppers, which revealed Groups N1 and N2 to meet the pressure criteria. Knitted fabric with a stretchability of ≤ 10.74% is suitable for making shoe caps for female diabetic patients. This finding helps improve the process of choosing suitable materials to make shoe caps that can ensure comfortable pressure for female diabetic patients. These results provide a guideline for selecting suitable materials for fabricating shoe uppers with good comfort and pressure relief for female diabetic patients.
KEY WORDS: pressure, knitted, shoe uppers, shoes for diabetic patients

RELAȚIA DINTRE ALUNGIREA ȘI PRESIUNEA MATERIALULUI TRICOTAT FOLOSIT LA FEȚELE DE ÎNCĂLȚĂMINTE PENTRU FEMEI CU DIABET

REZUMAT. Materialele utilizate în confecționarea încălțămintei pentru pacienții cu diabet trebuie să asigure un nivel ridicat de confort, protecția piciorului, prevenirea leziunilor și un aspect estetic adecvat. Scopul acestui studiu a fost de a analiza influența unei structuri tricotate asupra presiunii exercitate în zona căputei piciorului la femeile cu diabet. În cadrul cercetării, s-au analizat trei tipuri de mostre de încălțăminte cu construcție similară, având fețele realizate din două tipuri de materiale tricotate distanțate și un tip de material tristrat cu compoziție din poliester. Structura tricotului a fost alcătuită dintr-un strat superior (tricot simplu, raschel) și un strat inferior (interlock, tricot simplu și atlas). Presiunea a fost măsurată utilizând senzorul Flexiforce A301. Studiul a fost efectuat pe un eșantion de 45 de femei cu diabet, toate având aceeași lungime a piciorului, împărțite în trei grupe în funcție de circumferința articulației metatarsofalangiene, cu o diferență de 8 mm între grupe. Presiunea a fost măsurată în două puncte de pe picior. Rezultatele au arătat că odată cu creșterea alungirii feței, nivelul de compresie crește, conducând la o presiune mai mare asupra piciorului. De asemenea, valorile presiunii variază în funcție de poziția în timpul mersului. Proba M2 a înregistrat cele mai mici valori ale presiunii dintre toate cele trei grupe experimentale, cu o valoare maximă de 98,66 ± 2,03 mmHg în Postura 2 din Grupa 3. Proba M1 a generat cele mai mari valori ale presiunii la toate nivelurile de alungire, atingând 120,65 ± 2,50 mmHg în Postura 2 din Grupa 3. Pentru toate mostrele testate, presiunea maximă înregistrată în diferite zone ale piciorului a atins valoarea de 182 kPa, rămânând sub limita recomandată de 200 kPa. În plus, s-a determinat presiunea exercitată de trei tipuri de materiale tricotate utilizate la realizarea fețelor, iar grupele N1 și N2 au îndeplinit criteriile de presiune. Un material tricotat cu o capacitate de alungire ≤ 10,74% este considerat adecvat pentru realizarea fețelor de încălțăminte destinată femeilor diabetice. Această constatare contribuie la optimizarea procesului de selecție a materialelor textile utilizate în industria de încălțăminte, asigurând un confort optim și o presiune redusă asupra piciorului la purtare. Rezultatele oferă o bază științifică pentru alegerea materialelor potrivite în fabricarea fețelor cu caracteristici biomecanice adaptate nevoilor persoanelor cu diabet.
CUVINTE CHEIE: presiune, tricot, fețe de gătire, încălțăminte pentru diabetici

RELATION ENTRE L'ÉLONGATION ET LA PRESSION DES MATIÈRES TRICOTÉES UTILISÉES POUR LES TIGES DE CHAUSSURES DESTINÉES AUX FEMMES DIABÉTIQUES

RÉSUMÉ. Les matériaux utilisés pour la fabrication de chaussures pour les patients diabétiques doivent offrir un haut niveau de confort, protéger les pieds contre les blessures et conserver un aspect esthétique satisfaisant. L'objectif de cette étude est d'analyser l'impact d'une structure tricotée sur la pression exercée au niveau du cou-de-pied chez des femmes diabétiques. Trois prototypes de chaussures, de conception similaire, ont été étudiés. Les tiges ont été fabriquées à partir de deux types de textiles tricotés distants (space knit) et d'un textile à trois couches, tous composés de polyester. La structure tricotée comprend une couche supérieure (jersey simple, raschel) et une

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couche inférieure (interlock, jersey simple et atlas). Les mesures de pression ont été effectuées à l'aide d'un capteur Flexiforce A301. L'étude a été menée sur un échantillon de 45 femmes diabétiques présentant la même longueur de pied, réparties en trois groupes en fonction de la circonférence de l'articulation métatarso-phalangienne, avec une différence de 8 mm entre chaque groupe. La pression a été mesurée à deux points spécifiques du pied. Les résultats montrent que l'augmentation de l'élongation de la tige entraîne une élévation du niveau de compression, ce qui induit une pression accrue sur le pied. De plus, selon les différentes postures de marche, les valeurs de pression varient. L'échantillon M2 a enregistré la plus faible pression parmi les trois groupes expérimentaux, avec une valeur maximale de 98,66 ± 2,03 mmHg en posture 2 du groupe 3. En revanche, M1 a présenté les pressions les plus élevées à tous les niveaux d'élongation, atteignant 120,65 ± 2,50 mmHg dans la même posture. La pression maximale mesurée sur différentes zones du pied avec ces prototypes de chaussures a atteint 182 kPa, restant ainsi en dessous de la limite recommandée de 200 kPa. Par ailleurs, trois types de tissus tricotés ont été évalués pour leur application sur les tiges de chaussures, et les groupes N1 et N2 ont répondu aux critères de pression acceptables. Un tissu tricoté présentant une élasticité ≤ 10,74 % est considéré comme approprié pour la confection de tiges de chaussures destinées aux femmes diabétiques. Cette étude fournit des données précieuses pour améliorer la sélection des matériaux dans l'industrie de la chaussure, permettant la conception de tiges confortables et réduisant les pressions exercées sur les pieds sensibles des patientes diabétiques. Les résultats constituent une base pour orienter le choix des matériaux offrant à la fois confort et protection biomécanique.
MOTS CLÉS : pression, tricot, tige de chaussure, chaussures pour diabétiques

INTRODUCTION

Diabetes is known to exert a negative effect on the feet, with 3% of the diabetic patients worldwide suffering from foot ulcers [1], especially in the ball of the foot [2–5]. Therefore, appropriate selection of shoes is essential for diabetic patients to reduce foot damage and ulcers [6–15]. The shoe upper is particularly important because it contacts the entire instep, considerably affecting comfort. Shoe uppers for diabetic patients, in addition to meeting the hygienic and ecological requirements, must provide comfort and softness to avoid damage to the feet [16–19]. In this context, knitted fabrics have become popular for uppers in athletic shoes and fashion footwear, with companies such as Nike and Adidas releasing footwear with space knitted uppers [20]. Compared with leather shoes, these knitted fabrics increase wearing comfort and reduce waste during manufacturing. Notably, knitted fabrics such as spacer knitted fabrics are suitable for shoe uppers and shoe linings to reduce discomfort during physical activities due to their porous and elastic structures [21].

