Practical Aspects of 3D Scanning Results Application in Shoe Last Design

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Abstract

The need to improve the quality of manufactured footwear is especially acute today for special shoes. In order to analyze the conformity of the existing forms of lasts for military shoes with the shapes of the feet of consumers, a 3D study of the feet of representatives of the mobilization reserve has been carried out. Based on the results of anthropometric studies, taking into account the specified requirements, a new improved shape of a last with an increased width was developed, which allows placing an orthotic inside the finished shoe. The developed last was used for manufacturing the test footwear samples, which were tested by fighters in combat and during training. For four patients, individual insoles have been designed and manufactured based on the scanned footprints on polyfoam. A practical experiment has also been carried out on the development and manufacture of individual unloading insoles for a soldier who has recently been injured, had severe wounds on both legs and underwent a series of surgeries, as a result of which part of his lower leg muscles do not function, which leads to difficulty walking. The studies and practical experiments carried out in the work have shown that today, 3D scanning is an important and effective way to obtain initial data both for anthropometric studies as well as for the practical application of the results for designing the elements of the inner shape of footwear.

Keywords: 3d scan, footwear last, ergonomic footwear.

1. Introduction

Modern competitive footwear should be comfortable. The basis of comfortable shoes is the correct shape of the last, the parameters of which are based on the anthropometric data of the foot. A shoe last is a complex shape, the design of which is based on the principle of reverse engineering, most often with the help of special computer programs in the mode of comparing the shape of the last with the shape of the foot. Therefore, 3D scanning today is an irreplaceable, progressive and effective way of obtaining information about the shape and dimensions of the foot, which is necessary for the design of the shoe last [1].

The 3D scanning technique allows you to obtain information about the surface of the object, its volume, all dimensions and sections, as well as digital plantograms of the foot. The advantages of using 3D foot scanning are that it allows a large number of participants to be scanned quickly and the measurement is reliable and efficient [2]. The accuracy of the received data is higher than the accuracy of manual measurements.

The most effective method is the use of 3D scanning of the foot for the subsequent modeling of a shoe last, which involves the implementation of a wide range of advanced technologies from digitalization of the foot to the use of modern manufacturing methods, such as rapid prototyping of the last directly from a computer model [3].

In the 1990s, Glenn Copeland, a well-known American podiatrist and author of a number of books on foot diseases, preferred computer-based methods of obtaining information about the foot to create shoes and ortho-adjustments. Comparing the results obtained with the use of plaster casting and 3D scanning of the foot, his patients gave preference to shoes made on the basis of computer technology in 98% of cases [4].

The benefit of 3D scanning is not limited to the manufacture of custom-made lasts, but has wide-scale prospects for use, such as providing mass anthropometric measurements and studying the human foot morphology. Finally, analysis of a large sample of 3D foot scans can be used to obtain a general classification of human foot shapes. There can be possible research aimed at correlating foot parameters with the region, age, sex, athletic activity, and occupation, as shown by Grimmer [5]. The study of 1,2 millions 3d foot scans [6] confirms the existence of many statistically significant differences in mean foot measurements amongst the regions, and a large dispersion of foot measurements within each group of customers. Therefore, shoes should be developed separately for each group, region, and sex, and at least 3 shoe widths per length class are required to provide a proper fit for 90% of customers. These large-scale statistical reviews can help major shoe manufacturers to better adjust their products.

To compare the accuracy of anthropometric studies using different methods, six main linear dimensions of the foot were measured using four measurement methods (caliper, 3D foot scanner, digital footprint, and traditional plantogram)[7]. Anatomical landmarks were identified using markers pasted on the surface of the foot. The 3D scanning method proved to have higher accuracy results than the other three methods in four out of six dimensions. The results of this study showed that the foot measurements taken with the 3D scanner were more accurate than the foot measurements made by the other three methods. This was due to the fact that the 3D scanner detects the most convex points of the inner and outer beams more easily than manual methods. Another reason may be that the researcher may squeeze the soft tissue surrounding the landmark while taking measurements. Thus, the accuracy and adequacy of the results of manual measurements strongly depend on the expertise of the researcher. The method of 3D scanning of the foot demonstrated a higher accuracy of colecting anthropometric information. The benefits of using a 3D scanning system for foot sizing include saving time on measurement and greater efficiency for measuring large numbers of samples.

