The Role of 3D Technologies in Improving Design and Technological Processes of Orthopedic Footwear Production

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Abstract

Digital technologies today play an important role in all areas of design and production of industrial goods. However, in the footwear industry, the implementation of 3D technologies still causes numerous difficulties associated with the multi-component structure of the design object and the complexity of the production technology.

However, it is the complexity of the shoe shape that is the reason for the widespread use of digital technologies, as this will help reduce the complexity of the industry's design processes and bring them under a scientifically grounded approach. In addition, digitalization of production is a way to reduce dependence on complex manual operations, which is necessity in conditions of a shortage of professionals with required qualifications. The active implementation of 3D technologies in the production of orthopedic footwear is especially important.

Orthopedic footwear is one of the most important products related to additional rehabilitation aids, and is manufactured individually for each patient, taking into account his medical diagnosis, anthropometric parameters, recommendations of a rehabilitation doctor and personal requirements of the consumer. Today, inclusive products must meet high standards, as they play an extremely important role in improving the standard of living and normal activity of people with disabilities.

The process of manufacturing orthopedic shoes is one of the areas of shoe production, the target object of which is a medical device for the patient's rehabilitation. Although the process of manufacturing such shoes is close to the typical technological process of shoe production, orthopedic shoes are distinguished by the special shape of the personalized shoe last, as well as the presence of special orthoses, orthopedic insoles and other elements that perform a corrective, therapeutic or fixing function. It is the development of the shoe last and orthopedic inserts that represents the greatest complexity and should be digitalized in order to improve the properties of the final product.

The development and production of personalized orthopedic lasts in digital design and technology laboratories equipped with a 3D scanner, 3D printer and special software for 3D modeling can help solve the problem of producing the right orthopedic footwear on an individual order even in the absence of highly qualified specialists in the development of orthopedic shoe last at local production. The process of developing and manufacturing the elements of the form of orthopedic footwear involves such main stages as 3D scanning, 3D modeling and 3D printing (Fig. 1).

Fig.1 The main stages of the process of the orthopedic shoe last creating using digital technologies

The 3D foot scanning method allows us to obtain and collect initial information about patients' feet without the need to use huge areas for storing plaster models. Also, the digital information obtained is of great value for analyzing the processes of progress or regression in the clinical condition of consumers' feet.

The modern progressive orthopedic footwear production is very actively involving 3D printing technologies for manufacturing shoe last, orthopedic inserts, orthoses, test shoes, as this is an environmentally friendly way to manufacture elements of any complexity and purpose, which is a logical continuation of the sequence of 3D scanning and 3D product development processes.

3D modeling is the main design process, the result of which is a digital orthopedic shoe last and elements of the required shape, ready for 3D printing. To design a footwear last shape, a reverse engineering method is used, when a new product is modeled by modifying the basic shape. And this is where we encounter a large number of difficulties in the case of orthopedic footwear:

- The choice of software that provides the selected method and high design accuracy, has a wide functionality for implementing multi-stage modification of the shape of the shoe last and other 3d elements and provides converting 3d shape to 2d pattern
- The need to develop and manufacture the shoe last and other elements of a rational form for medical purposes, taking into account the medical diagnosis, the results of 3D scanning, functional features as well as technological requirements for production,
- The complexity of production of the footwear 3d elements.

Today the following most relevant approaches to modeling a personalized shape of an orthopedic shoe last can be identified:

- Parametric modeling, when the shape elements are created based on algorithmic processes, and the target shape is achieved by changing the parameters of the elements of the basic shape.
- Visual SubD modeling, when the basic shape of the shoe last is modified by editing the SubD surface frame in accordance with the shape of the 3D copy of the patient's foot
- NURBS modeling. A traditional method of modeling complex 3D shapes, based on manipulations with spatial surfaces using shape-forming curves and nodal points, which ensures high design accuracy.

Considering the advantages and disadvantages of the methods, the work used a combined approach that includes elements of parametric and SubD modeling to develop an improved method for designing a personalized orthopedic shoe last using such CAD as MindCAD3d (for Footwear), Rhinoceros. The general process of designing the shape of an orthopedic shoe last according to the proposed method is presented in Fig. 2.

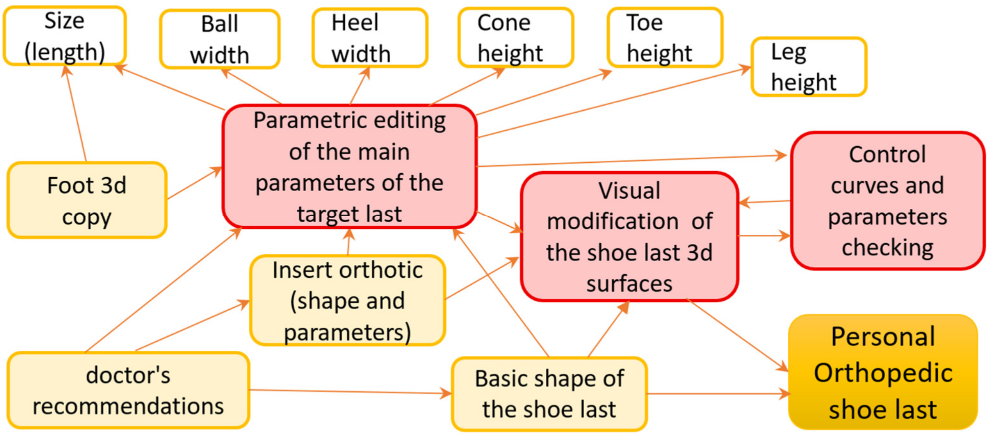


Fig. 2. The general structure of the process of the orthopedic shoe last engineering according to the proposal method

The developed shoe last can be manufactured using 3D printing. However, this method still causes a great difficulties for implementation in Ukrainian industry conditions. Therefore, the aim of the work was to study the possibility to produce a special shoe last shapes for individual orthopedic footwear based on the use of existing production shoe last.

