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Do commonly used postoperative orthopaedic shoes help off-load the forefoot?

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Purpose: The aim of the experiment presented in this study was to determine the pressure distribution within the forefoot depending on the type of orthopaedic footwear used. *Methods*: The study included 27 women aged 20 to 25. The Zebris FDM-2 dynamographic platform was used in foot pressure measurements. The load distribution was measured in three types of orthopaedic footwear: MedSurg, MedSurgPro and OrthoWedge. The full gait cycle was recorded. The Cavanagh masks were applied to the load distribution results processed into a graphic form. The data were analysed using Statistica v.13.1. *Results*: In the forefoot area, i.e. the metatarsal bones and toes 1–5, the lowest loads were reported in the shoes that off-load the forefoot (0.2 N/cm^2, $p < 0.001$). In the area of the first to fifth metatarsal bones and the hallux, the highest load was observed in the rocker shoe, accounting for 19.7 N/cm^2 ($p < 0.001$). For comparison, high pressure in the flat shoe was found in the area of toes 2 to 5 ($p < 0.001$). *Conclusions*: In the area of the metatarsal and toe bones, the pressure exerted was highest in the commonly used rocker shoe. The flat shoe provides an even and uniform load in all areas of the forefoot, while this type of shoe does not significantly reduce the pressure forces on the forefoot. The shoe that was the most effective in off-loading was the forefoot off-loading shoe (OrthoWedge). Barefoot walking puts less load on the forefoot compared to the flat and rocker shoes used after orthopaedic procedures.

Key words: *gait, orthopaedic shoes, distribution of foot pressure to the ground, Cavanagh masks*

1. Introduction

The use of orthopaedic footwear in medicine focuses mainly on postoperative management in patients in whom interventions include the forefoot area, such as surgical correction of hallux valgus, deformations of toes 2–5, neuralgias of interdigital nerves, joint stiffening or treatment of ulcers resulting from the development of advanced diabetic lesions [6]. The pressure exerted on some areas of the foot may determine therapeutic success or failure. The objectives of the orthopaedic footwear are, first of all, to off-load specific areas of the forefoot, to enable the foot to roll, or to temporarily reduce mobility within the foot joints, allowing the patient to walk with relative ease [15]. The choice of a correct shoe for the patient is made by measuring the distribution of foot pressure on the ground using specialized measuring equipment and integrated computer software. The measurement of pressure distribution is a clinically useful tool enabling the identification of anatomical deformations within the forefoot and the need to off-load or protect the given foot area [25]. In general, during human gait, foot loads can be monitored using two different systems, i.e., podobarographic platforms or inserts with piezoelectric sensors [20], [29]. The most common method is the use of inserts. However, recent research proves that it is possible to obtain reliable and consistent results of pressure distribution in a shoe without the use of inserts, instead of them using special platforms, also called podometric tracks [1], [31].

The examinations that analyse the distribution of pressure in individual areas of the foot allow for the

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correct choice of the footwear. The disproportion of the access to literature, which is mainly focused on off--loading footwear, makes it impossible to make a comparative analysis of the footwear used, thus limiting the possibility of developing a gold standard of adapting the footwear to a given patient. There is no clear evidence as to which postoperative shoe is most effective in off-loading the given foot area [24]. The researchers agree that the off-loading shoes with the reduced toe area minimize the load to a value close to zero [6]. However, they significantly disrupt the normal gait cycle, thus significantly reducing their usefulness in common situations, where partial off--loading is needed rather than the total elimination of the load. The greatest ambiguity appears in the case of rocker shoes and flat shoes, which are, however, most often recommended by orthopaedists. The multitude of designs of these shoes and materials used in their production may disturb the distribution of loads and possibilities of use in orthopaedic practice [30]. Many studies have been conducted among diabetic patients on mechanical models or on bare feet from corpses, which may not reflect the actual gait mechanics [14], [3], [24]. The literature describing the load in flat shoes compared to bare feet often presents conflicting views in the context of forefoot off-loading [27]. There is a need to enrich the reports with further results necessary for clinical work, in which the pressure distribution is compared between the foot in shoes and barefoot. The research should also involve comparative analyses to systematise and classify available orthopaedic shoes.

The aim of the experiment was to assess the distribution of pressure within the forefoot in barefoot walking and in three types of postoperative orthopaedic footwear.