Traditionally, orthotics are made using a plaster cast of the patient's foot (a negative cast), making a positive plaster cast of the foot by filling the negative with a plaster solution and then molding the orthosis around the positive cast to obtain a high-quality mold [8]. A positive cast can be adjusted by removing or adding to it. Modern scanning systems allow obtaining a "positive" shape of the foot directly by scanning, where the casting stage is no longer necessary. And a number of software packages (for example, Orthomodel, Automated Orthotic Manufacturing System, Sharp Shape, etc.) have the ability to design orthopedic products for feet directly on the basis of a 3D copy of the foot obtained by surface scanning. With the help of communication with the computer control of the CNC machines, this approach reduces the number of stages in the production process and helps avoid many human errors.

It is worth noting that at the moment, three-dimensional scanning is limited by the patient's need in correcting the foot in the process of obtaining a copy. Some clinical conditions of the foot require the intervention of a doctor in the process of obtaining a copy of the foot, then the stage of forming a plaster negative and positive in the corrected position of the foot is necessary, which corresponds to the traditional method [9].

The modern shoe industry has a tendency to increase the comfort of the manufactured products. However, unfortunately, the vast majority of shoes available on the market have a shape and parameters that are not justified from a scientific point of view. This problem is especially acute for certain categories of consumers: people with foot pathologies, the elderly, diabetics, etc. There are studies that show that the feet of older people are wider in the area of the front part of the foot and have a flatter medial longitudinal arch, compared to young people [10]. Publications [11] indicated that shoe width is a particular problem for the elderly people.

Today's prevailing trend of sustainable fashion involves the introduction of comfortable forms of shoes, the inner shape of which repeats the natural shape of the foot. Such ergonomic shoes should be produced in several sizes (at least three widths for each size) to meet the needs of different groups of consumers.

Orthopedic, prophylactic and comfort footwear should be equipped with special inserts - an orthopedic (or anatomical) insole that corrects the position of the foot, redistributes the load and facilitates a person's gait. To manufacture such insoles using innovative technologies, the sole surface of the feet is scanned using a 3D scanner. Then, the geometric shapes of the 3D foot models are used to design the surface of the orthopedic insole and are integrated with CAM (automated manufacturing) [12]. In general, inserted orthopedic and preventive insoles can significantly increase the comfort of shoes and create a more ergonomic shape.

2. Methods

The practice of shoe last design based on a 3D scan of the foot involves different foot scanning techniques depending on the foot condition and the type of footwear being developed:

- Foot scanning with a special 3D scanner in a standing position with equal weight on both legs
- Scanning of the foot without load, in a sitting position
- Scanning of the foot, set in a corrected biomechanical position, held by special fixators or by the doctor's hand
- Scanning of the foot installed on an orthopedic insole or special orthoses
- Scanning of the foot placed in a foam box

The standard way of scanning the foot in a standing position with an equal load on both legs is most often used (Fig.1). This method is used for mass anthropometric measurements to assess the clinical condition of the feet of a particular sex-age group of consumers to create an averaged model of the foot of a certain consumer group, as well as to develop an individual form of a last in cases of the feet without significant pathologies.