A previous study [22] investigated the ergonomic design of orthopedic footwear for patients with diabetic foot syndrome. Specifically, a 3D knitted fabric with a thickness of 7–11 mm and a longitudinal elastic elongation of 45–90 kPa was used as a cushion between the foot and floor to measure the pressure caused by the foot, revealing that the pressure on the patient's legs was reduced by 30%.

In another study [23], three popular footwear models with identical design but different shoe upper materials which are leather (M1), knitted fabric (M2), and a combination of knitted fabric and calf leather (M3) were explored. The elastic elongation of the material was found to directly affect the pressure distribution and deformation inside the shoe. The introduction of the knitted fabric into the footwear structure helped reduce stress in the shoe with its upper made from M3.

A previous study [24] determined the peak pressure value of the toe designs on the instep in three types of shoes. It showed that the shape and width of the toe affect the pressure on the forefoot. Another study [25] compared the instep, as well as the pressure from it, in three types of sports shoes and reported that pressure on the instep at the toe joints differs among the shoes studied. Specifically, the shoes used for basketball presented the highest pressure of 41.1 ± 19.1 kPa; shoes used for running presented the lowest pressure of 31.2 ± 15.0 kPa; and the tennis shoes presented a pressure of 38.0 ± 20.3 kPa.

Studies [26, 27] have been conducted on the mechanical properties of different types of knitted fabrics to show that antibacterial knitted fabrics can prove to be useful for application in medical shoe linings. In view of this usefulness, studies [28] have investigated the application of knitted fabrics with different weaves in shoe linings for diabetic patients. Specifically, a recent study [29] explored the suitability of three types of knitted fabrics for use in shoe uppers (i.e., as space fabrics). They further study six types of knitted fabrics for use in shoe linings and three types of leather for use in shoe linings. The study suggested that knitted fabrics may be the best materials for use in linings, especially knitted fabrics composed of 100% polyamide or those with 80% polyester and 20% modified polyamide. These two types of fabrics were recommended based on their good thermal insulation and ability to help maintain hygiene. As for the three leather samples tested, it was observed that the porous structure of leather enhanced the ability to absorb and release water, which improved its use. However, leather linings had weaker thermal insulation than the knitted fabrics. The study suggested the use of space fabrics for shoe uppers to achieve improved thermal insulation.

Research was conducted on fabric bandage [30–32]. Short-stretch bandage achieves a high level of working pressure and a low level of resting pressure [30], the elasticity of 100% cotton short-stretch bandage followed the exponential behaviour whereas the cotton-polyamide-polyurethane long-stretch bandage behaved in a linear function due to the higher level of elastic recovery gained by polyurethane filament [30]. The results [31] confirmed that 100% cotton bandages achieved the highest pressure that ranges 18–33, 27–43 and 36–61 mmHg for ankle at radius 3.9 cm and 8–16, 18–27 and 35–51mmHg for mid-calf at radius 6.2 cm. The best selection of bandage type and optimum gradual pressure decreasing at the ankle through the calf to the knee depends on the type of patient disease, age, and suitable healing rate [31]. The cotton woven compression bandage tested samples achieved 95–99% bacteria reduction and bandage pressure by PicoPress showed significant deviations compared with theoretical pressure calculated by Laplace's equation ranges ±0.68 to ±15.64% especially at the highest extension levels [32]. The elastic single jersey knitted fabrics could be used in summer and winter with a feeling of comfort. For all elastic single jersey knitted samples, the water vapor resistance values were < 5 and it is within excellent level of water vapor resistance transferability, which gives comfort during wearing [33].

Studies [36] shows that increasing moisture content in the studied socks caused a significant increase in their conductive heat loss. Plain knitted socks with different fiber composition were wetted to a saturated level, and then their moisture content was reduced stepwise.

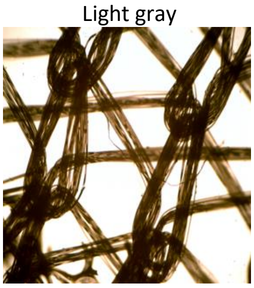
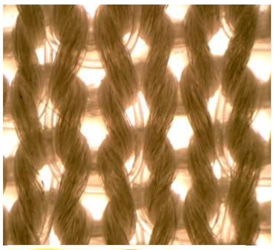
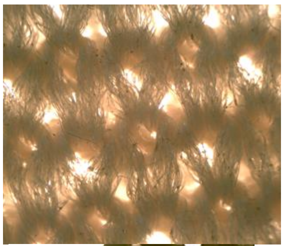
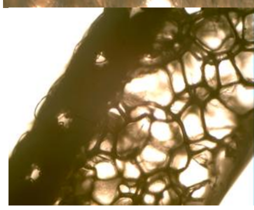
Thus, studies [20–34] have focused on determining the influence of the 3D knitted fabric structure, density, component, thickness on the hygiene, insulation of shoe uppers, shoe insoles, and the pressure-reducing effect of shoe insoles using knitted fabric. The effect of the relationship between the stretch and pressure of shoe uppers made from knitted fabric systems on the instep of female diabetic patients has not been considered; instead, studies have only been experimental on models or healthy subjects without pathology. Therefore, research on materials, design, production and the role of shoes for users, especially patients with foot diseases, is extremely necessary. In this context, the goal of this study is to determine the pressure-reducing role of knitted fabrics for shoe uppers for female diabetic patients. The results of this study can then help shoe manufacturers and diabetic patients understand more deeply regarding the role of shoes, can choose shoe upper materials, and choose the right shoe size for female diabetic patients to ensure comfort and prevent foot injuries.

EXPERIMENTAL

Materials

Knitted fabrics are increasingly used to fabricate shoe uppers because they are soft, breathable, well-ventilated, and exhibit good elasticity. Recently, knitted fabric (3D fabric) materials have gradually replaced traditional material systems made of many layers, e.g., knitted fabric + foam + shoe lining fabric, changing the shoe production technology [35]. A survey of commercially available shoe-upper materials and materials used in multiple footwear manufacturing facilities indicates that polyester knitted fabrics incorporating fundamental knitted structures – namely single jersey, interlock, and Raschel – are prevalent and demonstrate advantageous performance properties. Therefore, the authors chose to test to determine stretch and pressure on three typical knitted fabric samples. The characteristics of these three knitted fabric samples are shown in Table 1.