2. Materials and methods

2.1. Participants

The study involved 27 women aged 24.4 ± 3.8 years old, with a body height of 1.72 ± 0.98 m and body weight of 71 ± 19.4 kg. The criteria for inclusion in the study were: female, aged 20–25 years, and normal BMI. The exclusion criteria were: tibiocalcaneal angle > 5°, the difference in limb length >0.005 m, injury in the foot during the last 6 months and presence of pain in the ankle. The approval was obtained from the Institute's Research Ethics Commission and an additional informed consent was obtained from all participants.

2.2. Data collection

The Zebris FDM-2 dynamographic platform (Zebris Medical GmbH, Isny, Germany) was used for the examination, with a dynamic Gate module to analyse the foot pressure distribution during gait. A 10-area mask proposed by Cavanagh was applied to the load distribution graphics [8]. The maximum pressure values are expressed in N/cm^2 in each area of the mask. The mask was applied to the load distribution obtained from measurements in each of the tested orthopaedic and barefoot shoes.

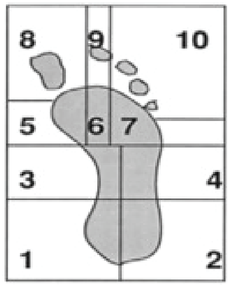

Fig. 1. Diagram of the 10-dimensional mask proposed by Cavanagh [8]

2.3. Protocol

The examination included the recording of four passages of the participant through the measurement track. The load distribution was measured in three types of orthopaedic footwear (Fig. 2). The MedSurg model of a flat shoe, CHV Confort model of a rocker shoe (by Sober) and the OrthoWedge forefoot off-loading shoe were used. The full gait cycle was recorded. The first measurement recorded barefoot gait. Next, the participant put an orthopaedic shoe on the dominant leg and a sports shoe with a sole height comparable to that used in the experimental shoe on the non-dominant leg. The participant covered the measurement track several times to adapt to the laboratory environment and footwear. In the proper measurement, the women covered the track distance three times. The smoothest and flawless passage

Fig. 2. Types of orthopaedic shoes used in the experiment: (a) flat shoe, (b) rocker shoe, (c) forefoot off-loading shoe

through the platform was recorded. In subsequent stages, the shoe was changed. The adaptation and measurement procedures were repeated.

2.4. Statistical analysis

The collected data were placed in a spreadsheet and statistical analysis was performed using Statistica v.13.1. Normality of distribution was verified using the Shapiro–Wilk test. Since the distribution of variables was not close to the normal distribution in most of the parameters measured, the non-parametric ANOVA Friedman test and the Wilcoxon test with Bonferroni correction were used to check the significance of differences between shoes. The differences were assumed to be statistically significant at ($p \leq 0.05$).

3. Results

The figure below presents the results of the foot load analysis in various types of orthopaedic footwear (Fig. 3) and in barefoot walking.

The analysis showed that the maximum pressure in the area of the metatarsal bones 1–5 and the hallux during walking in the rocker shoe was the highest that was obtained in the entire experiment. Furthermore, the gait in the rocker shoe causes statistically significantly higher pressure in the forefoot compared to the barefoot walking and walking in a flat shoe.

The smallest loads in the forefoot area were recorded in the forefoot off-loading shoe (0.2 N/cm^2)

