THE IMPROVED APPROACH TO THE DEVELOPMENT OF PARAMETERS FOR THE INNER SHAPE OF MILITARY BOOTS

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ABSTRACT. In the work, anthropometric studies of the feet were performed by means of 3D scanning. The results of scanning have been used for two main purposes. Firstly, the features and morphological structure of the feet of young men aged 20-30 were studied, who are the representatives of the Ukrainian population that are subject to mobilization into the ranks of the Armed Forces. Apart from this, the quantitative distribution of the main morphological features of the feet of the sample population was analyzed. During measurements, it was noticed that a large number of men had hypertrophy of the heads of the 1st and 5th metatarsal bones. In order to rationalize the range of lasts with different sizes and fullness, while trying to fully satisfy the requirements of compliance with the anthropometric parameters of the feet of consumers, the parameters of the feet with the hypertrophy of the heads of the 1st and 5th metatarsal bones must be taken into account in the lasts with increased width. Furthermore, the results of scanning constitute the basis for calculating and developing basic parameters of lasts. For this, the work suggested the method of designing a last shape based on such types of input data as a digital foot model, dimensional foot parameters, and a foot print obtained as a result of mass 3D scanning of the feet.

KEY WORDS: footwear last, shoe last design, footwear inner shape, military boots, 3D scanning, foot parameters

O ABORDARE MAI BUNĂ PRIVIND DEZVOLTAREA PARAMETRILOR PENTRU FORMA INTERIOARĂ A BOCANCILOR PENTRU ARMATĂ

REZUMAT. În lucrare s-au efectuat studii antropometrice ale piciorului prin scanare 3D. Rezultatele scanării au fost utilizate în două scopuri principale. În primul rând, s-au studiat caracteristicile și structura morfologică a picioarelor tinerilor cu vârste cuprinse între 20-30 de ani, care sunt reprezentanții populației ucrainene supuse mobilizării în rândurile Forțelor Armate. În afară de aceasta, s-a analizat distribuția cantitativă a principalelor caracteristici morfologice ale picioarelor populației eșantion. În timpul măsurătorilor, s-a observat că un număr mare de bărbați prezentau hipertrofie a capetelor metatarsiene 1 și 5. Pentru a raționaliza gama de calapoade cu diferite dimensiuni și volume, încercându-se în același timp să se îndeplinească cerințele de conformitate cu parametrii antropometrici ai picioarelor consumatorilor, trebuie să se țină seama de parametrii picioarelor cu hipertrofia capetelor metatarsiene 1 și 5 la calapoadele cu lățime mare. În plus, rezultatele scanării constituie fundamentul pentru calcularea și dezvoltarea parametrilor de bază ai calapodului. Pentru aceasta, în lucrare a fost sugerată metoda de proiectare a unui calapod pe baza unor date de intrare precum un model digital al piciorului, parametrii dimensionali ai piciorului și o amprentă a piciorului obținută ca urmare a scanării 3D în masă a picioarelor.

CUVINTE CHEIE: calapod, designul calapodului, forma interioară a încălțămintei, bocanci pentru armată, scanare 3D, parametrii piciorului

UNE MEILLEURE APPROCHE POUR LE DÉVELOPPEMENT DES PARAMÈTRES POUR LA FORME INTÉRIEURE DES BOTTES MILITAIRES

RÉSUMÉ. Dans le travail, des études anthropométriques des pieds ont été réalisées au moyen de la numérisation 3D. Les résultats de l'analyse ont été utilisés à deux fins principales. Premièrement, ont été étudiées les caractéristiques et la structure morphologique des pieds de jeunes hommes âgés de 20 à 30 ans, qui sont les représentants de la population ukrainienne soumise à la mobilisation dans les rangs des Forces Armées. En dehors de cela, la distribution quantitative des principales caractéristiques morphologiques des pieds de la population de l'échantillon a été analysée. Lors des mesures, il a été remarqué qu'un grand nombre d'hommes présentaient une hypertrophie des têtes des 1er et 5e métatarsiens. Afin de rationaliser la gamme de formes chaussures avec différentes tailles et plénitude, tout en essayant de satisfaire pleinement aux exigences de respect des paramètres anthropométriques des pieds des consommateurs, il faut prendre en compte les paramètres des pieds avec l'hypertrophie des têtes des 1er et 5e métatarsiens dans les formes avec une largeur augmentée. De plus, les résultats de la numérisation constituent la fondation pour le calcul et le développement des paramètres de base des formes. Pour cela, dans le travail, on a suggéré la méthode de conception d'une forme chaussures basée sur des types de données d'entrée tels qu'un modèle de pied numérique, des paramètres dimensionnels du pied et une empreinte de pied obtenue à la suite d'un balayage 3D des pieds en masse.

MOTS CLÉS : forme de la chaussure, conception de la forme de la chaussure, forme intérieure de la chaussure, bottes militaires, numérisation 3D, paramètres du pied

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INTRODUCTION

Despite the fact that scientific progress has reached all the spheres of life, making it more comfortable and convenient, we still often wear uncomfortable shoes. Today, in manufacturing footwear of mass production, all the features of three-dimensional shape of the foot of a potential consumer are rarely taken into account. Instead, in the best-case scenario, 2 or 3 measurements of the typical average foot of certain population are relied upon. This results in the production of shoes that consumers need to wear in and adapt to the shapes of their feet. This variant is unacceptable for children, the elderly, as well as consumers with feet deformities. In addition, it is inappropriate for specialized shoes that are to be actively worn during a long time and those that are supposed to be used in harsh conditions. The requirements for sports and military footwear are linked to the increased comfort as a factor that influences achieving high results or performing professional tasks.