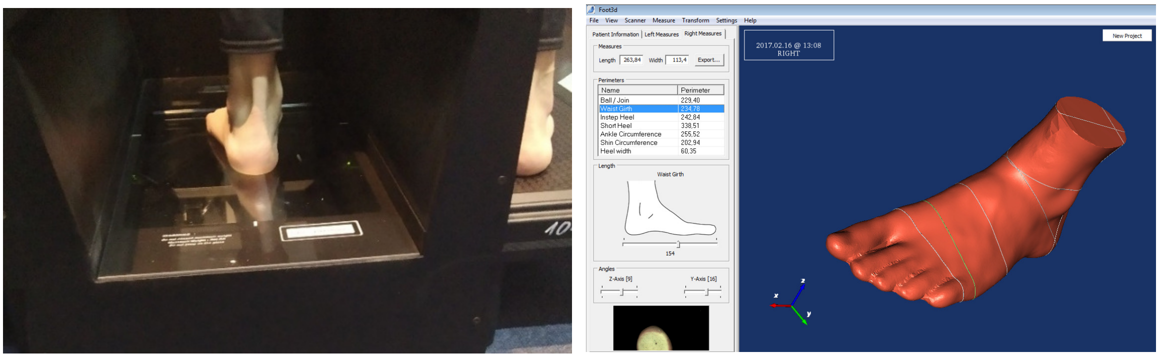


Fig. 1. The standard way of scanning the foot in a standing position with an equal load on both legs

The foot in a sitting or lying position, without load, is scanned to obtain an auxiliary foot model when it is necessary to develop an shoe last shape for elegant or fashionable custom shoes, as well as for the development of anatomical insoles (Fig.2).

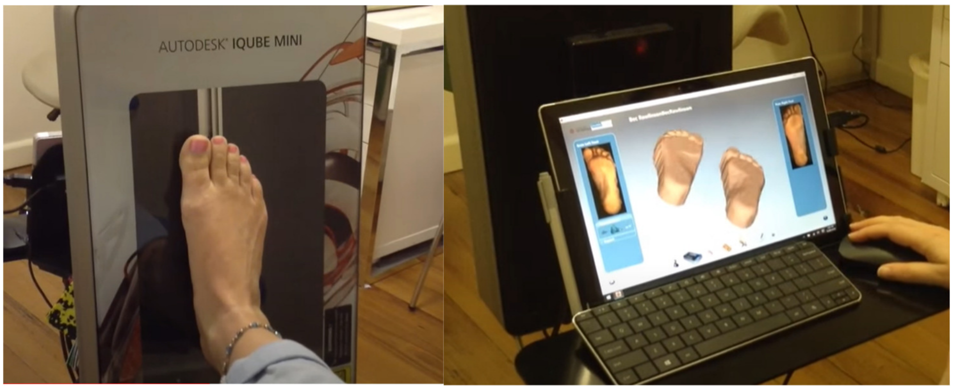


Fig. 2. The foot in a sitting or lying position without load is scanned

The foot put in the adjusted biomechanical position and the foot put to the orthopedic insole are scanned in cases of the development of orthopedic corrective shoes. In some cases, there is a need to bring the foot into the right position and fix it using plaster bandages. After that, a plaster positive of the foot is obtained in the correct position, which is then scanned on a 3D scanner (Fig.3).

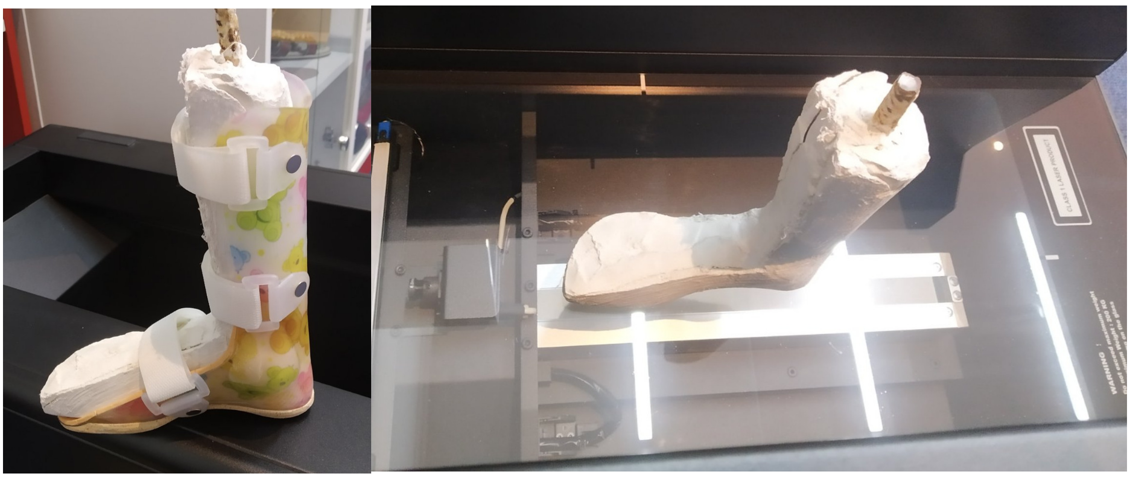


Fig. 3. A plaster positive of the foot is obtained in the correct position, which is then scanned on a 3D scanner