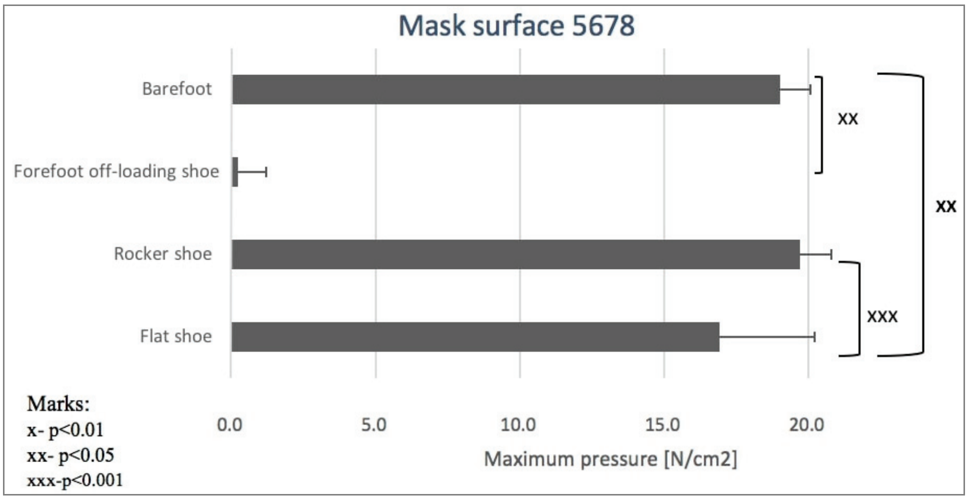

Fig. 3. Distribution of maximum load in orthopaedic footwear and barefoot in the area of metatarsal bones 1–5 and the hallux. According to the Cavanagh mask, these areas are marked as 5, 6, 7 and 8, respectively

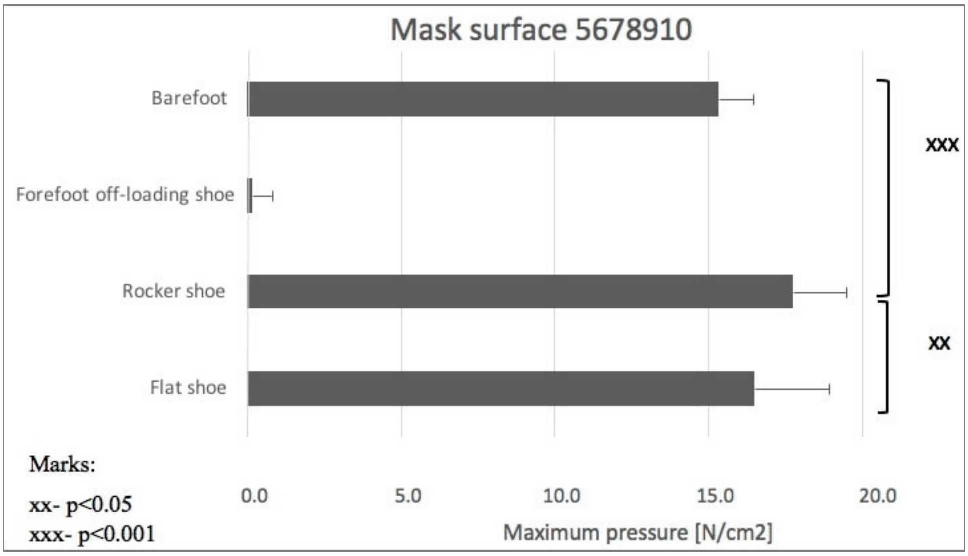

Fig. 4. Distribution of maximum load within the forefoot in orthopaedic footwear and barefoot. According to the Cavanagh mask, these areas are marked as 5, 6, 7, 8, 9 and 10, respectively

(Fig. 4). Comparable pressures were obtained in a flat shoe and during barefoot walking.

The mask areas 9 and 10 represent the area of toes 2–5, where the barefoot load is the lowest. Twice the value was obtained for the flat shoe (Fig. 5).

The highest values within the rear foot were obtained in the forefoot off-loading shoe, where the heel and metatarsus exerted the only pressure on the ground ($p < 0.001$). In the area of metatarsal and toe bones, the pressure was highest in the rocker shoe. Slightly smaller pressure (15–17 N/cm^2) was obtained in the same shoe within the area of toes 2–5. The same pressure range was found for the pressure of distribution in the flat shoe in the area of the hallux and metatarsal bones, while a higher load was carried by the toes 2–5. During the barefoot gait, the load in the area of metatarsal bones, the hallux and toes 2–5 was significantly lower compared to all orthopaedic shoes analysed (Fig. 6).