In the context of current military aggression against Ukraine and with the need to mobilize men into the ranks of the Armed Forces of Ukraine, it is particularly important to properly provide military personnel with the necessary equipment and ammunition. Comfortable footwear is an essential and indispensable component of the apparel of fighters and other members of the security agencies of Ukraine. With that, the convenience of boots is one of the most important factors in the quality of uniforms, which contributes to the overall feeling of comfort, reduces fatigue, and increases performance during the entire period of wearing them [1]. One of the major conditions of making footwear comfortable is the conformity of the shoe last on which a shoe is made to the shape and size of consumer's foot. Analyzing the quality of domestically produced military footwear, consumers highlight that it is not comfortable enough. The fact is that domestically produced military boots are manufactured either on the outdated lasts of the Soviet model of the 70's, or on random lasts, the shape of which is not substantiated from the anthropomorphological point of view.

The need for regular mass anthropometric measurements of the feet of different population categories results from the gradual changes in the dimensional parameters and morphology of the feet of people, as well as modern requirements for certain types of footwear. Designing shoes based on the measurements of a foot and taking into account its shape will improve fitness (correspondence to the parameters of the foot) and make shoes more comfortable [1-3].

The current level of development of digital technologies and their wide range of applications require conducting anthropometric studies using the advanced contactless methodologies and high-tech equipment. 3D scanning allows obtaining information about the entire surface, dimensions, as well as all the sizes and cross sections of a body, as well as digital foot prints. The advantages of using 3D scanning of feet lie in the fact that it allows scanning large numbers of participants quite quickly and this type of measurement is reliable and efficient [4, 5]. The measurement results are stored as information files that are available for use at any time. The accuracy of the obtained data is higher than the accuracy of manual measurements.

The use of 3D scanning to obtain anthropometric information about a foot and study the compliance between feet and shoes is described in numerous scientific works and most researchers have focused on quantifying the degree of correspondence by comparing major parameters of the last with the anthropometric data related to the feet [6, 7]. Selection of the last that corresponds most to a customer's foot is carried out in a similar way [8].

Research conducted by Rossi and Tennant [9] explained which anthropometric measurements are most important for the fitness (correspondence) of footwear. Mochimaru [10], Luximon [11], as well as Borchers [6] used full 3D foot shapes to determine the degree of correspondence between feet and shoes.

However, in the publications, we have not found any reasonable methodologies and recommendations for designing the parameters of the dimensional shape of a shoe last based on the results of mass 3D scanning of the feet of certain population groups. Therefore, this became the main task of our work.

EXPERIMENTAL

Materials and Methods

The most progressive and effective method of anthropometric measurements is 3D scanning. In this work the feet were scanned using the InFoot 3D (OrthoBaltic, Lithuania), a specialized 3D scanner with an accuracy of 0.3 mm. During the scanning process, the person stood on their feet and their body weight was distributed evenly over the two legs. Both the right and left feet were scanned. As the results we received the files of three main formats: (a) a file with the digital copy of foot surface in STL format; (b) a file with the footprint in JPG format; and (c) a file with the main digital foot parameters.

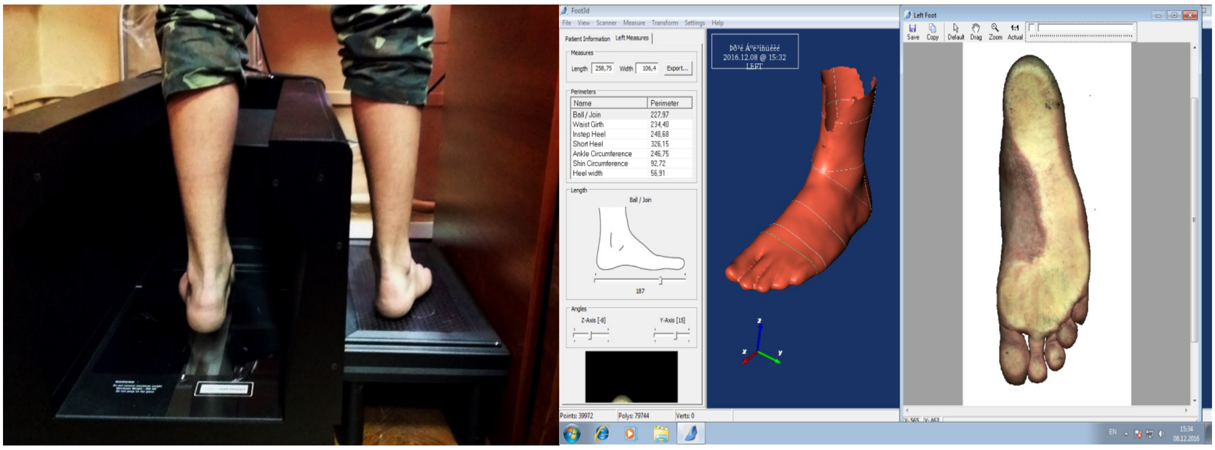


Figure 1. The foot scanning process using special 3D scanner InFoot 3D

The method of research of the feet anthropometric and morphological parameters applied in the work includes the parameters [3, 12] based on the main points of the foot showed in Figure 2.