The adaptation of these shoe lasts can be achieved by compensating for the difference between the standard and individual orthopedic last shapes using 3D-printed pads for patients with pathological foot conditions.

Key words: 3d scanner, 3d printer, footwear last, orthopedic footwear, 3d design, shoe last pads.

1. Introduction

Footwear today is one of the most important elements of a costume, serving not only aesthetic and fashion demands but also playing a crucial role in ensuring comfort, mobility, work efficiency, and the physiological health of the wearer. The modern footwear industry is increasingly focused on comfort and functionality in the interaction between the human foot and the shoe [1]. The rising demand for ergonomic products is driven by the desire to improve consumers' quality of life. Therefore, a significant number of scientific studies are dedicated to the investigation of human foot anthropometry and biomechanics for the development of rational footwear designs [2].

Numerous problems, such as pain in the forefoot, swelling in the lower legs and feet, hammer toes, bunions (hallux valgus), ingrown nails, calluses and skin abrasions, fungal infections, valgus deformities, Achilles tendon inflammation, flat feet, spinal misalignment, and discomfort in the back and knees, among others, are all side effects of improperly fitted footwear available on the market, designed primarily according to fashion trends [3].

At the same time, some of these problems are caused by age-related and pathological changes characteristic of populations in economically developed countries. Increased life expectancy and the aging of the population, especially in economically advanced nations, lead to a rise in civilization-related diseases such as diabetes, obesity, cardiovascular disorders, rheumatic conditions, and neurodegenerative diseases. All of these have a certain impact on the development of musculoskeletal and foot deformities [4].

The issue of providing properly fitting and comfortable footwear is particularly relevant for the elderly, as well as for individuals with diabetes, obesity, or musculoskeletal disorders. In such cases, orthopedic footwear, which supports, corrects, and relieves the foot, is widely used [5].

Orthopedic footwear serves a specific purpose. While the primary requirement for comfortable footwear designed for healthy consumers is not to impede the natural movement of the foot, the main criterion for the utility of orthopedic footwear is to support a deformed foot, correct its position, assist during movement, and reduce pain or discomfort. The effectiveness of orthopedic footwear is determined by several structural elements: the shape of the last, insole, sole, upper, and framework components. One of the most important elements that defines the proper shape of the shoe is the last. At the same time, the last presents the greatest challenges in design and manufacturing.

The simplest way to model a new last shape in the 3D graphic environment of modern CAD systems is by modifying and deforming the last that most closely matches the style and size parameters of the customer's foot. In practice, developers of orthopedic lasts use the following methods:

1) SubD modeling – modification of the base last shape according to the patient's foot parameters by comparing the last with the foot and adjusting the SubD mesh nodes.
2) Parametric modeling – modification of the last shape by changing the parameters of the model represented in a specialized software environment as a parametric model.
3) NURBS surface modeling and modification – adjusting the surfaces that define the last shape based on boundary profiles and the contours of support cross-sections.
4) Polygonal mesh morphing – deforming the polygonal mesh that represents the last shape in comparison with the foot.

The main stages of digital last modeling according to the foot shape include 3D scanning of the foot, creating a digital model of the last, assessing deviations between the foot and the last, and applying spatial deformation (morphing) methods to adjust.

Digitalization of orthopedic footwear production helps reduce dependence on complex manual operations and compensates for the lack of skilled specialists, which is especially relevant for local manufacturing conditions.

2. Analysis of modern methods for modeling orthopedic lasts

Analysis of foreign scientific publications has revealed research directions and main trends in the modern approach to automated footwear last design in a graphic environment:

1) Selection of a reference last based on the similarity of physical parameters of the foot–last system.
2) Comparison of the customer's foot with standard feet, which serve as the basis for last development from a database, and adjusting the last shape according to identified deviations.
3) Use of a deviation map between the foot replica and the last to determine the necessary corrections to be applied to the last shape.
4) Application of a deformation grid to calculate the required adjustments to the last shape based on the deformations applied to the reference last to match the parameters of the examined foot.

Luximon [6, 7] developed a method for analyzing the shape of a last based on color 3D deviation maps between the foot and the last, enabling the determination of an optimal base shape for further modifications. However, the author does not provide recommendations for selecting the optimal last shape nor specify the methods for its modification.

Li [8] proposed a method of smooth surface interpolation between the heel and toe regions of the last, providing more precise adaptation to the anatomical parameters of the foot. This method is designed for mass-produced lasts and does not account for the anthropometric characteristics of the customer's foot. Such an approach could also be applied to orthopedic footwear; however, it requires complex algorithms for implementation in an automated mode.