A 3D scan of a foot placed in a foam box is used to develop the inner shape of a shoe with increased comfort, when a last is designed together with an anatomically profiled insole (Fig.4).

Fig. 4. A 3D scan of a foot placed in a foam box.

From the point of view of shoe last parameters generating features based on the results of 3D scanning, taking into account our practical experience, we can conditionally highlight the following options (Fig. 5):
1) Designing a last for low-heeled elegant fashion shoes
2) Designing a last for women's high-heeled shoes
3) Designing of lasts for orthopedic shoes
4) Designing the inner shape of increased comfort shoes
At the same time, the first two options involve the use of a 3D scan of a foot only as a initial reference for modifying the basic shape of the last. The shape of the last adapts to the main parameters of the foot, while remaining fundamentally unchanged.
The last two options, on the other hand, are focused on the maximum reconstitution of the anatomical and morphological structure of a foot in the form of a last, therefore, in such cases, the 3D scan of a foot is the main base form for further modeling of a last.

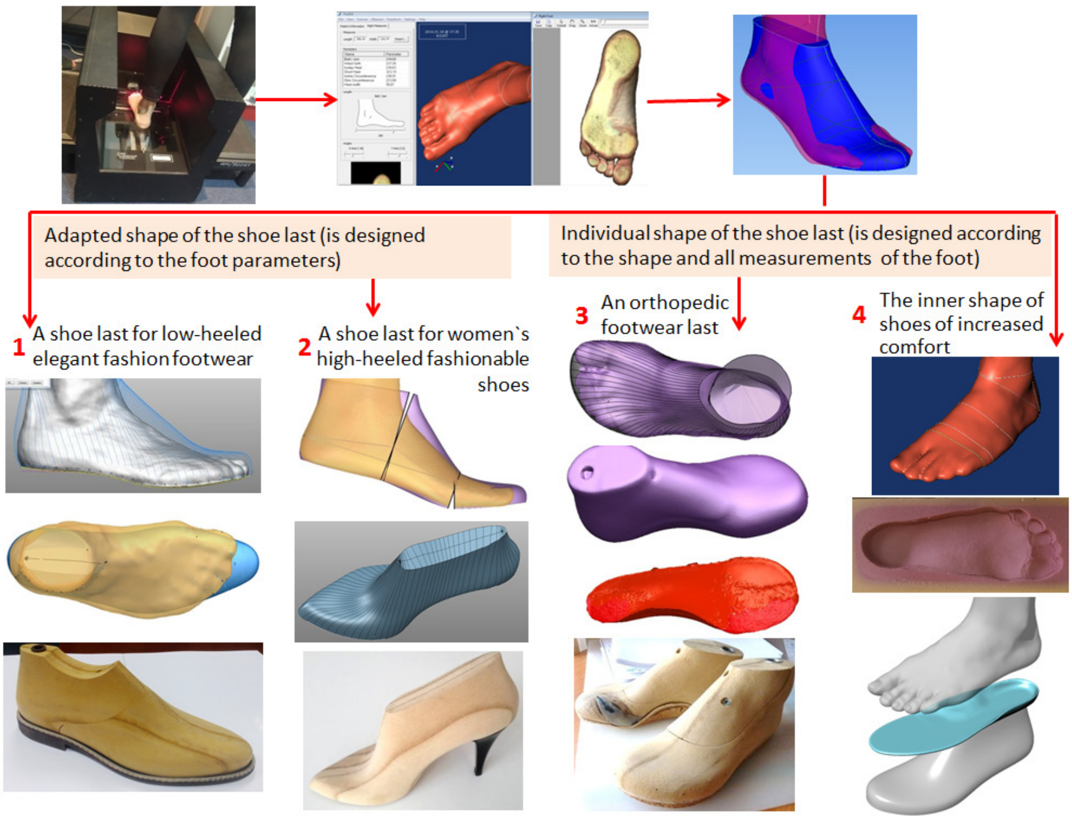
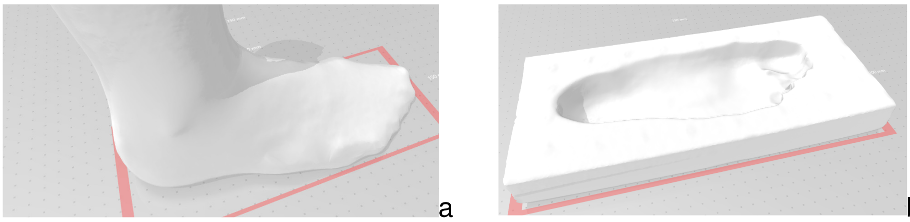