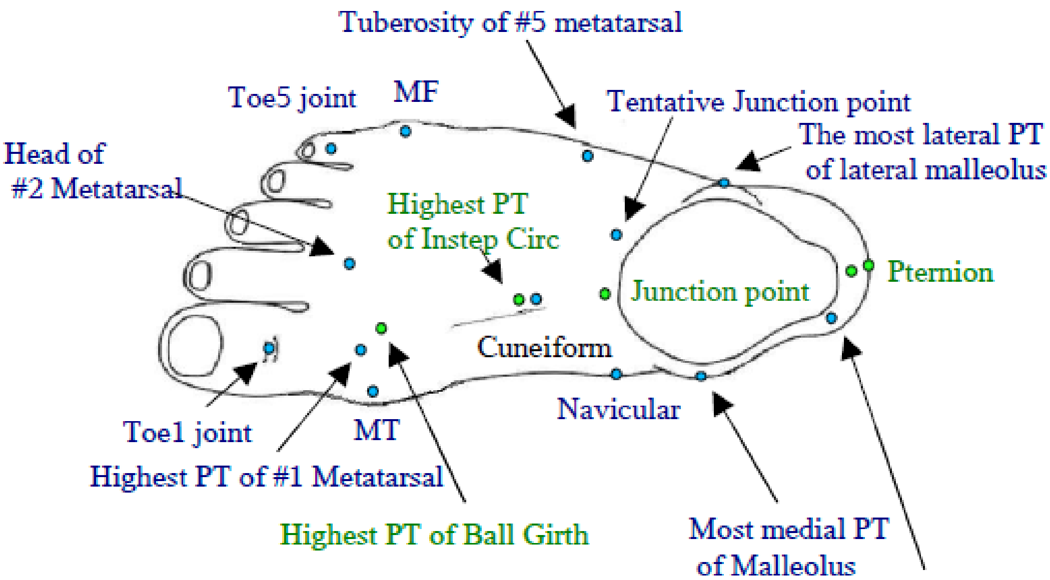
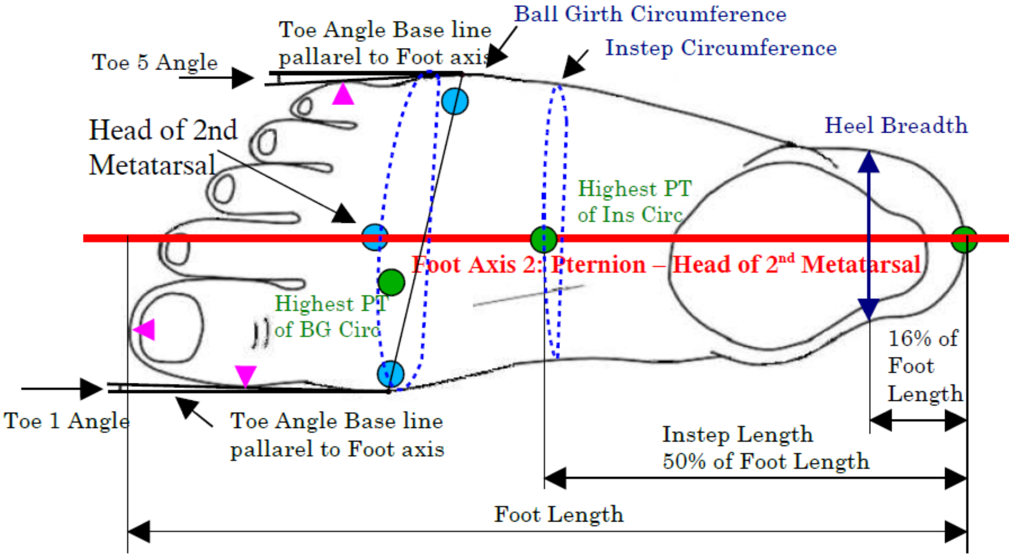


Figure 2. The main anthropometric points of the foot

Most parameters are obtained on the basis of a digital 3D model of the scanned foot (Figure 3): They include length, width, girth and height values according the main anthropometric points.