Table 1: Characteristics of three knitted fabric samples

Characteristics		Fabric Sample 1 (M1)	Fabric Sample Fabric Sample 2 (M2)	Fabric Sample 3 (M3)
Fabric Style		Spacer knitted fabric	Spacer knitted fabric	Knitted fabric + foam + thin knitted fabric
Color		Dark gray	Off white	Light gray
Images of the top layer surface of knitted fabric				
Images of the bottom layer surface of knitted fabric				
Cross-section image of knitted fabric				
Weight, GSM		325.0	350.0	295.0
Thickness, mm		2.13	1.13	2.66
Top Layer	Composition	PET	PET	PET
	Density (loop/100 mm)	Wales: 200 Course: 230	Wales: 160 Course: 220	Wales: 180 Course: 130
	Type of knitted fabric	Single Jersey	Single Jersey	Raschel
Bottom Layer	Composition	PET	PET	PET
	Density (loop/100 mm)	Wales: 190 Course: 180	Wales: 160 Course: 220	Wales: 80 Course: 80
	Type of knitted fabric	Interlock	Single Jersey	Atlas 2 × 1

Equipment

A Flexiforce pressure sensor obtained from Tekscan in America was used to perform measurements. The design and manufacture of the measuring equipment were set similar to the author's previous studies. The equipment was calibrated, tested, and evaluated to ensure that measurements are within allowable errors. The process of manufacturing and evaluating the measuring equipment set is presented in detail in a previous study [36].

The Flexiforce A301 sensor is a force

measurement sensor based on the relationship between resistance and pressure. The sensor impedance is high when the sensor is not affected by force. When a force is applied to the sensor, the resistance value decreases. The impedance value was read using a power meter to determine the resistance between the two outermost pins of the sensor.

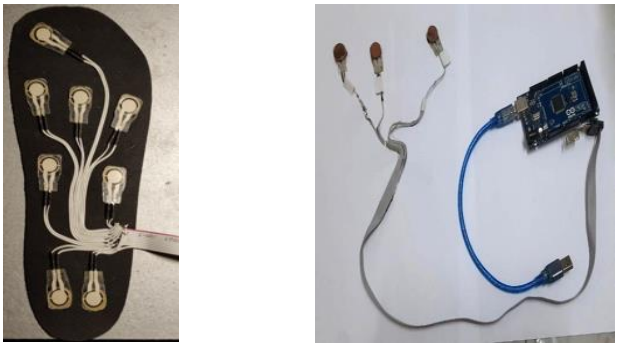


Figure 1. Sensors for measuring the pressure of the shoe on the foot [36]

Participants

Diabetic patients often suffer from foot pain, skin disorders, calluses, foot deformities, foot ulcers, and even aggravated diseases that may require foot amputations. Deformed and damaged feet must often be fitted with specially designed shoes. Our research subjects included females, aged over 35, with Type-2 diabetes in low and moderate-risk groups for foot complications. This age group is the most susceptible to diabetes, especially Type-2 diabetes. Type-2 diabetes accounts for 90 to 95% of all diabetic occurrences, of which female patients account for over 60% of the recorded patients [37]. In the laboratory, our preliminary study included 45 female diabetics with undamaged feet and good foot sensation. They were divided into three groups, according to their foot size and weight as follows:

- Group 1 (N1): 15 female diabetics with a foot length of 230.0 mm, a toe joint circumference of 223 mm, a body height of 155.9 ± 2 cm, and a weight of 47.7 ± 1.6 kg.
- Group 2 (N2): 15 female diabetics with a foot length of 230.0 mm, a toe joint circumference of 231 mm, a body height of 158.1 ± 2 cm, and a weight of 48.5 ± 1.8 kg.
- Group 3 (N3): 15 female diabetics with a foot length of 230.0 mm, a toe joint circumference of 239 mm, a body height of 154.4 ± 4 cm, and a weight of 54.2 ± 1.5 kg.

The subjects in the three groups wore 37 shoe size designed according to the results of a study on the foot size of female diabetics in Vietnam [38], in particular a foot length of 230 mm and a toe joint circumference of 230 mm. Shoe uppers were produced using the respective materials M1, M2, and M3. The shoe samples were made at the Shoe Manufacturing Workshop of the Footwear Research Institute (Figure 2).

a b c

Figure 2. Prototype shoes made from three knitted fabric samples: a) fabric sample M1, b) fabric sample M2, and c) fabric sample M3

Methods

To determine the participants' feelings when wearing the sample shoes, they wore shoes made of all three material samples and performed activities according to EN ISO 20344: 2004 [39]. The tests were performed using a relatively simple method often used for evaluating the shoe quality, especially in cases where there was no testing of equipment or equipment to simulate the process of using shoes. In this method, participants wore shoes under specific conditions, felt the shoe quality, and evaluated changes in the shoe quality during use.

The ergonomic characteristics of shoes were evaluated according to EN ISO 20344: 2004. The participants were assessed by examining shoes with three testers with appropriate foot sizes. During the test, they wore correctly fitting shoes and performed normal everyday activities, i.e., walking for five minutes at a speed of about 6 km/h, going up and down at a rate of 17 ± 3 steps in one minute, and kneeling and bending down (Figure 3). The participants finally rated the perceived comfort levels.

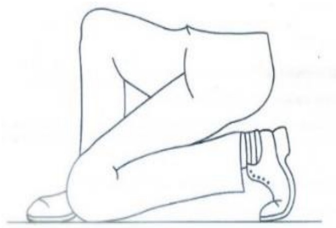


Figure 3. Posture during the kneeling/bending test [39]

The gait cycle (phases of footsteps) is the sequence of human steps, which begins and ends with heel contact by one and the same leg. In this study, two typical measurement positions were selected according to the phases of the foot cycle. In these positions, the value and direction of the load on the toe change during walking. The pressure at the instep and sole of the foot was measured in the two positions to evaluate the level of sensation.

Posture 1 (TT1): both legs stand straight with feet in complete contact with the ground.

Posture 2 (TT2): legs tilted back with toes in complete contact with the ground.