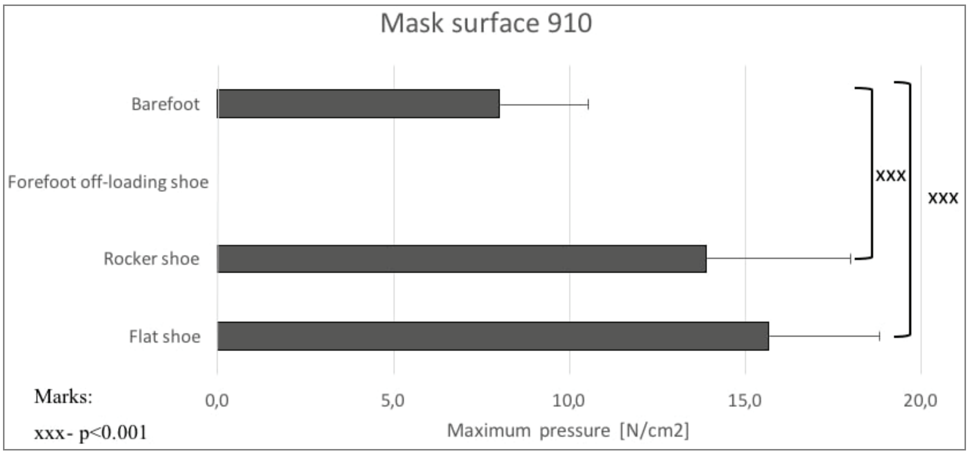

Fig. 5. Maximum load distribution in the toe areas 2–5.
According to the Cavanagh mask, these are areas 9 and 10, respectively

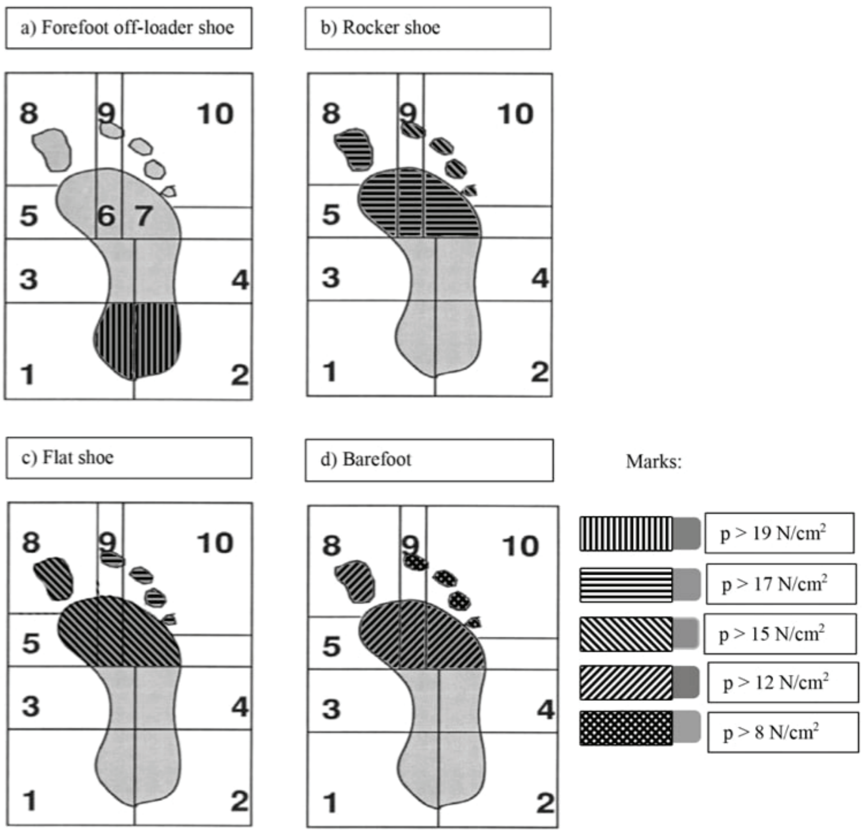

Fig. 6. Summary of pressure distribution for the foot in orthopaedic footwear and barefoot during gait

4. Discussion

In this experiment, the effect of various types of the most commonly used postoperative footwear on the distribution of foot pressure on the ground during gait was investigated. Special attention was paid to the distribution of pressure within the forefoot, as well as to the comparative analysis of gait in postoperative footwear and the barefoot gait.