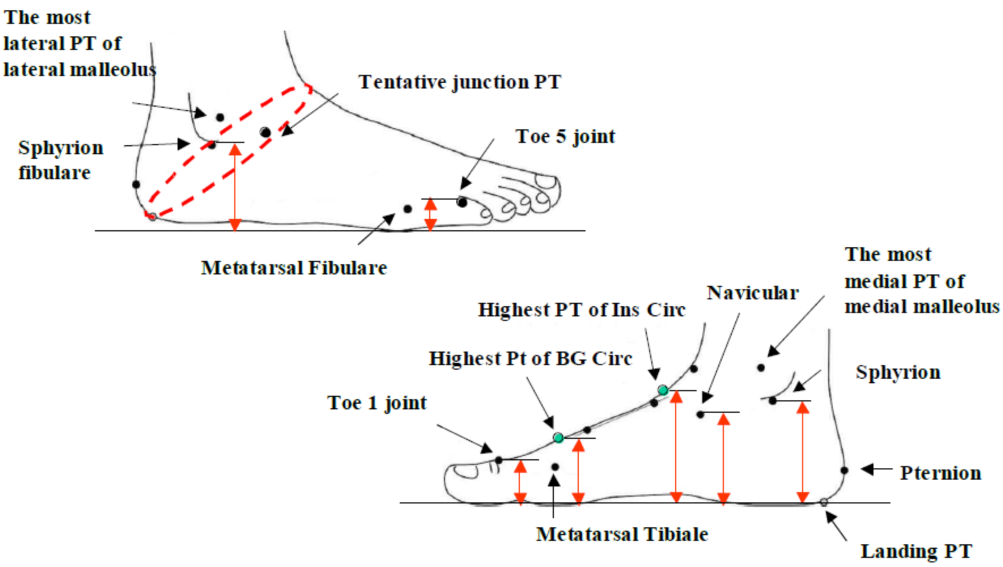


Figure 3. The main anthropometric parameters were measured on the feet

The latitudinal and longitudinal dimensions required to design the contour of the footprint are more convenient to determine on the basis of a footprint, which is obtained automatically when scanning the foot on a specialized 3D scanner. The method of footprint analysis involves determining the parameters associated with the shape and size of the outline and imprint (Figure 4). Popular graphics programs for working with vector graphics (AutoCAD, Corel Draw) were used to calculate the needed parameters and analyze the footprint.

In addition to the parameters of width, girth and length (Figure 4), it is necessary to obtain the angular dimensions of the foot to form the ergonomic shape of the insole (which corresponds to the shoe last bottom surface):

- the angle of deviation of the hallux;
- heel position angle;
- the angle of the foot position.

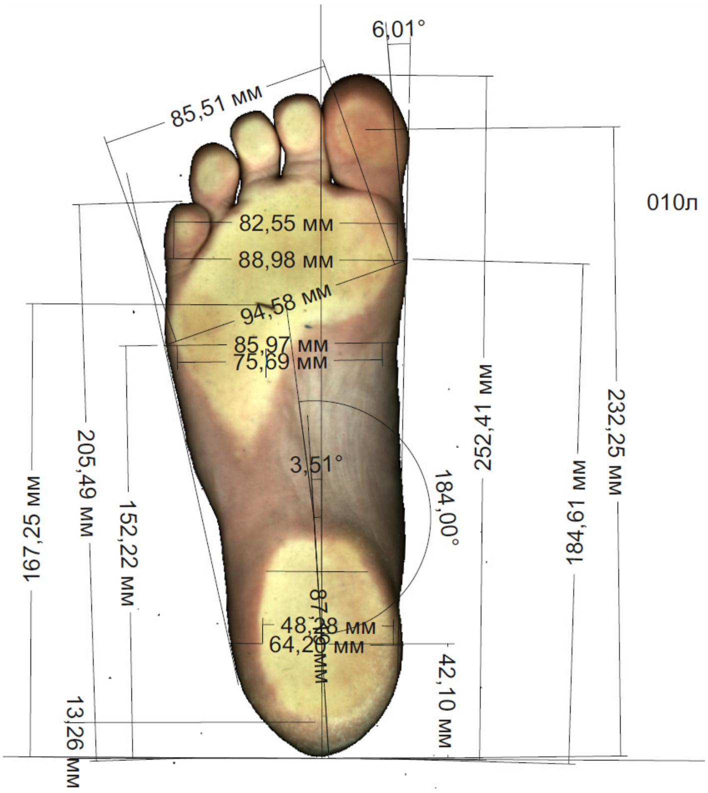


Figure 4. Definition the parameters of the foot on the basis of the footprint

To determine the height and circumference parameters, it is necessary to use the functions of graphic 3D programs (Figure 5). PowerShape software was used in this work.

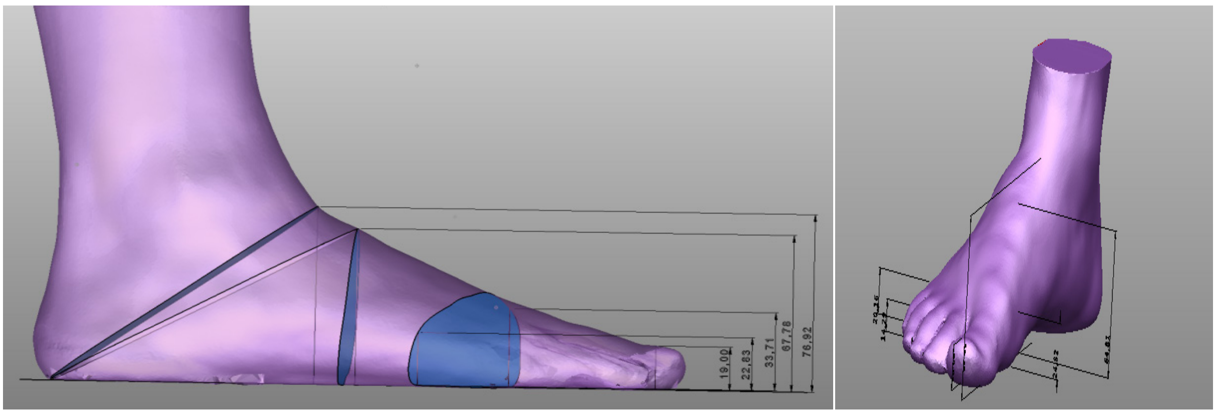


Figure 5. Definition the height parameters of the foot on the basis of measuring the foot 3D model

RESULTS AND DISCUSSIONS

The sample size for anthropometric studies consisted of 254 people. The sample is homogeneous; it includes young men aged from 21 to 30 years, without significant foot pathologies. According to the research results, the minimum (min) and maximum (max) values of the foot length in the sample (min = 243 mm, max = 301 mm) were defined.