Mochimaru [9, 10] described a spatial grid deformation method for modeling a custom last according to foot parameters. The method is highly labor-intensive, especially in the case of orthopedic lasts for complex deformities.

An example of integrating digital workflows into orthopedic footwear design is provided by Podotools, a Dutch initiative that publishes 3D models of lasts, casts, and drawings with open access on the Sketchfab platform [11]. Their portfolio includes specialized models, such as the "Charcot last," demonstrating the capability of digital modeling for shoe components adapted to severe foot pathologies. The founder, Erik Hondebrink, one of Europe’s leading developers of orthopedic lasts, uses SubD modeling in his practice to create complex shapes for custom lasts.

The aforementioned modeling approaches are widely used in CAD/CAM systems and form the foundation for the automated design of orthopedic lasts.

Footwear last modeling is based on the principles of reverse engineering, comparing the shape of the shoe with the shape of the foot. Therefore, 3D scanning is today an indispensable, advanced, and efficient method for obtaining information about the shape and dimensions of the foot for last design [12]. 3D foot scanning allows for the rapid and accurate acquisition of anthropometric parameters, which is especially important in cases of complex deformities [13].

The development of orthopedic footwear often requires additional information about the shape and condition of the patient’s foot, which can be provided in the form of a plaster cast of the foot in a fixed position, a footprint on polymer foam, and other methods [14]. 3D scanning allows for the comparison and correlation of this information to analyze foot conditions, assess the dynamics of the rehabilitation process, and model functional products, taking into account the complete set of initial data.

The development of additive technologies has simplified and expanded the possibilities for creating individual 3D components. For example, the significant potential of 3D printing can be utilized to develop personalized shoe lasts with individual adaptation to the customer’s parameters and requirements [15]. Companies and startups offer the creation of custom lasts with high precision and speed using additive technologies. For example, the German companies Dreve and PROTIQ, in collaboration with Forward AM [16, 17]. The study by Amza et al. [18] demonstrates the feasibility of 3D printing custom shoe lasts with the required physical-mechanical properties suitable for use in production conditions. The algorithm for adapting a 3D last model to the customer’s parameters allows for rapid fabrication of a personalized product, avoiding repetitive processes of designing new last shapes and preparing them for 3D printing. The combination of 3D scanning, digital modeling, and 3D printing forms an advanced production scheme – “scan–model–print” – which is being actively implemented in European orthopedic laboratories.

Despite technological advantages, the use of 3D printing in Ukraine has certain limitations:

- The high cost of quality printing filaments;
- The long printing time poses a problem given the energy instability of enterprises: a single orthopedic last with a mid-height shank requires more than 9 hours of continuous printing on a standard FDM printer, which is a significant constraint in Ukraine under energy crises;
- Low strength of the finished product, considering the specific use of the last in the shoe manufacturing process.

Therefore, hybrid approaches that combine traditional methods (forms, inserts) with modern digital technologies are currently relevant.

This study analyzed publications dedicated to the use of inserts on lasts to adapt their shape to the anatomical parameters of the foot. Such inserts are added to a standard last for local adjustment of dimensions and volumes in areas where discrepancies are observed between the shape of the foot and the last.

In the study by Leshchyshyn et al. [19], the creation of custom 3D-printed pads, which are attached to the last, to eliminate local discrepancies, was examined. It was demonstrated that this approach significantly reduces the differences between the foot and last parameters and enhances comfort. The authors also proposed a methodology for identifying correction zones and modeling the pads.

In the study by Costea et al. [20], the possibility of using fitting components to modify the shape of a last according to individual needs without producing a new one was analyzed. This approach allows for reduced material consumption and decreased manufacturing waste.

This approach is promising, as it enables the adaptation of existing lasts to the required parameters with minimal time and resource expenditure. The 3D printing time for pads is several times shorter than that for a new last, which is especially relevant given the large number of old plastic lasts of various sizes available in Ukrainian enterprises.

At the same time, the studies reviewed do not investigate the possibilities of adapting standard lasts to the shape of orthopedic footwear, which highlights the relevance of further research in this area.

Many patients today require footwear with increased width and/or depth [21]:

- Those with endocrine system disorders causing significant swelling of the lower limbs or weight gain, such as diabetes, etc.;
- Those with central nervous system (CNS) impairments who use orthoses such as SMO, AFO, or KAFO;
- Those with musculoskeletal and locomotor system disorders: third-degree hallux valgus (deviation angle greater than 40°), hammer toe deformities, gout;
- Individuals with various congenital defects and pathologies causing significant changes in foot shape or necessitating the use of lower limb orthoses;
- Patients who, due to injuries (fractures, mine-explosion wounds, traumatic or surgical amputations), have alterations in foot shape and/or size.

While in some general cases a patient may choose mass-produced footwear with increased width and volume, in more severe cases, mass-produced shoes cannot be fitted. In such situations, custom-made footwear is required, manufactured on an individual last that replicates the shape of the foot and corresponds to its dimensions.

In such cases, the lasts of the right and left feet often differ significantly in width and sometimes in length (for example, if one of the lower limbs has been altered due to an injury). In these situations, either individual lasts for both feet can be used, or a set consisting of one custom last and one standard last for the patient’s two feet.