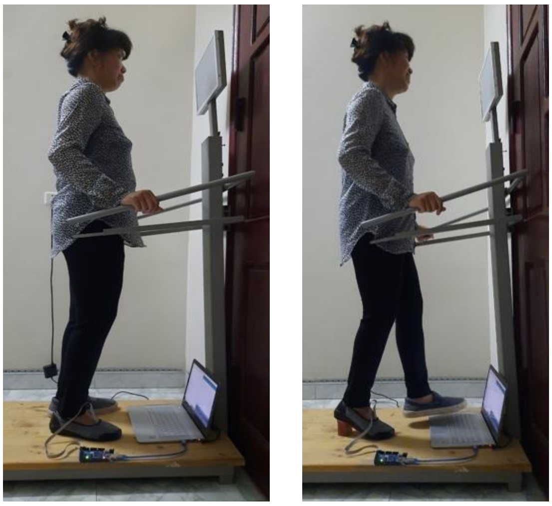


Figure 4. Measurement posture of participant wearing shoes

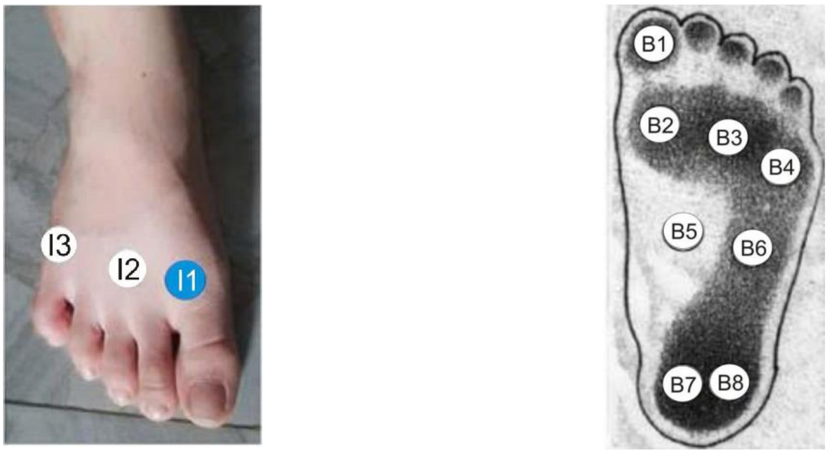
The effect of changes in the elongation and pressure of the three knitted fabric samples on the instep in the two postures was investigated.

The pressure of the material on the instep was determined by measuring the width of the toe joint circumference of the shoe upper material on the feet of female diabetic patients when walking according to the two positions. Then, the difference between the width of the toe joint circumference of the shoe upper material before wearing and when wearing the sample shoes at the time of measuring the pressure in the two postures was determined, and the result was used to calculate the elongation of each knitted fabric sample as follows [40]:

$$f = \frac{K_{td} - K_{tm}}{K_{tm}} * 100 \quad (1)$$

where f is the elongation of the material (%), $K_{tđ}$ is the width of the upper shoe material sample at the toe joint circumference measured when wearing shoes to measure pressure in the two positions (mm), and K_{tm} is the width of the upper shoe material sample at the toe joint circumference before wearing (mm).

Foot ulcers commonly occur on the toes, the toe joints on the dorsum, as well as the soles of the feet [3, 4, 41]. The percent occurrence of ulcers reported at the tip of the foot is up to 76.7% [5]. During common movements, muscle flexion is experienced at the ankle and toe joints. Similarly, muscles are flexed during heel lifting when joints bend between the bones of the foot. However, during walking, the toe joint is subjected to a greater load. The center of bending of the metatarsal bones is located in the central region of the foot, which is higher than the center of bending at rest. In addition, due to the layers of tissue, ligaments, fat, and skin under the metatarsal heads, the center of bending becomes higher. In particular, sensors were placed on the instep of the foot at the position of the first metatarsal joint (sensor 1 – I1, Figure 5a), longitudinal axis of the foot (between the second and third metatarsal joints) (sensor 2 – I2, Figure 5a), and fifth metatarsal joint (sensor 3 – I3, Figure 5a). To measure the pressure on the soles of the feet when wearing the shoe samples, sensors were placed at eight locations under the sole of the foot at the tip of the big toe (sensor 1 – B1, Figure 5b), at the first position of the metatarsal head (sensor 2 – B2, Figure 5b), at the position of the third metatarsal head (sensor 3 – B3, Figure 5b), at the fifth metatarsal head (sensor 4 – B4, Figure 5b), at the middle of the foot arch (sensor 5 – B5, Figure 5b), at the middle of the outer foot (sensor 6 – B6, Figure 5b), at the inward heel position (sensor 7 – B7, Figure 5b), and at the external heel position (sensor 8 – B8, Figure 5b). Along with the pressure value, the feelings of the participants were rated according to the following five levels: level 1, very comfortable; level 2, comfortable; level 3, slightly uncomfortable; level 4, uncomfortable; and level 5, very uncomfortable.



a b

Figure 5. Sensor locations on the instep and bottom of the foot

Data were processed using the Excel, SPSS software, and analysis of variance (ANOVA) to compare the pressure on the instep when wearing the sample shoes for group 1 and group 2, group 1 and group 3, and group 2 and group 3. Moreover, the pressure under the soles of the feet when wearing the sample shoes was compared between group 1 and group 2, group 1 and group 3, and group 2 and group 3.

RESULTS AND DISCUSSIONS

Evaluation of the Feelings of Female Diabetic Patients when Wearing Shoes

In the process of testing shoes, the shoe shape on the feet of the three groups of participants was observed during walking and exercising for 15 min according to EN ISO 20344:2004 [39] to evaluate whether the shape was retained, that is, the shoes hugged the feet and were not deformed, especially when tested on group 2 and group 3 (the toe joint circumference of the participants in the group 3 was 8 mm larger than that in the group 2, which was in turn 8 mm larger than that in the group 1). The result showed that the knitted fabric for shoe uppers has good elasticity.

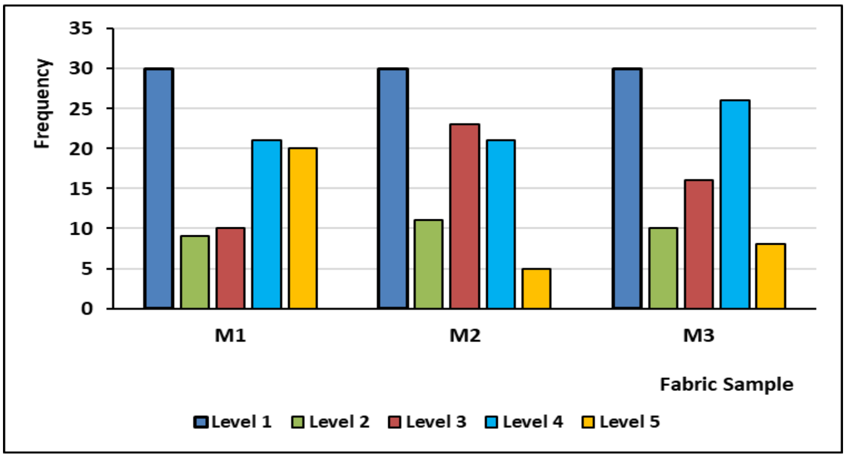


Figure 6. Frequency of five subjective perception levels for three material samples

Figure 6 shows the level of perception on each material upon applying pressure on the instep. According to the established method, the subjective feelings of 45 female diabetics in the three groups were determined for the three materials at two measurement postures, corresponding to 270 assessments (90 assessments for each material).