As a result of the measurements made in the context of the experiment, the arithmetic mean values (M) of dimensional features and their root-mean-square deviations (Table 1) were obtained for the feet of men aged from 21 to 30. These values can be used to design products and develop a dimensional typology.

Table 1: Arithmetic mean values (M, mm) and root-mean-square deviations (σ, mm) of the dimensional features of the feet of men aged from 21 to 30 who are from different regions of Ukraine

Dimensional Feature	Arithmetic Mean Values (μ, mm)	Standard Deviations (σ, mm)
Foot length	271.41	10.59
Balls girth	255.69	12.14
Short heel girth	345.36	18.05
Outer ball girth	250.01	18.28
Inner ball girth	248.21	11.85
Instep girth	269.16	15.55
Ankle girth	265.68	17.72
Sn (distance from the contour to the imprint of a heel)	11.79	3.65
D 0.18 (distance to the center of a heel)	45.723	3.78
D 0.62 (outer ball part)	166.82	7.01
D 0.73 (inner pall part)	202.02	5.90
D 0.68 (middle of the ball parts)	176.58	14.93
D 0.8 (tip of the fifth toe)	223.92	6.63
D 0.9 (the middle of the first toe)	257.16	5.49
Heel width (based on the contour)	62.67	5.06
Heel width (based on the imprint)	51.79	5.91
W 0.62 (based on the contour)	94.75	4.91
W 0.62 (based on the imprint)	88.27	4.62
W 0.73 (based on the contour)	95.17	4.37
W 0.73 (based on the imprint)	86.02	5.42
W 0.68 (based on the contour)	106.33	6.17
W 0.68 (based on the imprint)	97.80	4.65
<L	9.93	4.09
<m	9.20	10
<n	168.02	7.26

A complex three-dimensional shape of the foot is characterized by many morphometric components. Some of them appear to be the most significant ones [12] and they define the limits of variation of the foot shape (± 3σ) based on the studied population. These variations should be taken into account when designing the last parameters and calculating the range of dimensions and fullness parameters.

Thus, high variability of such an important parameter as the width of the ball parts, as well as their girth, indicates the need to develop a complete range of lasts and shoes based on their fullness within single size.

In order to assess the differences in the morphological structure of the feet of the same size, it is first necessary to align digital foot models according to a single coordinate system. The longitudinal axis passes through the projection of the pternion point onto the support area and the first inter-toe gap [3].

While analyzing the 3D shape of young males' feet, we have identified the parameters that most clearly characterize the differences in the morphological structure of the foot, which affects the shapes and sizes of the lasts:

- ball width;
- inner and outer ball girth;
- height of the longitudinal arch of the foot;
- width and girth of the midfoot;
- deviation angle of the first toe;
- position angle of a foot;
- distance between toes (the width of toe area);
- the height of the head of the first instep bone;
- the height of the first toe.

One of the most variable parameters with significant dispersion is the width of the foot in the ball parts and ball girth. This is the second major parameter that determines the correspondence of shapes and sizes of a last to a foot. According to the results of the anthropometric studies, the difference in the girth of the foot in this area can reach 30 mm for certain length of a foot. Thus, for the average length of the foot among the studied population (270 ± 2.5 mm), the inner and outer ball girths ranged from Bgmin = 244.3 mm to Bgmax = 270.1 mm. The average girth of the balls was 256.5 ± 12.14 mm. Comparison of the shapes of narrow, medium, and large feet is presented in Fig. 6.

The foot width and the ball parts girth are crucial for calculating the width of a last. Based on the results of the research and the recommendations of industry standards, there should be at least three fullness values of a last of certain size (narrow, standard, and wide ones).

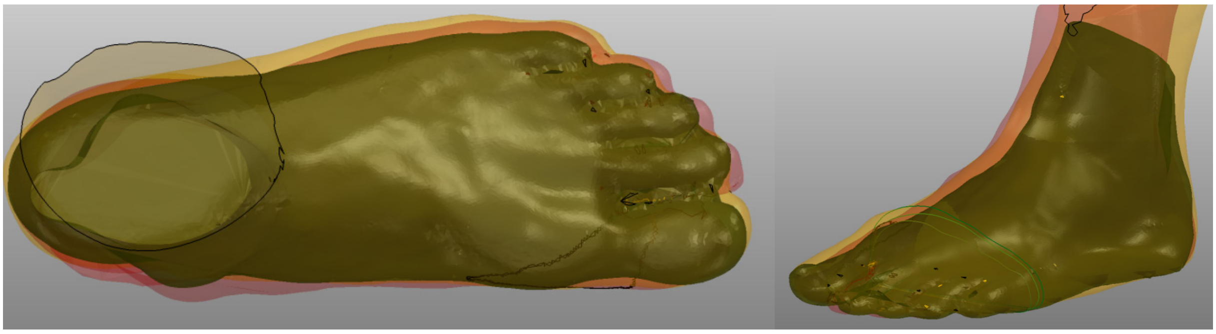


Figure 6. The comparison of 3D models of medium-sized feet with different ball widths

The foot print, which was obtained automatically during the study when scanning the foot, is very indicative for the characterization of foot morphology. According to a foot print, a large number of the most important morphological indicators are defined. One of these indicators is the position of the foot (normal, abducted or adducted one) and it is determined according to the angle between the axis of symmetry of the heel part and the axis of the front part of a foot. In the studied sample, this angle ranged from 152 to 187° (Figure 7).