A traditional method for compensating insufficient last volume is the application of shims—layers of leather or cardboard, pre-soaked and shaped to fit the last. They are fixed in several places using nails. Thermoplastic materials, preheated and molded, can also be used. The thickness of a single shim in its thickest area is approximately 5–6 mm, with the edges tapered for a smooth transition to the last. The total added volume to the base last depends on the number of shims used.

This study aimed to assess the feasibility of effectively using 3D printing technology for the rapid adaptation of a standard shoe last to the individual parameters of a patient’s foot for the subsequent production of custom orthopedic footwear. The adaptation of the last is achieved by compensating for the difference between the standard and individual orthopedic last shapes using 3D-printed pads for patients with pathological foot conditions. To this end, the study aimed to develop and produce typical pad shapes that can be used for the most common foot pathologies, as well as to design individual pad shapes for complex pathologies based on the results of 3D scanning of the patient’s foot.

3. Methods

The development and production of personalized orthopedic lasts in digital design and technology laboratories equipped with a 3D scanner, 3D printer, and special software for 3D modeling can help solve the problem of producing the right orthopedic footwear on an individual order, even in the lack of highly qualified specialists in the development of orthopedic shoe lasts at local footwear productions in Ukraine. The process of developing and manufacturing the elements of the form of orthopedic footwear involves such main stages as 3D scanning, 3D modeling, and 3D printing (Fig. 1) and can be made separately from the footwear factory.

During 3D scanning, initial data on the patient’s foot and leg anatomy are captured with high precision, eliminating the need for traditional plaster models. The obtained 3D data are then processed and analyzed in specialized CAD environments to develop a digital model of the last and associated orthopedic elements. Finally, 3D printing enables the physical production of the designed components with high reproducibility and environmental efficiency.

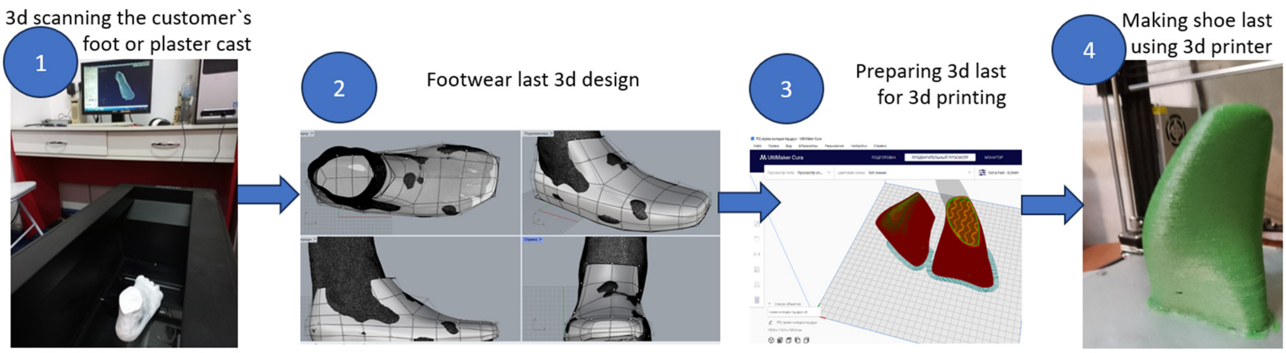


Fig.1. The main stages of the process of creating an orthopedic shoe last using digital technologies

The initial information on both the patient's foot shape and the base last was obtained using 3D scanning on a professional FootIn3D scanner (OrthoBaltic, Lithuania). The scanning results are processed using the specialized Foot3D software, which allows for the calculation of the main foot parameters and surface triangulation for subsequent conversion into an STL file.
Next, in the 3D CAD software environment, after importing the foot and last files, a comparison of the parameters and shapes of the foot and the base last was performed. Based on the comparison results, two pathways for further processing were proposed:

1) In the case of local discrepancies – selection of typical digital pads;
2) In the case of large areas with significant differences, model a new customized last shape and subsequent development of a custom pad.

Modeling of the individual last shape was carried out using the functions of specialized footwear CAD software (Crispin LastMaker 2016 and MindCAD 3D Last 5.4). Comparative analysis was performed in the PowerShape 2016 environment. The 3D modeling of pad shapes was carried out using surface and solid modeling functions in Rhinoceros 7 and PowerShape 2016. Scanned feet and base lasts were compared in CAD to identify the most significant discrepancies that needed to be compensated. The algorithm for pad development is shown in Fig. 2.