The total number of ratings at levels 1–5 was 90, 30, 49, 68, and 33, respectively. The ANOVA results gave a *p* value of 0.003 when comparing each sensory level for the three material samples. This result shows that the level of subjective perception on each material sample was different. The M1, M2, and M3 materials received the same rating at level 1, the M2 material exhibited the lowest rating at levels 4 and 5, and the M1 material was rated at level 1. This evaluation is consistent with the elongation characteristics of the three studied fabric samples.

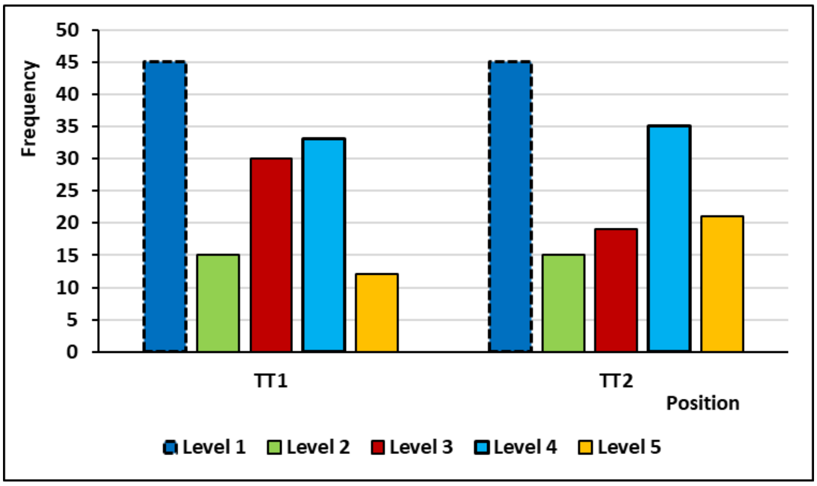


Figure 7. Frequency of five subjective perception levels for three material samples in two measurement postures

Figure 7 shows that each measurement posture resulted in a different level of feeling. The total number of sensory evaluation ratings at each posture was 135. The evaluation frequency at perception levels 1, 2, and 3 decreased gradually according to the measurement posture. By contrast, perception levels 4 and 5 showed an increased evaluation frequency according to the measurement posture. This result is due to the fact that in posture 1, the body's load is evenly distributed on both feet. Meanwhile, in posture 2, in addition to bearing a large load, the foot is bent at the toe joint area, causing a more substantial increase in the foot circumference. The ANOVA results gave a *p* value of 0.016 when comparing the values given to each sensory level for the two postures, indicating that the perception level differed between positions. As the foot size increased, the shoe upper elongated, increasing the compression of the shoe upper on the instep and resulting in discomfort for the patient. Therefore, levels 4 and 5 received more ratings in posture 2 than in posture 1.

Determination of the Pressure on the Instep According to Measurement Postures

The foot size increases from posture 1 to posture 2. The elongation values of shoe uppers for the three groups of female diabetic patients in the two measurement postures are shown in Table 2.

A comparison of the elongation of shoe uppers between posture 1 (TT1) and posture 2 (TT2) reveals that the shoe uppers elongate with increasing foot size. The results summarized in Table 2 show that shoe upper elongation differs considerably among the three groups of participants. For instance, in posture 1, the elongation of the M1, M2, and M3 materials changes from 1.97% ± 0.02% for the N1 group to 11.67% ± 0.09% for the N3 group, from 3.07% ± 0.02% for the N1 group to 15.59 ± 0.09% for the N3 group, and from 2.67% ± 0.03% for the N1 group to 14.89% ± 0.10% for the N3 group, respectively. Thus, the elongation of the three types of fabric samples is different. This leads to a difference in the pressure increase of the shoe upper material on the instep joint corresponding to the elongation of the material (Tables 3 and 4 and Figures 8 and 9).

The pressure values of the shoe uppers made from the M1, M2, and M3 materials on the instep of the three groups of female diabetic patients measured with the three sensors shown in Figure 5a are summarized in Table 3 and Table 4. The results show that the pressure at the first metatarsal joint (first sensor) exhibits the highest value. This is also the most damaged area on the instep of diabetic patients [3–5]. Therefore, the pressure value at the first metatarsal joint position was selected to analyze the relationship between the elongation of the material and pressure on the toe joint of the instep.

Table 2: Elongation (f) of the shoe upper materials M1, M2, and M3 worn by female diabetic patients in postures 1 (TT1) and 2 (TT2)

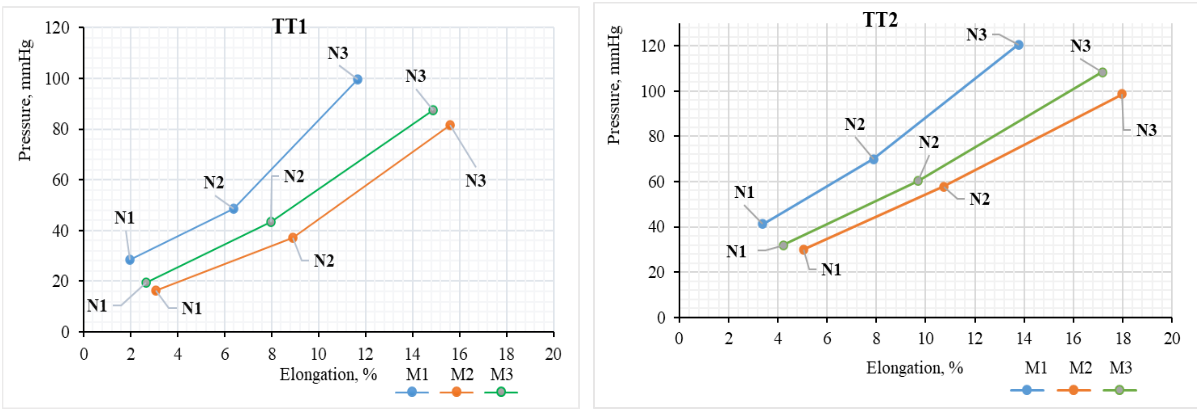
Participant Group	M1					M2					M3				
	TT1		TT2		Diff	TT1		TT2		Diff	TT1		TT2		Diff
	f1, %	SD, %	f2, %	SD, %	f2 – f1, %	f1, %	SD, %	f2, %	SD, %	f2 – f1, %	f1, %	SD, %	f2, %	SD, %	f2 – f1, %
N1 (n = 15)	1.97	0.02	3.39	0.03	1.42	3.07	0.02	5.06	0.02	1.99	2.67	0.03	4.23	0.05	1.56
N2 (n = 15)	6.38	0.07	7.88	0.08	1.5	8.92	0.05	10.74	0.05	1.82	7.98	0.06	9.68	0.10	1.7
N3 (n = 15)	11.67	0.09	13.78	0.10	2.11	15.59	0.09	17.97	0.15	2.38	14.89	0.10	17.17	0.12	2.28