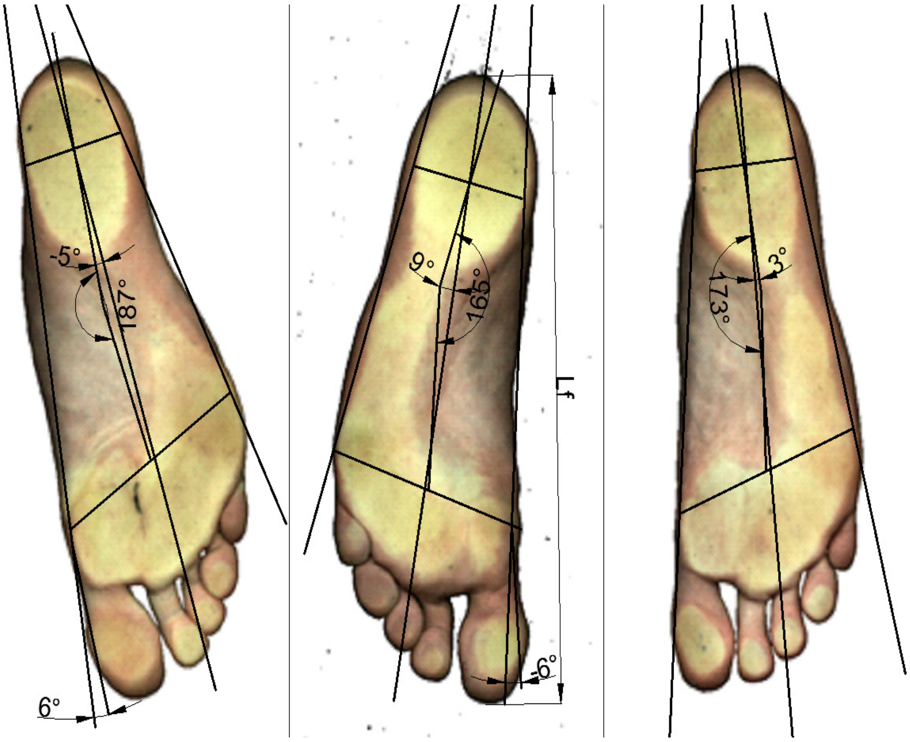


Figure 7. Defining the major angle parameters based on the most typical foot prints of the average-sized feet

While analyzing the shape of the toe section, we have noticed the significant variability of the parameters of the angle of the first toe. Individuals with the high values of this angle had the feet with hallux valgus, while low values of this angle characterized the feet with hallux varus. The average value of the angle, which is typical for a normal foot, ranges between 4 and 8 degrees. The angle parameter of the first toe is also subject to the law of normal distribution.

According to the results of the conducted studies, the most common deformities of the feet of young men were longitudinal flatfoot of various degrees (up to 40% of the measured feet), claw toes (about 20% of the measured feet), hypertrophy of the heads of the 1st metatarsal bone (about 30% measured feet), fan-shaped toes (20% of the feet), hallux varus, hallux valgus, and the fifth toe muscles hypertrophy (32% of the feet). Hypertrophy of the head of the 1st metatarsal bone is often combined with hallux valgus. The onset and development of the head of the 1st metatarsal bone and the deformity known as the "claw toe" are most often caused by the use of inadequate shoes. Such deformity as the fifth toe muscles hypertrophy usually results from the adaptive changes in the morphological structure of feet of the young men engaged in certain sports (in our case, a significant number of men play football, go skiing, and do gymnastics).

When designing the lasts for the mass consumer of the studied sample population, it is necessary to focus on the typical average feet with consideration of each of the studied parameters [3, 11, 13]. However, if it is observed that there are a large number of similar deformations or deviations of a parameter that is important in terms of anthropometrics, this should not be ignored. Thus, during measurements, it was noticed that a large number of men had hypertrophy of the heads of the 1st and 5th metatarsal bones. On the other hand, the fact that there is a considerable percentage of feet with large balls requires the increased parameters of the ball section of the last. In order to rationalize the range of lasts with different sizes and fullness, while trying to fully satisfy the requirements of compliance with the anthropometric parameters of the feet of consumers, it is considered effective to take into account the parameters of the feet with the hypertrophy of the heads of the 1st and 5th metatarsal bones in the lasts with significant fullness. Given the large difference in the girths of the ball areas of the feet of the studied population, the lasts are to be made in accordance with at least two width values for each size (standard and wide ones).

The following basic requirements should be adhered to when designing lasts. The toe area of the foot should not be squeezed by the shoe since there is a hard toe box in this place which will have a painful effect on the foot, therefore, in the toe part, the last bottom surface must take into account the parameters of the wide shape of the toe area of the foot. The height of the last at the level of the first toe is calculated based on the greatest height of the toe in a certain size class. At the level of instep part, the width and girth of the last are calculated based on the average parameters for each size. For the flat foot, it is possible to additionally apply a profile insole that partially compensates for the excess space inside the shoe. For a foot with the high instep, it is sufficient to adjust the tightness of the laces on the army boots.