Fig. 5. Information Base for Designing the Inner Shape of the Footwear for Various Purposes

Each of the above options (methods) of shoe design involves a particular method of using a 3D scan of the foot:
1) When designing a shoe last for low-heeled elegant shoes, it is necessary to adjust the basic shape of the last shape in accordance with the anatomical and morphological parameters of the foot, while maintaining an elegant design. This option involves modeling a shoe last for a foot without significant pathologies. The basis is a 3d scan of the last from the existing database, which is modified in accordance with the parameters of the customer's foot: length, width of the foot, girth in the ball area, girth in the instep area, angle of rotation of the heel and toe, etc. To facilitate the comparison of the shape of the last with the shape of the 3D scan of the foot, we use morphing of the 3D model of the foot, bringing it in line with the bottom profile of the last. With this version of the design, the shape of the resulting last is significantly different from the shape of the foot, narrower in width in the ball area, narrower and higher in the cone area.
2) Designing a shoe last for women's high-heeled shoes is one of the most difficult cases of using a 3D scan of the foot to design a shoe last shape. Since it is far from possible to always obtain a 3D scan of the foot for different elevation of the heel part, it is often necessary to use a 3D copy of the foot obtained by a standard method on a flat platform. To compare the basic shape of the last with the foot, it is necessary to resort to 3D modification of the 3d scan of the foot in accordance with the peculiarities of its shape change when lifting on the heel, we suggest using a modular shape design, having previously dissected the 3D shape of the foot into three parts that change their mutual orientation relative to each other when the heel rises.
3) The orthopedic last maximally copies the shape of the foot brought to the correct biomechanical position, taking into account the orthopedic corrective insole. The shape of the foot is described by three surfaces, which are smoothed to obtain a smooth shape of the last, while the toe part is lengthened by several millimeters, taking into account the normal increase of the foot while moving.
4) The inner shape of the increased comfort shoes is formed on the basis of an anthropometrically correct shape of the last and an insert orthotic - an anatomical unloading insole, which provides support for the longitudinal and transverse arches of the foot. This design method requires initial information about both the general shape of the foot and the shape of the plantar surface, which is obtained by scanning the plantar surface of the foot in polymer foam. Next, the shape of the last is designed in two stages. First, we design the form of a standardized last, increased by the thickness of the anatomical insole, to ensure the possibility of inserting the anatomical insole into the the completed shoe. The second stage involves the design of a last in which the bottom surface corresponds to the upper surface of the anatomical insole - for this, we cut off the shape of the anatomical insole from the first last.
We consider this method of designing the inner shape of shoes to be the most progressive and effective, and therefore it has been used in this project. The initial information about the shape of the customer's foot was presented in the form of a 3d shape of the foot (Fig. 6 a) and a 3d shape of the plantar surface of the foot (Fig. 6 b). To obtain this information, a specialized InFoot 3D foot scanner was used in this project.