Table 3: Pressure of shoe upper materials M1, M2, and M3 on the instep of the three groups of female diabetic patients measured in posture 1 (TT1)

Fabric Sample	N1 (n = 15)							N2 (n = 15)							N3 (n = 15)						
	f, %	1st Sensor		2nd Sensor		3rd Sensor		f, %	1st Sensor		2nd Sensor		3rd Sensor		f, %	1st Sensor		2nd Sensor		3rd Sensor	
		Mean, mmHg	SD, mmHg	Mean, mmHg	SD, mmHg	Mean, mmHg	SD, mmHg		Mean, mmHg	SD, mmHg	Mean, mmHg	SD, mmHg	Mean, mmHg	SD, mmHg		Mean, mmHg	SD, mmHg	Mean, mmHg	SD, mmHg	Mean, mmHg	SD, mmHg
M1	1.97	28.63	1.52	11.45	1.26	19.86	1.82	6.38	48.46	1.88	28.76	1.65	37.68	1.65	11.67	99.53	2.54	74.17	1.48	87.63	1.84
M2	3.07	16.48	1.70	4.78	1.47	10.64	1.34	8.92	37.33	1.97	16.17	1.67	26.06	1.89	15.59	81.44	2.13	58.12	2.12	72.43	2.45
M3	2.67	19.56	1.25	8.07	1.19	12.15	1.51	7.98	43.41	1.87	20.49	1.62	31.74	1.78	14.89	87.63	2.46	65.76	2.08	78.39	1.65

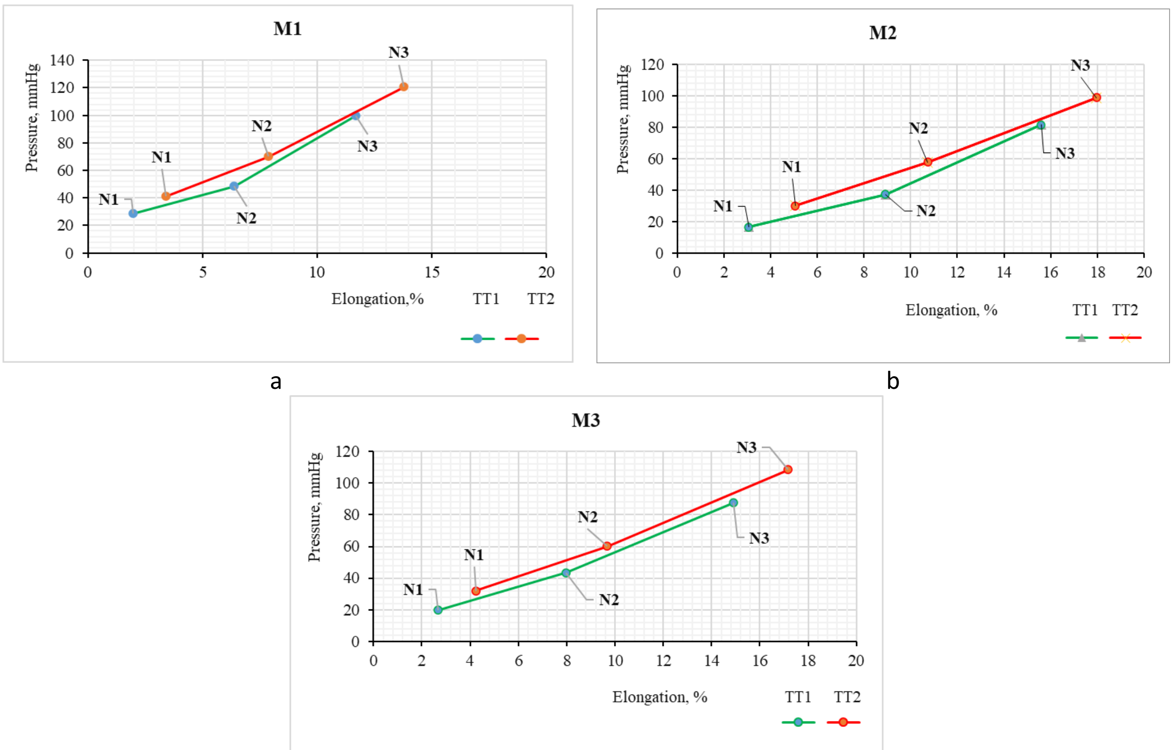
Table 4: Pressure of shoe upper materials M1, M2, and M3 on the instep of the three groups of female diabetic patients measured in posture 2 (TT2)

Fabric Sample	N1 (n = 15)							N2 (n = 15)							N3 (n = 15)						
	f, %	1st Sensor		2nd Sensor		3rd Sensor		f, %	1st Sensor		2nd Sensor		3rd Sensor		f, %	1st Sensor		2nd Sensor		3rd Sensor	
		Mean, mmHg	SD, mmHg	Mean, mmHg	SD, mmHg	Mean, mmHg	SD, mmHg		Mean, mmHg	SD, mmHg	Mean, mmHg	SD, mmHg	Mean, mmHg	SD, mmHg		Mean, mmHg	SD, mmHg	Mean, mmHg	SD, mmHg	Mean, mmHg	SD, mmHg
M1	3.39	41.21	1.22	28.42	2.33	32.15	1.43	7.88	69.96	1.86	49.32	1.89	57.54	2.24	13.78	120.65	2.50	91.58	1.64	103.76	1.74
M2	5.06	30.04	1.17	14.75	1.17	19.32	1.68	10.74	57.78	1.48	35.89	2.53	44.67	1.96	17.97	98.66	2.03	69.36	2.12	84.85	2.45
M3	4.23	31.94	1.18	18.14	2.13	23.67	1.45	9.68	60.19	1.77	42.65	2.13	51.94	1.64	17.17	108.48	2.36	81.35	2.34	97.96	1.75



a b

Figure 8. Pressure values on the instep of three groups of female diabetic patients measured at the first sensor position for the three shoe upper materials: (a) Posture 1, (b) Posture 2



a b

c

Figure 9. Pressure values on the instep of three groups of female diabetic patients measured in posture 1 and posture 2 at the first sensor position for the three shoe upper materials: (a) M1, (b) M2, (c) M3