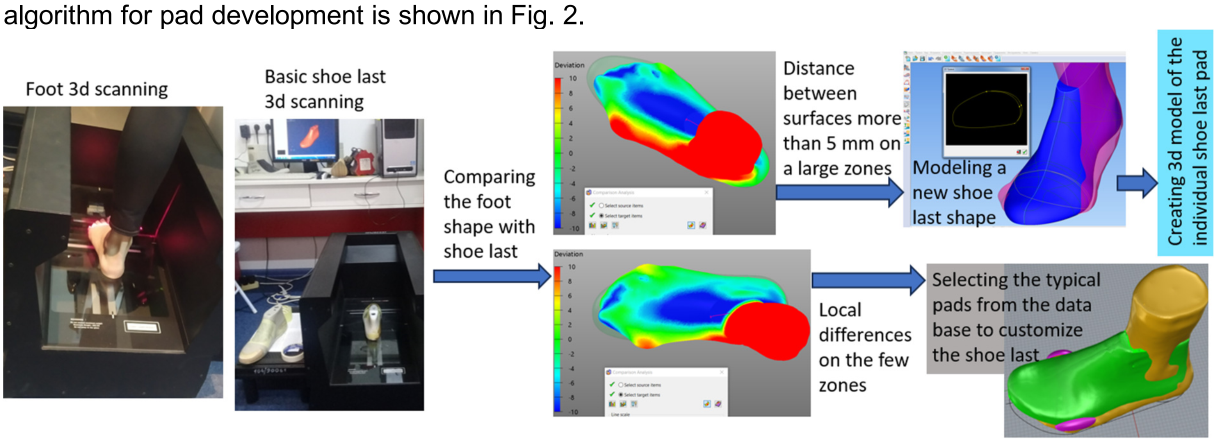


Fig. 2. Algorithm for pad development using 3D scanning and digital modeling

The modeled 3D pad shapes are saved in STL format and prepared for 3D printing using slicer software. FDM technology was chosen for printing because both the materials and printers are accessible, and there is virtually no waste (for example, compared to SLP printing). Moreover, the variety of filament materials and the wide range of settings allow for the production of sufficiently strong parts within a relatively short period of time.
When printing pads on the FDM Anet A8 printer, model preparation was carried out in the Cura slicer. To increase the production speed of large pads, a more advanced and progressive FLSUN printer was used (Fig. 3).

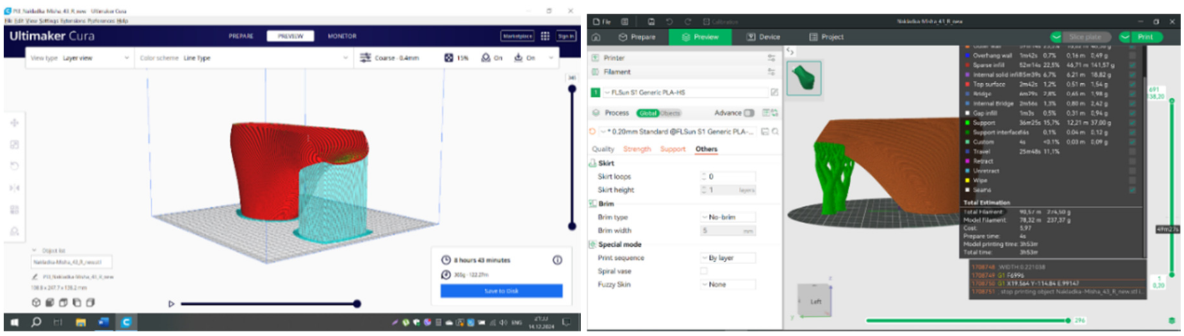


Fig. 3. Preparation of the part for printing in Cura and FLSUN slicers

After printing, all supports were removed. No further post-processing (layer smoothing, sanding) was required, as the surface appearance of the pad is not important.
The applied algorithm, which combines 3D scanning, parametric modeling, visual modeling, and 3D printing, ensures high accuracy in reproducing foot geometry and simplifies the process of adapting a standard last. The methodology allows for the creation of both local and full pads depending on the nature of the deformities, confirming the versatility of the approach.

4. Results and Discussion

The study proposes a method for adapting the shape of a standard last to the anatomical features and requirements of the patient. Depending on the condition of the foot and the degree of deformity, one of two options can be chosen:

a. Shape adaptation using separate local pads, which are pre-designed and stored in a virtual database;
b. Shape adaptation using a large full pad, which is individually modeled.

Possible typical shapes of local pads, which help adjust the base last to the patient's foot shape, are shown in Fig. 4.