The Darco OrthoWedge off-loading shoe [21] is a commonly used orthopaedic shoe, designed to off-load the forefoot as much as possible. Classified as a casual shoe with a high-profile rear part and midsole and a low-profile front part. Consequently, the body weight is transferred to the middle and rear areas, and the off-loading is ensured by limiting the contact with the ground in the forefoot. Our study shows that this shoe, by off-loading the forefoot, increases the pressure forces in the rear foot and also in the lateral part of the metatarsus, i.e., in the area of the M4 mask. The values obtained in the areas of masks M9 and M10 represent the maximum pressure that was recorded during walking in this shoe. Schuch et al. [30] emphasize that the off-loading shoe reduces the load in the hallux area, whereas it is not suitable for patients following the metatarsus surgery. The forces in this area are high, and, in the lateral part, they are close to the high values obtained in the rear foot. Caravagii et al. [6] used an off-loading shoe with a similar design, with the 18-mm difference in sole height between the front and the rear parts of the shoe. The results obtained by this author are consistent with the results of the present study. The most loaded area was the heel, whereas slightly smaller values were recorded in the metatarsal area. The greatest reduction was observed in the area of the metatarsal bones and the hallux and toes 2–5. Our study showed a significantly higher load in the forefoot area during barefoot walking compared to the off-loading shoe. Interesting observations were made by Navarro-Cano et al. [24], who showed a significant ($p < 0.05$) reduction of the load at the forefoot in this type of shoe. The basis for obtaining a significant reduction was the value of foot pressure on the ground of thirty kilograms and more, i.e., at a pressure equal to forty, fifty or sixty kilograms, i.e., a body weight close to the average body weight of women participating in this study. However, below thirty kilograms, the load distribution on the bare foot and foot in the off-loading shoe did not differ statistically. It is worth noting, however, that the study was carried out in isolated conditions, using a dynamometer and a foot from the corpse, which could have affected the final results. Palmanovich et al. [26] emphasized the importance of shoe height adjustment, in research protocols using only one shoe. They demonstrated clinical relevance in the load distribution between the application of height compensation and its absence. The use of a shoe that compensated for limb length shifts the load to the lateral side of the opposite foot, thus providing additional off-loading to the medial, post-operative part of the forefoot. In our study, we used a sports shoe with a higher sole to compensate for the limb length. The mediolateral projection of the foot over its entire length also showed higher values compared to the medial side, which is confirmed by the observations of Palmanovich et al. [26].

Orthopaedic shoes, especially those that off-load the forefoot, are commonly used among diabetic patients, hence a plethora of the literature in this field [3], [4], [9], [14], [32]. Bus et al. [5] used an off-loading shoe, with the difference in height between the front and rear parts of the shoe twice as high as in our study. It achieved a load reduction in the forefoot ranging from 38 to 58%. However, it was stressed that, in the case of the neuropathic foot, the biomechanical off-loading mechanism is not fully understood. In later studies, Bus et al. [3] confirmed the efficacy of the tested shoes, in which the forefoot off-loading accounted for 37–54%. Carl et al. [7] demonstrated a 100% load reduction both in the forefoot and metatarsal areas. It is worth noting, however, that the off-loading of the metatarsal foot was due to the modified shoe design, with a higher shoe heel only in the foot heel area. Deleu et al. [9] reported 79–96% off-loading in the forefoot using a Barouk shoe with increased support under the heel and middle part of the foot. An additional design difference compared to the Darco OrthoWedge shoe was that the shoe was placed in a 10° dorsal flexion, which further reduced the load. The second leading and well-documented biomechanical orthopaedic shoe is the shoe manufactured by Sober, as the CHV Confort used in our research, the so-called rocker shoe [16], [18]. The basic idea behind this shoe design is to facilitate foot rolling while minimising the movement of the metatarsophalangeal joints in the sagittal plane. The rocker shoe is the most frequently recommended type of orthopaedic footwear, combining both off-loading features and allowing the patient to walk using a gait as close as possible to natural. This is in contrast to OrthoWedge, which provides real off-loading to the forefoot, but forces a specific form of movement, expressed both by a significant shortening of the stride length and the double support phase. [11]. It is also stressed that by reducing the pressure in the toe area as compensation, the increased pressure can occur within the metatarsal bones. On the other hand, the authors note that the reduction of flexion in the sagittal plane directly affects the reduction of the load in this area [17]. Such extreme two views may be related to different models of rocker shoes used for testing, which directly affects the value of pressure. The models differ in the place where the peak of the rollover falls, i.e., the highest and most convex part of the sole [2]. In our study, the highest pressure values among the other shoes analysed were recorded in both the hallux and metatarsal areas. According to the latest research, there is no one verified and valid model recommended as the gold standard. Therefore, it seems justified to carry out further research on various models to adjust the shoe to the patient's needs [17].