The fabric characteristics affected its pressure value [41–44], and the elastic elongation of the fabric affected the pressure distribution and pressure value [22, 23]. Tables 3 and 4 show that as the elongation of the material increases, the pressure of the shoe upper on the instep increases to the same extent. The pressure value and its increase with elongation differ among the studied materials (Tables 3 and 4 and Figures 8 and 9). In the N1 group of diabetic female participants tested in posture 1, the pressure value of the M1 material was 28.63 ± 1.52 mmHg (with 1.97% elongation), that of the M2 material was 16.48 ± 1.7 mmHg (with 3.07% elongation), and that of the M3 material was 19.56 ± 1.25 mmHg (with 2.67% elongation). Thus, for the same foot size, the material with the highest elongation exhibited the smallest pressure value and vice versa. This result shows that using knitted fabrics as shoe uppers for female diabetic patients can reduce the pressure of the shoe uppers on the feet, avoiding swelling and ulcers. The ANOVA results comparing the difference in the pressure values between the three groups of female diabetic patients on the same material showed $p < 0.05$, proving that the pressure value on the instep changes with the elongation of the material. The M2 material exhibited the smallest pressure value among the three groups (the highest pressure in posture 2 in the N3 group reached 98.66 ± 2.03 mmHg). The M1 material showed the highest pressured value at all relaxation levels (the maximum pressure at posture 2 in the N3 group was 120.65 ± 2.50 mmHg). Although the M1 and M2 materials have the same composition but weave style, their density of the wales and course was different, affecting the pressure value. The M1 material has a higher density of wales and course of top layer than M2 material, thus a higher pressure value on the instep. The uniformity of type of fabric, the density of wale and course of the top layer and bottom layer of each material sample also affect the pressure on the patient's feet. The top layer and bottom layer of M2 material have the same single jersey and the density of wale and course which give the smallest pressure value.

The human foot is constructed to resist forces, to maintain balance and to co-ordinate movements in static and dynamic conditions. The insertion of muscle tendons optimizes the required moments typical of the human gait [45]. The prolongation of the gastrocnemius muscle into the Achilles tendon allows the generation of the moment required at the toe-off [45, 46]. The foot acts on the ground, and the ground reacts on the foot. Basically, at the toe-off, an opposite force, i.e., the ground reaction force, is transmitted through the metatarsal joint. The magnitude of the ground reaction force is directly proportional to the body weight, velocity, and force generated by the calf muscles, and thus, the plantar pressure transmitted through the forefoot as well [47]. When using shoes, the foot moved and changed size due to the long-term body load, variations in the load on the foot, bending of the foot (or to edema or swelling in patients with foot comlications), and elongation of the shoe upper material. Due to changes in the load on the foot and flexion of the foot, compared with posture 1, in posture 2 (the position where the foot size is larger), the shoe upper material was elongated (Table 2) and pressure of the shoe upper on the joint instep area increased (Table 4). This result shows that the elongation of the shoe upper material due to the foot posture increases the pressure on the instep joint. Research found that shoes constructed from soft suede were more comfortable than those fabricated from a stiffer leather upper [48], shoes with a round toe-box and those with a stretchable fabric upper generated lower toe pressures and were perceived to be the most comfortable [49]. Therefore, selecting materials for shoe uppers is essential to ensure pressure comfort and prevent foot damage, especially for patients with foot complications such as diabetics.

In previous research [36], the author recommended that the maximum pressure value allowed on the toe joint of the instep of a woman's foot should be 69.2 mmHg to ensure retention. The shape of the shoe does not affect the normal physiological functioning of a diabetic female's feet. The results summarized in Tables 2–4 show that Groups N1 and N2 differ in the sizes of the toe joint by 8 mm, but they can wear the same shoe size of 37; three types of knitted fabrics were studied for use in shoe uppers, and they all met the pressure criteria. The size of the toe joint size was 16 mm larger in Group N3 compared to Group N1. Therefore, the pressure for all three knitted fabric samples was also generally greater than the recommended pressure limit. These observations indicate that knitted fabrics with a stretchability of ≤ 10.74% are suitable for making shoe uppers for female diabetic patients, who should choose shoes that fit the foot to avoid compression.

Determination of the Pressure on the Soles of the Feet when Wearing Shoes

The pressure on the soles of the feet of the three groups of participants was determined at eight locations (Figure 5b). The results are summarized in Table 5.

Table 5: Pressure on the soles of the feet of the three groups of participants

Participant Group	Fabric Sample					
	M1		M2		M3	
	TT1	TT2	TT1	TT2	TT1	TT2
Pressure value (kPa) at the tip of the big toe (B1, Figure 5b)						
N1 (n = 15)	**9.0 ± 3.66**	**130.80 ± 4.39**	**8.84 ± 2.96**	**129.2 ± 4.23**	**8.98 ± 3.01**	**130.12 ± 4.83**
N2 (n = 15)	8.34 ± 4.24	129.34 ± 4.61	7.95 ± 5.10	134.34 ± 5.14	8.17 ± 4.54	129.37 ± 5.63
N3 (n = 15)	10.1 ± 2.13	136.35 ± 5.91	9.68 ± 3.12	137.13 ± 3.32	9.43 ± 4.35	134.23 ± 3.35
Pressure value (kPa) at the first position of metatarsal head (B2, Figure 5b)						
N1 (n = 15)	18.52 ± 4.04	154.30 ± 6.54	18.01 ± 3.98	153.8 ± 5.63	18.43 ± 3.65	152.1 ± 5.36
N2 (n = 15)	23.94 ± 4.24	160.58 ± 6.87	22.79 ± 5.04	154.85 ± 5.78	23.02 ± 5.13	156.23 ± 5.87
N3 (n = 15)	26.83 ± 5.36	165.47 ± 7.48	27.14 ± 5.83	170.23 ± 4.37	24.85 ± 5.32	174.65 ± 5.94
Pressure value (kPa) at the position of the third metatarsal head (B3, Figure 5b)						
N1 (n = 15)	21.43 ± 3.99	171.18 ± 5.85	21.16 ± 3.92	170.45 ± 5.34	21.6 ± 3.34	170.0 ± 5.43
N2 (n = 15)	24.60 ± 4.19	175.23 ± 6.14	23.34 ± 4.65	176.90 ± 5.76	24.43 ± 4.58	173.1 ± 5.86
N3 (n = 15)	26.96 ± 4.89	181.3 ± 6.56	25.6 ± 4.98	182.1 ± 6.58	28.1 ± 5.41	178.62 ± 6.3
Pressure value (kPa) at the fifth metatarsal head (B4, Figure 5b)						
N1 (n = 15)	16.18 ± 3.14	139.62 ± 6.84	15.23 ± 3.41	137.56 ± 6.30	15.89 ± 3.64	138.68 ± 6.35
N2 (n = 15)	21.44 ± 3.30	145.61 ± 7.19	21.12 ± 3.83	144.43 ± 7.94	21.42 ± 3.91	140.32 ± 7.48
N3 (n = 15)	20.6 ± 4.45	149.24 ± 7.98	12.7 ± 4.74	151.1 ± 7.83	19.92 ± 5.49	145.16 ± 7.43
Pressure value (kPa) at the middle of the foot arch (B5, Figure 5b)						
N1 (n = 15)	5.33 ± 2.97	-	3.79 ± 3.67	-	4.28 ± 3.78	-
N2 (n = 15)	6.60 ± 3.12	-	5.11 ± 2.23	-	5.56 ± 2.89	-
N3 (n = 15)	10.96 ± 3.71	-	9.68 ± 4.52	-	12.45 ± 5.82	-
Pressure value (kPa) at the middle of the outer foot (B6, Figure 5b)						
N1 (n = 15)	13.07 ± 2.11	-	12.74 ± 3.03	-	12.94 ± 3.10	-
N2 (n = 15)	11.97 ± 2.21	-	11.85 ± 2.65	-	10.96 ± 2.36	-
N3 (n = 15)	19.3 ± 4.13	-	21.41 ± 5.46	-	19.08 ± 4.5	-
Pressure value (kPa) at the inward heel position (B7, Figure 5b)						
N1 (n = 15)	25.63 ± 9.0	-	25.21 ± 8.61	-	23.61 ± 8.17	-
N2 (n = 15)	24.77 ± 9.45	-	23.64 ± 9.76	-	24.12 ± 8.94	-
N3 (n = 15)	35.84 ± 10.8	-	31.9 ± 10.13	-	32.98 ± 10.7	-
Pressure value (kPa) at the external heel position (B8, Figure 5b)						
N1 (n = 15)	30.63 ± 9.12	-	30.01 ± 8.84	-	29.58 ± 8.53	-
N2 (n = 15)	32.92 ± 9.58	-	31.24 ± 9.36	-	29.92 ± 9.56	-
N3 (n = 15)	34.89 ± 11.4	-	37.38 ±10.92	-	37.91 ± 11.32	-