The basis for the construction of the frame of the complex 3D body of the last is the contour of its bottom surface [3]. The last bottom surface is designed on the basis of averaged foot print of a certain size class. However, given that our task is to develop an ergonomic last shape that will meet the requirements of convenience of the maximum number of consumers, we must also take into account the parameters and peculiarities of the morphological structure of the most common types of feet. Apart from that, we need to develop a single shape of a last (which will be of the medium size and with medium fullness) that will fit most of the existing morphological types of the feet of the studied category. The following are some of the morphological features that influence the shape of the last and affect a significant part of the target consumer segment: the hypertrophy of the heads of the 1st and 5th metatarsal bones; fan-shaped toes and hallux varus; the fifth toe muscles hypertrophy. These are the deformities that result in the changes in the anthropometric parameters of the foot and cause discomfort when they are ignored in the inner shape of a shoe. To build the basic contours of the last frame, we selected 3D models and foot prints which reflect the most common morphological types. Thus, Fig. 8 presents the comparison of 3D models of medium-sized feet with the average fullness that have the following common morphological features: the fifth toe muscles hypertrophy, which is indicated with the green color, the hypertrophy of the head of the 1st metatarsal bone, which is indicated with the purple color; and fan-shaped toes, as well as hallux varus, which are represented with the yellow color.

Figure 9 represents the comparison of the contours of the last bottom surface of a medium-sized shoe, which is designed on the basis of mass anthropometric studies of the feet of young Ukrainian men. The last bottom surface designed based on the print of the average-sized foot that has no deformities is indicated with the red contour. The last bottom surface designed with the consideration of the common morphological peculiarities is indicated with the black contour.

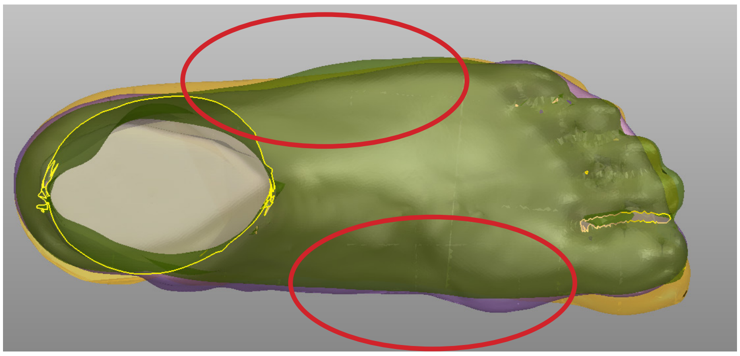


Figure 8. The comparison of the 3D models of average-sized feet of different morphological types

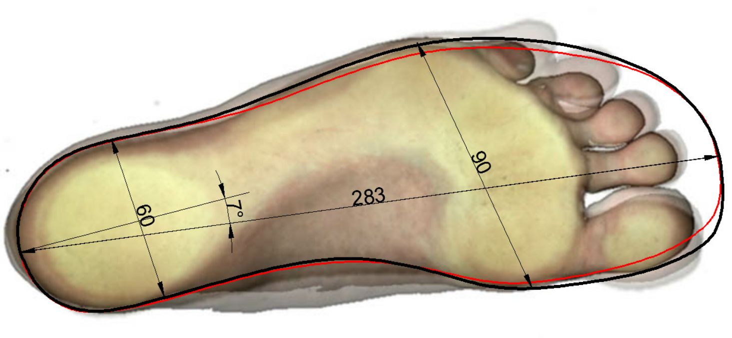


Figure 9. The comparison of the last bottom surface contours designed based on the foot prints with and without the consideration of common deformities

Based on the results of anthropometric studies, the parameters of a last of the average size (270 mm) with two width values (Table 2) were developed.

Table 2: The parameters of the feet and lasts with the medium and large fullness

Dimensional feature	Arithmetic mean value, μ, mm	min according to the average dimensional interval, mm	max according to the average dimensional interval, mm	The last of the medium width, mm	The last of the wide width, mm
Foot length	271.4	268.9	272.2	290	290
Foot length (based on the imprint)	262.1	260.3	265.2	283	283
Ball girth	256.5	244.3	270.1	256	268
Short heel girth	349.6	342.2	370.0	360	372
Instep girth	267.2	249.8	275.7	268	280
Ankle girth	267.1	253.5	282.2	270	282
Heel width (based on the contour)	63.5	56.8	70.5	67	71
Heel width (based on the imprint)	51.79	45.5	60.1	60	63
Ball width (based on the contour)	104.5	99.0	110.3	96	101
Ball width (based on the imprint)	97.8	93.0	102.1	90	94
Height of the first toe	23.5	20.1	26.8	27	28
Ball cross section height	45.4	42.1	49.8	48	54
Last height at the level of the short heel	86.7	79.8	93.1	92	99

Figure 10 presents the sequence of obtaining the necessary data for the design of the last shape on the basis of mass anthropometric studies of the feet of the selected sample population, which was carried out using 3D scanning of the feet.