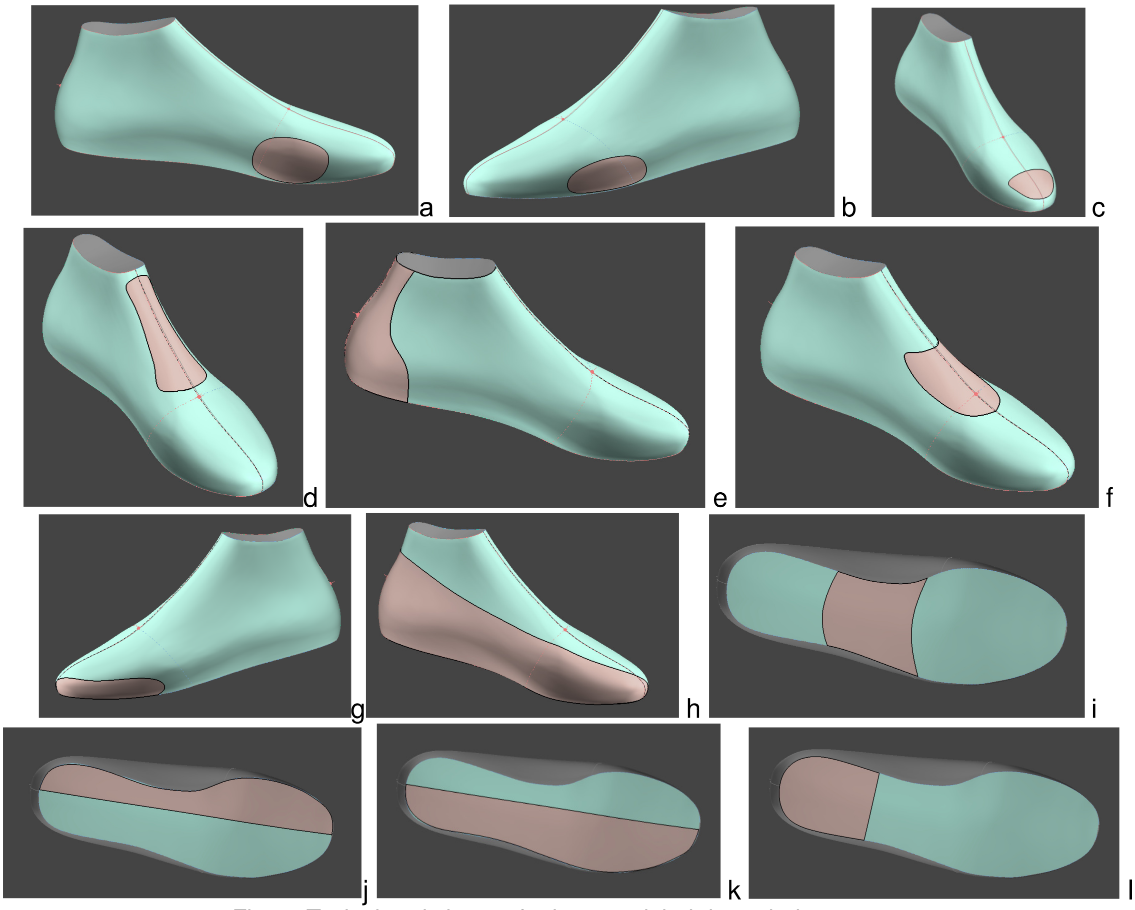


Fig. 4. Typical pad shapes for lasts and their intended purposes.

a) Hallux valgus, hypertrophy of the first metatarsal head
b) Pain in the fifth metatarsal head, corns in the zone of the fifth toe, etc.
c) Toe deformities (hammer toes or claw toes)
d) Need to increase the area of the direct and oblique instep in cases of swelling, skin damage in this zone, etc.
e) Need to increase volume in the heel area (painful corns, etc.)
f) Need to increase volume in the forefoot–instep area in cases of swelling, skin damage in this zone, etc.
g) To widen the toe box area for feet with broad toes
h) To build up volume along the inner side of the last in cases of pronounced hallux valgus
i) Reduction of the last's arch in the midfoot area for deformities such as severe longitudinal flatfoot, arch collapse (e.g., Charcot foot), etc.
j) Supinator pad for excessively pronated foot position
k) Pronator pad for supinated foot position
l) Heel elevation in cases of lower limb shortening

Pads in zones a, b, and c can be standardized according to the shapes of typical pads used in traditional footwear manufacturing for custom orders. Table 1 presents the main parameters for typical pads a and b, as well as the increase in forefoot perimeter (ΔP) provided by the pad.

Table 1. Main Parameters for Typical Oval Pads.

Purpose	Width, mm		Length, mm	Height, mm	∆P, mm
1st metatarsal	34		48	18	16
1st metatarsal	25		40	10	15
1st metatarsal	30		42	13	11
5th metatarsal	16		47	8	7
5th metatarsal	24		60	10,5	10
5th metatarsal	22		56	10	8,5

To test the hypothesis regarding the possibility of simplifying the process of adapting a last to a patient's foot parameters, an experiment was conducted to produce a pad in the area of the fifth metatarsal head (Fig. 5). The patient has a foot deformity in this area and painful corns. The required correction was an increase in girth by 7 mm. For this purpose, a typical pad with dimensions 60 × 24 × 10.3 mm was selected, which provides an increase in the last's girth in the required area by 7.1 mm.
PLA was chosen for printing, and the printing parameters are presented in Table 2.

Table 2. Printing Parameters for a Local Pad on the Metatarsal.

Parameter	Value
Wall loops	2
Wall height	0,2 mm
Infill	Monotonic lines, 25%
Printing speed	60 mm/s
Bed temperature	$60\ ^{0}$ C
Nozzle temperature	$215\ ^{0}$ C
Additional	Brim added

Fig. 5. 3D model and printed pad on the last

The printing took less than 4 minutes, which is fast and does not create additional difficulties under conditions of energy instability in production. The pad was installed using a peg inserted into a hole made in the last. Verification of the last's parameters with a measuring tape and comparison with the foot measurements showed satisfactory results.
The advantages of using local standard shims produced by 3D printing include:

- Quick and convenient selection of the required shims for different shoe models.
- Simple and precise positioning on the last, which increases forming accuracy and reduces the risk of deformation.
- Rapid adaptation of the last to the individual features of the foot, thanks to the ability to precisely adjust the shim parameters.
- Reduction of production cycle time, as 3D printing allows shims to be manufactured on-site and their design updated as needed.
- Minimization of material costs compared to traditional methods of producing metal or wooden forms.
- Versatility and modularity, enabling the same series of shims to be used for different shoe models and sizes.