The pressure values on the soles of the feet at eight measurement locations exhibit significant differences. When standing on two feet, the pressure on the foot's heel is the highest. The lowest pressure is exerted on the medial gills, corresponding to the medial longitudinal arch of the foot. The pressure distribution shows that despite wearing 5-mm-thick elastic shoe insoles, the ability to disperse the pressure on the soles of the feet is not good because the insoles are flat, especially in the longitudinal arch area of the foot, where the pressure is only approximately 20% of the pressure on the heel. This result demonstrates the need for designing and manufacturing shoe insoles shaped to the patient's soles.

At sensor B2 (Figure 5b) for the N1 and N2 groups of participants in posture 1, the pressure value is 18.52 ± 4.04 and 23.94 ± 4.24 kPa with the M1 material, 18.35 ± 3.98 and 22.79 ± 5.04 kPa with the M2 material, and 18.43 ± 3.65 and 23.02 ± 5.13 kPa with the M3 material, respectively. In the N2 group, shoe uppers are elongated more strongly because of its larger toe ring than N1 group, causing an increase in the pressure on the instep that increases the pressure on the upper part of the foot. In particular, the pressure value measured in posture 2 increases substantially compared with that in posture 1 due to the weight placed on the toe joint when the foot is bent. These results show that using elastic materials such as knitted fabrics to fabricate shoe uppers create a comfortable pressure feeling for the shoe uppers and reduce the pressure on the soles of the feet.

In the N3 group, the pressure on the soles of the feet is generally greater than those in the N1 and N2 groups because of the greater body mass of the participants in the N3 group (average 54 kg vs. 48 kg in the N1 and N2 groups). The pressure on the middle part (arches) of the feet of the participants in the N3 group is much greater than those of the other two groups, which is related to the degree of arch lowering in female diabetic patients.

For the three groups of the participants in posture 2, at sensor measurement positions B5, B6, B7, and B8, there is no contact; therefore, there is no pressure in the area between the sole and heel of the shoe. Furthermore, shoe insoles with a flat surface that does not shape the sole of the foot were used in this study; hence, the ability of the shoe insoles to disperse pressure on the sole of the foot is not good, especially in the longitudinal arch area of the foot.

The following ANOVA results were obtained when comparing pressure values at different locations on the soles of the feet: N1 and N2 groups, $p = 0.01$; N1 and N3 groups, $p = 0.0001$; and N2 and N3 groups, $p = 0.001$. Thus, the pressure values at the soles of the feet of the three groups are different.

The peak pressure on foot areas in the measured postures reaches a maximum value of 182 kPa, which does not exceed the recommended threshold of 200 kPa required to avoid foot ulcers [50–53]. Thus, the fabricated shoes meet foot pressure requirements for use by female diabetic patients.

CONCLUSIONS

The purpose of this study was to evaluate the impact of three different knitted fabric samples used to fabricate shoe uppers on various locations at the instep of female diabetic patients. The shoes had the same design structure; however, their uppers exhibited different characteristics. The design of the size 37 shoe model complied with the specifications proposed based on the research team's anthropometric data on female diabetic patients, and the shoe was manufactured at the Leather and Footwear Research Institute. The foot pressure values were measured for 45 female diabetic patients; furthermore, based on the size of the toe joint ring, they were divided into three different groups with a difference of 8 mm in the toe ring size between groups. The pressure was measured by placing the foot on two postures: posture 1, which is the upright position with the body weight evenly distributed on both legs, and posture 2, in which the feet are bent.

The results of this study provide a different perspective on comfort, convenience, and pressure values depending on the phase of the gait cycle and choice of materials for the shoe uppers. The pressure of knitted fabrics on the instep changed according to material elongation. Due to a change in the load on the foot and the bending of the foot, the shoe upper material was more elongated in the bending position of the foot compared with the upright position, which increased the pressure of the shoe upper on the instep joint area. With the change in the pressure on the instep, the pressure under the sole of the foot at the joints of the toes increased. The pressure under the sole at the joints of the toes increases with a change in the pressure on the instep. The sample M2 presented the least pressure among all three experimental groups, where the highest pressure of 98.66 ± 2.03 mmHg was observed at TT2 in Group 3. Sample M1 faced the strongest pressure at all elongated levels, where the maximum pressure was 120.65 ± 2.50 mmHg at TT2 in Group 3. Among the shoe models tested here, the maximum pressure measured on the different areas of the foot reached 182 kPa, which is within the recommended threshold of 200 kPa to prevent foot ulcers. All samples in Groups N1 and group N2 met the pressure criteria with three types of knitted fabrics assessed in this study in shoe uppers. Particularly, knitted fabrics with elongation of ≤ 10.74% are suitable for making shoe uppers for female diabetics, who should choose shoes that fit the foot to avoid compression. This study provides important insights into the selection of materials to fabricate shoe uppers that ensure a comfortable pressure at all times to prevent foot damage, especially in patients with foot complications, such as diabetic individuals.

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