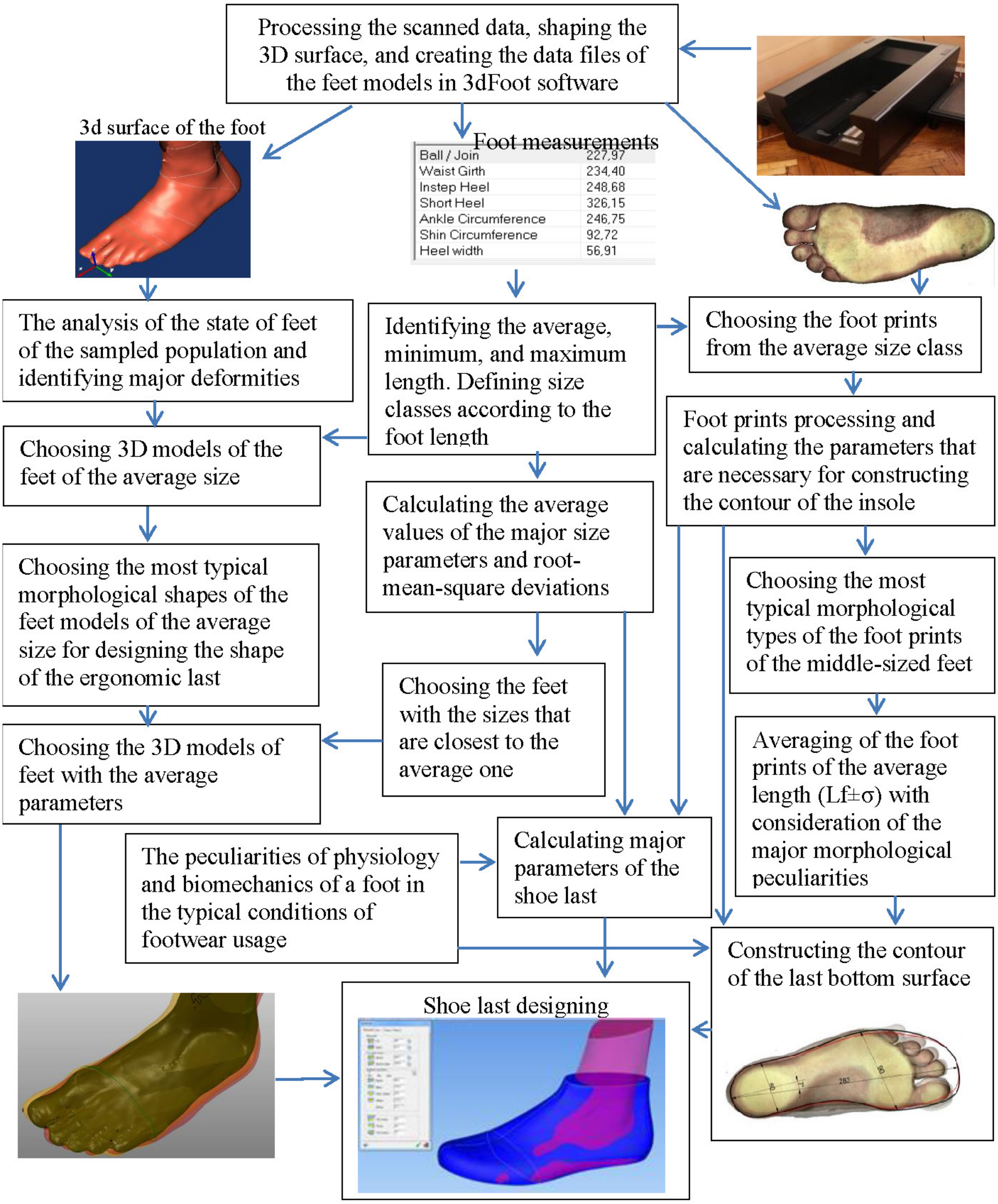


Figure 10. The algorithm of developing the ergonomic last shape for military footwear

CONCLUSIONS

Analyzing the quality of domestically produced military footwear, consumers highlight that it is not comfortable enough. The fact is that domestically produced military boots are manufactured either on the outdated lasts of the Soviet model of the 70's, or on random lasts, the shape of which is not substantiated from the anthropomorphological point of view.

In the work, anthropometric studies of the feet were performed by means of 3D scanning. The results of scanning have been used for two main purposes. Firstly, there were studied the features and morphological structure of the feet of young men aged 20-30, who are the representatives of the Ukrainian population that are subject to mobilization into the ranks of the Armed Forces. Apart from this, the quantitative distribution of the main morphological features of the feet of the sample population was analyzed. During measurements, it was noticed that a large number of men had hypertrophy of the heads of the 1st and 5th metatarsal bones. On the other hand, the fact that there is a considerable percentage of feet with large balls requires the increased parameters of the ball section of the last. In order to rationalize the range of lasts with different sizes and widths, while trying to fully satisfy the requirements of compliance with the anthropometric parameters of the feet of consumers, the parameters of the feet with the hypertrophy of the heads of the 1st and 5th metatarsal bones must be taken into account in the lasts with increased width. Furthermore, the results of scanning constitute the basis for calculating and developing basic parameters of lasts. For this, the work suggested the method of designing a last shape based on such types of input data as a digital foot model, dimensional foot parameters, and a foot print obtained as a result of mass 3D scanning of the feet.

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