Unfortunately, in cases of severe deformities and pathologies, local pads are not always sufficient. However, even when it is necessary to develop a complex last shape for complicated orthopedic cases, a standard last can still be used as a base, which is then adapted to the foot shape using a custom pad. The study also included a practical investigation of the possibility of developing an orthopedic last based on an existing standard last for the subsequent production of orthopedic footwear for a 23-year-old patient with right-sided spastic tetraparesis, accompanied by equinovarus deformity of the right foot.

The patient wears a rigid ankle-foot orthosis (AFO) that stabilizes the foot and ankle joint. His nervous system condition, which is associated with right foot deformity and severe biomechanical impairments, requires an individually designed orthopedic shoe last.

Based on the clinical examination of the patient's feet (while standing and during different phases of movement), the main requirements for the individually designed orthopedic footwear were formulated:

- Individual last shape to ensure correct positioning of the foot with the orthosis inside the shoe.
- Compensation for functional shortening of the right limb caused by spastic tetraparesis.
- Foot pronation and correction of varus position to improve biomechanics.
- Special sole shape with widening along the outer edge to support the foot during the walking phase when maximum load is applied to the affected foot.

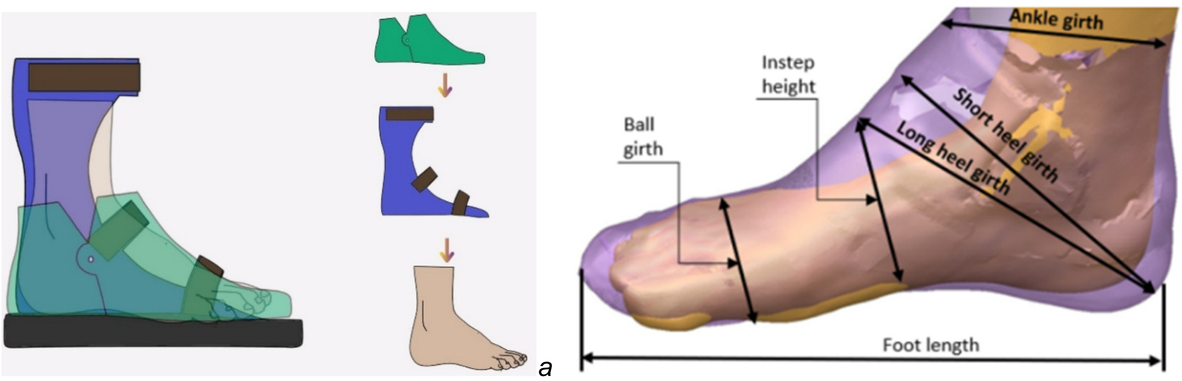
To obtain baseline data on the patient's feet, 3D scanning was performed using a professional FootIn 3D scanner.

The patient's right and left feet were scanned in an unloaded state, as the scanning procedure could only be performed while seated. The left foot is healthy, with only a slight valgus position that can be compensated using a supination insole. The right foot, due to spastic tetraparesis, is in an equinovarus position and stabilized with an AFO orthosis. The right foot was scanned together with the orthosis (Fig. 6b).


a b

Fig. 6. Scanning process of the patient's left and right feet using an AFO

A distinctive feature of designing such orthopedic footwear is that the shoe interacts not directly with the foot, but with the foot-orthosis system, which imposes strict requirements on the parameters of the last and the sole (Fig. 7a). Incorrect last parameters in this case can lead to orthosis breakage, patient discomfort, or rapid wear of the shoe. The rigid high orthosis with a flat, wide sole, combined with the deformed foot in a spastic equinovarus position, determines the parameters of the orthopedic last (Fig. 7b).



a b

Fig. 7. Foot–orthosis–last relationship and main parameters of the last for a foot in an orthosis

According to the results of the non-contact 3d anthropometric study, the left foot fully corresponds to the standard parameters of a size 42 last. This last was taken as the base. However, the right foot with the orthosis shows significantly larger dimensions due to the use of the orthosis, and for the development of the right orthopedic last, a last of the same style but size 43 was used.

After 3D scanning of the basic last and the foot with the orthosis, and comparing them in a 3D CAD environment, it was concluded that a large custom pad should be modeled. This pad will be fitted onto the base last and compensate for the difference between the base last shape and the foot with the orthosis. The greatest difference is observed in the rear part of the last (Fig. 8). For this type of orthopedic footwear, the last must include a higher ankle section, making it significantly taller than the standard last.

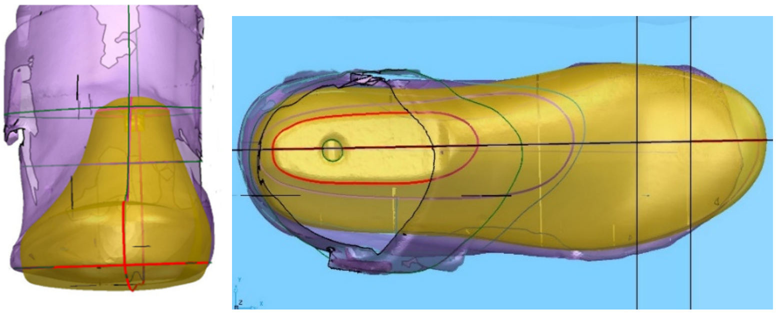


Fig. 8. Difference between the last and the foot with the orthosis.