a b

Fig. 6. The Obtained Foot 3d Scan and the 3d Scan of the Plantar Surface of the Foot on Polymer Foam

3. Results and Discussion

Based on today's urgent requests and taking into account the need to improve the level of comfort of shoes for the Ukrainian military, we have conducted anthropometric studies of the feet of mobilization reserve representatives. Using the results of previous mass anthropometric studies [13], we focused on men with a foot size in the range of 42-43. In this research, 28 men (56 feet) aged 21-35 with a foot length of 265-280 mm, without serious foot deformities, were examined. The research was conducted using the InFoot 3D scanner, as it provides sufficient measurement accuracy at a high scanning speed. The scanner software allows you to quickly convert the obtained point cloud into a triangulated polygonal grid, which is convenient to work with in 3D engineering software (Fig. 7)

Fig. 7. Fragment of a Sample of the Feet of the Target Consumer Group, Studied by 3D Scanning

The analysis of the results of the 3d studies showed a wide range of foot shapes and parameters among the representatives of the group under research. The circumference of the foot in the ball area and in the instep area of the foot has large discrepancies: the difference between the circumferences reaches 18 mm within the same size. Common deviations of the feet from the norm are valgus installation of the foot, hypertrophy of the abductor muscle of the fifth toe, and flat feet.

Today, the Ukrainian shoe industry is in a situation where there are strict requirements for materials and technological features of footwear for the military, but there are no clear requirements for shoe parameters. Those lasts that are being used by Ukrainian manufacturers today have various parameters that are quite random and not justified from the point of view of mass anthropometric studies. Thus, after comparing one of today's common lasts, used by local manufacturers, with one of the wide foot shapes found in the group of men studied, we see that the shape and dimensions of the last do not correspond with the anthropometry of the wide consumer`s feet (Fig. 8)

The state standard regulates the size range of shoes, which are produced with the same width. Men with wide feet, which are observed in more than 15% of them (according to the results of anthropometric studies), are forced to look for shoes of special manufacturers. Taking into account the fact that the age of those mobilized into the ranks of the Armed Forces is 22-60 years old, and we have so far studied only men aged 21-35, the actual number of military personnel who are unsatisfied with the military boots of local production is even greater. So, having singled out 8 feet of wide width, we examined their average parameters (see Table 1). In addition, we calculated the parameters of the average foot installed on an orthosis (insert anatomical insole). Based on the obtained data, we calculated the parameters of an improved last of wide width, which will satisfy the requirements of most representatives of the target segment, taking into account the need to use additional insert devices.

Table 1. Initial Data for Design and the Improved Last Resulting Parameters

Dimensional Feature	Arithmetic Mean Values (μ, mm)	Standard Deviations (σ, mm)	Parameters of the real shoe last (mm)	Arithmetic Mean Values for wide feet (μ, mm)	Mean Parameters of the average feet with orthotics, mm	Parameters of the improved shoe last, mm
Foot length	272.6	3.4	278	273.9	278	278
Balls girth	255.9	5.6	252	263.8	260.8	265
Short heel girth	343.8	6.5	350	352.4	350.1	375
Instep girth	268.1	5.9	270	270.9	280.4	282
Heel width (based on the contour)	62.2	3.2	61	64.5	62.2	64
Ball width (based on the contour)	105.4	4.4	99	108.3	105.4	104

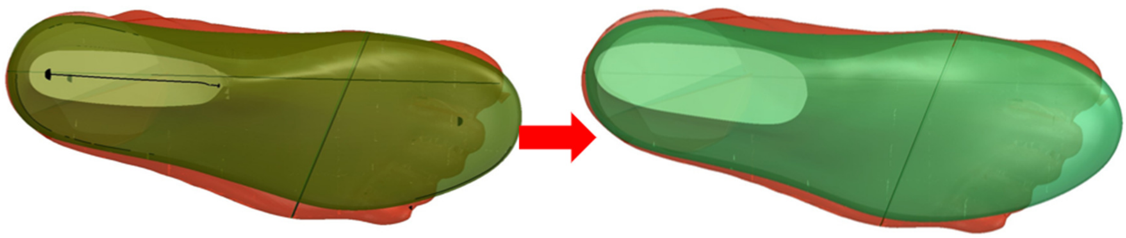


Fig. 8. Comparison of the Wide Foot Shape with the Real Standard and Improved Lasts