The last shoe that underwent a thorough analysis was the flat shoe Darco MedSurg, used in orthopaedic foot surgeries. To the best of the author's knowledge, there are few literature reports on the load distribution in this shoe. Our study shows that the loads in a flat shoe carried by the forefoot are by 7.3% lower than in a rocker shoe. Similar results were obtained by Westra et al. [32], who determined this difference in the range of 1.2–13%. Navarro-Cano et al. [24] confirmed a slight difference in load reduction in a flat shoe compared to a rocker shoe. An important element of our measurements was to determine the differences compared to barefoot walking. The differences in the forefoot area were statistically insignificant, while in the information brochure [10], the shoe manufacturer Darco presents a load reduction of 57% in the area of toes 1–5 and 48% in the area of all metatarsophalangeal joints. It is worth noting, however, that Darco did not use a completely bare foot, but a soft ballet shoe, emphasizing its mechanical characteristics similar to the bare foot. A comparable degree of load reduction was obtained by Navarro-Cano [24]. However, the procedure for the use of the dynamometer, and the foot from the corpse and for the examination performed in static conditions raise reasonable doubts. Glod et al. [13] used the original model of a flat shoe and made a comparison with a bare foot. The authors of the present paper have shown a reduction in the load to the forefoot in a flat shoe by 14.4% on average. Our study showed a statistically insignificant difference in the load (7.3%) in barefoot walking, which was not reflected in the available literature.

Differences may result from the testing method, namely measurements using a barometric insert. Unfortunately, the inserts tend to move during walking. Therefore, in our study, measurements were made using a track with fixed sensors. Results on the tracks seem to be more reliable than measurements with inserts.

A small increase in load in both the toe area (by 3%) and the first metatarsal bone (by 7.3%) in a flat shoe was demonstrated by Pirozzi et al. [27]. However, the flat shoe was compared to the classic sports shoe. By using rigid materials for the construction, which are intended to protect the postoperative area from moving, the flat shoe generates, as has been shown, adverse high pressure acting on the forefoot. This is done by using a carbon fibre part in the toe area of the sole, which, instead of reducing, increases the forces acting on the forefoot. Furthermore, the shoe does not have the natural rolling surface, thus disturbing the optimal rolling properties [30]. These properties are reflected in the results of our study, where no significant differences in pressure values were observed within the entire forefoot in a flat shoe and barefoot.

Surgeons or physiotherapists who fit shoes for patients should be able to conduct regular diagnostic tests. These tests should be performed under different postoperative conditions for different types of orthopaedic footwear, taking many biomechanical gait parameters into account. Over the last ten years, few studies have concerned, in addition to the distribution of pressure in shoes, a comparison with a bare foot [24]. Orthopaedic shoes, despite the different forms of soles, add a certain type of stabilization and reduction of natural barefoot motion during locomotion [22]. At the beginning of the stance phase, the foot's evertion dominates. At the end of stance, the foot changes its position towards inversion and during the swing phase again it moves towards dorsiflexion and eversion [23]. Therefore, this continuous movement of the foot affects the pressure distribution and must be taken into account when comparing with walking in stiff footwear.

In the future, it is advisable to carry out research extending the analysis of pressure distribution with that concerning other kinematic gait parameters, such as stride length, loading time, and joint angles in order to select the most optimal shoes for the patient.

However, the study has some limitations in its practical conclusions since the research was conducted only with the participation of healthy and physically fit individuals aged 20–25. However, this allowed for the comparison with the results of many other authors [7], [19], [26]. In the future, the same research is planned to be carried out with patients divided into certain groups of specific postoperative dysfunctions within the foot.

5. Conclusions

The analysis of load distribution in shoes and barefoot allowed for the classification of the footwear that actually helps off-load the forefoot during walking. The only shoe that significantly reduces pressure is the forefoot off-loading shoe. The rocker shoe is the least effective in off-loading the most important areas of the foot, i.e., the hallux and metatarsal bones and should therefore not be used as the shoe of choice in patients who have undergone surgery in the forefoot area. On the other hand, the flat shoe provides an even and uniform load in all forefoot areas tested, but not very effectively, yet it off-loads the area of the hallux and toes 2–5 slightly more than the rocker shoe. The barefoot gait has the least load in the forefoot area, compared to the flat and rocker shoe, but it must be emphasized that the natural movement of the foot in the shoes was disturbed.

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