Therefore, in this project, we set the task of developing a new form of shoe insole for military footwear, which would eliminate the listed shortcomings and more closely correspond to the anthropomorphological parameters of the feet.
Another problem of the current situation is the advanced age of mobilized men. According to the recommendations of podiatrists, people over the age of 40, with significant physical exertion, must constantly use an shoe inserts (orthotics),- preventive anatomical unloading insoles, to ensure the normal operation of the musculoskeletal system and reduce muscle fatigue. For people with certain foot pathologies and problems with the musculoskeletal system, such inserts are vitally necessary. The high frequency of cases of foot valgus, which was diagnosed during anthropometric studies, is also a good reason for the use of inserts - preventive (or orthopedic in case of significant pathology) insoles with support for the internal longitudinal arch. The use of profiled insoles requires the use of shoe lasts of increased width. According to the results of anthropometric studies, taking into account the specified requirements, a form of a last of increased width was developed, which would provide sufficient comfort for the foot of wide width with the possibility of placing a preventive or orthopedic insole in the shoe (Fig. 9). For four patients, individual insoles were designed and manufactured, that is relief insoles, based on scanned foot prints on polymer foam. The scheme of the design process is presented in Fig 10.

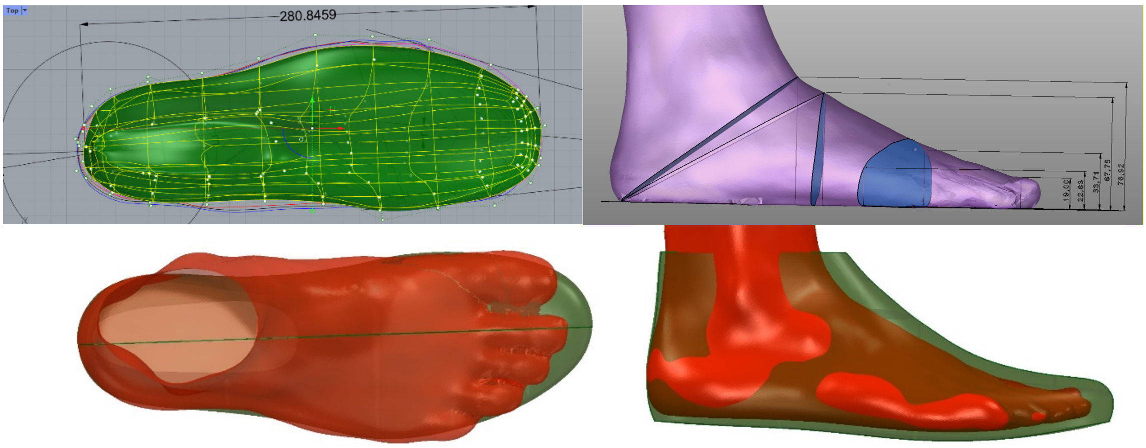


Fig. 9. The Shoe Last Shape Designing with the Method of Reverse Engineering in a Graphic 3D Environment

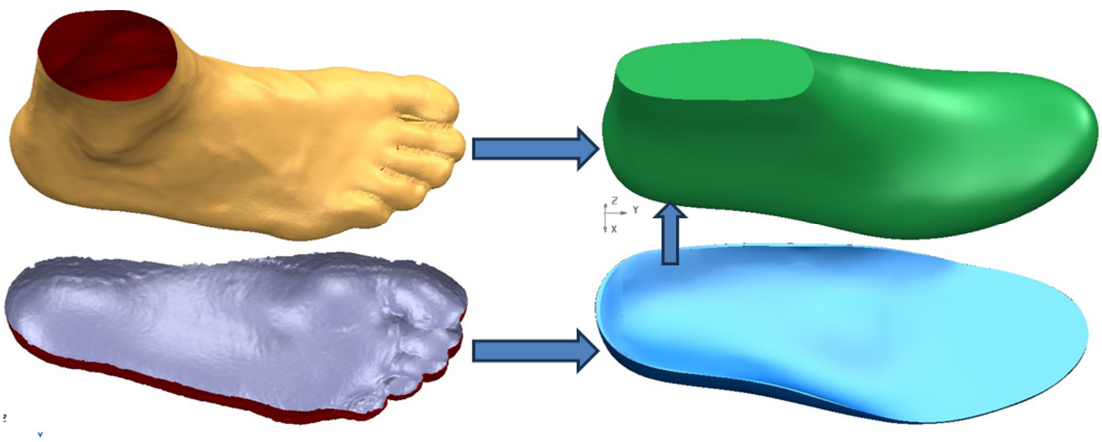


Fig. 10. Designing the Elements of the Inner Shape of Shoes Based on the Results of a 3D Scan of the Foot and the Plantar Surface 3d Imprint

This last shape was used to manufacture a physical shoe last (Fig. 11a), on which the test samples of military footwear (Fig. 11b) were made using high-quality materials and natural textile lining based on hemp fiber, which has good hygienic properties. These samples were operated in various conditions, including directly in the combat zone, and proved themselves well, having received positive feedbacks from the soldiers.
Inside the manufactured shoes of increased width, various options of insoles were inserted, depending on the characteristics of the soldier's foot, his physical condition and needs (Fig. 11c, d). Insoles can significantly improve the comfort level of shoes, especially during long-term loads.

Fig. 11. The Elements of the Inner Shape of Shoes and Ready-made Samples of Military Shoes

In this project, a practical experiment was also carried out on the development and manufacture of individual load relieving insoles for a soldier who has recently suffered a severe wound to both legs and a number of operations, as a result of which part of the lower leg muscles do not function, which leads to difficulties in walking. With the participation of an orthopedic doctor, an analysis of the condition of the foot was carried out through a medical examination and a study of its shape using a 3D scan. Scanning of the foot was performed using a foam box, in which the foot was placed in the correct biomechanical position with the help of a podiatrist's manipulations (Fig. 12).

Fig. 12. The Process of Developing Special Inserts to Improve the Comfort of Military Shoes after the Legs are Wounded

On the basis of 3D scans of the foot and the foam box print, the shape of the individual load relieving insole was designed. The design of the insole has an internal longitudinal arch lining, a metatarsal roller to support the transverse arch, and a heel shock absorber. After modeling the shape of the insole in the Rhinoceros environment, it was milled on a 3-axis CNC machine from EVA-pore material. After only three days of wearing shoes with these insoles, the patient noted a decrease of pain in the area of the first toe and a general improvement in the physical condition of the legs while walking.
In further research, it would be worthwhile to investigate the possibilities of improving the comfort of military footwear with the help of special inserts (insoles) for various clinical conditions of the foot, as well as the possibility of developing a universal shape of improved orthotic for the foot load redistribution.

Conclusions

3D scanning of the foot today is a necessary method for studying consumers' feet both for obtaining initial information for designing the shape of the shoe last and the anatomical insole, and for analyzing the clinical condition of the feet of individual consumers or population groups. For this purpose, it is most effective to use specialized professional 3D foot scanners, as they provide sufficient accuracy, high process speed, and are easy to use. As practical experiments show, designing the shape of an anatomical insole requires additional information about the plantar surface of the foot, obtained with the help of a special polymer foam for footprints.
Using the results of a 3D foot scan to design a shoe last requires a lot of practical experience and numerous experiments, because each type of shoe has its own shape design features, which further get complicated by the individual features of a customer's foot, his requirements for shoes, and the conditions of shoe operation.
The ongoing war in Ukraine creates new challenges, including for workers in the shoe industry. One of the main problems is ensuring comfort for the Ukrainian soldiers' feet in military shoes during long-term operations in very difficult conditions, and this requires numerous further studies and practical experiments. 3D scanning is an important and effective way today to obtain initial data for these tasks.

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