To create the pad shape first we need to design the correct orthopedic shoe last shape based on the patient`s foot with AFO. The work proposes the following algorithm for the process of modeling a new form of orthopedic shoe last according to 3D information about the foot and the patient's needs (Fig. 9):
1) selection of the basic form of shoe last
2) parametric changes in the shoe last shape:
- scaling the basic shape according to the needed length
- scaling the 3d shape according to the needed ball width
- adjusting the heel width
- scaling the 3d shape according to the needed instep height
- adjusting the height of the shoe last (tibial tube)
- adjusting the height of the toe part
2) visual modeling the 3d shape using control sections and shape-forming profiles.
The modeling process was implemented in the MindCAD3d Footwear and Rhinoceros7 software.

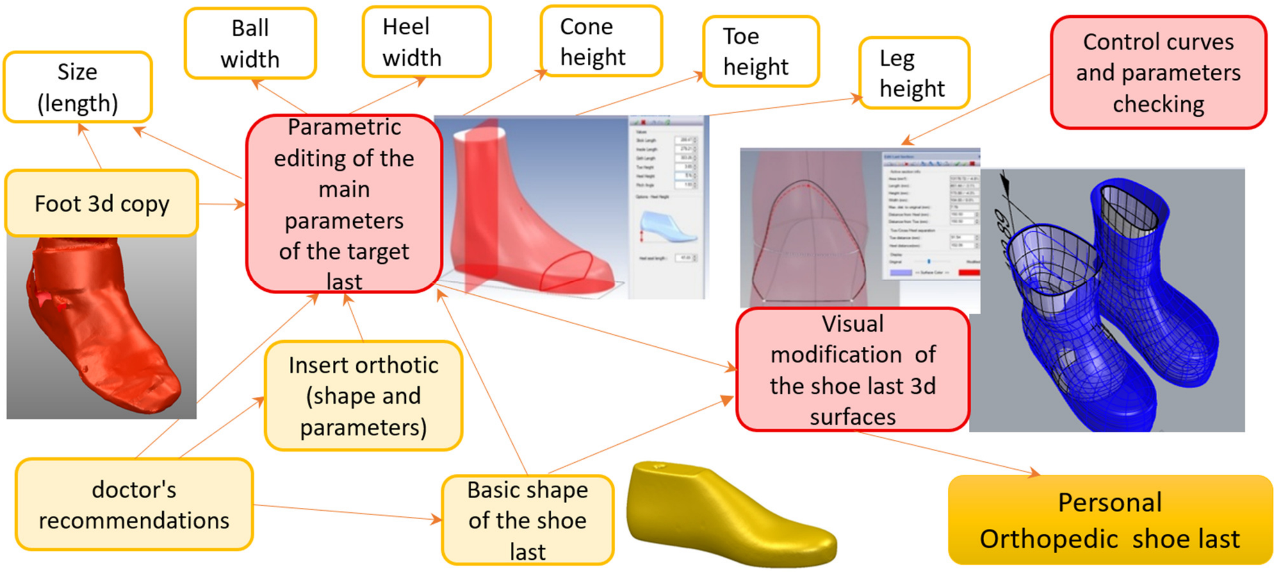


Fig. 9. The main stages of the process of the orthopedic shoe last engineering according to the progressive method of orthopedic last design.

Modifications of the base shoe last shape for our patient according to the foot with the orthosis included:
a) Increasing the width of the last
b) Expanding the upper platform
c) Increasing the height of the last (modeling the ankle section to the required parameters)
d) Increasing the volume in the areas of the straight and oblique insteps
e) Adjusting the contours of the shaping profiles according to the required parameters of the support areas of the new shape
f) Adjusting the contours of the cross-sections
As shown in Fig. 10, the designed last shape (left) significantly differs from the base last (right).

Fig. 10. From left to right: designed individual last, foot with orthosis and individual last, foot without orthosis with base last, and base last.

A comparison of the parameters of the standard last and the personalized orthopedic last is presented in Table 3.

Table 3. Parameters of the Base and Personalized Last for the Right Foot

Parameter	Basic Shape of Standard Shoe Last for the Right Foot	Right Foot with AFO	Created Personal Shape of Shoe Last for Right Foot
General length, mm	282.5	285,7	287.0
Bottom template length, mm	277.2	282	281.2
Ball width, mm	87.2	98,0	99.4
Heel width, mm	55,8	68.2	73.5
Ball girth, mm	244.1	255,1	285.8
Instep girth, mm	254.4	298,5	317.8
Short heel girth, mm	344.0	442,5	450.6
Ankle girth, mm	-	356.4	363.7
Toe height, mm	32.0	33.5	34.4
Last leg height, mm	76.2	200.0	214.5
Toe angle, degrees °	4	6.5	6.5
Heel angle, degrees °	6.5	5	5
Cone axis angle, degrees °	0	-2	-2
Heel lift, mm	10	0	4
Toe spring, mm	8	3	5
Angle of ball pronation °	0	0	2
Angle of heel pronation °	0	0	4

Next, the pad shape was designed by subtracting the base last shape from the modeled last shape (Fig. 11).

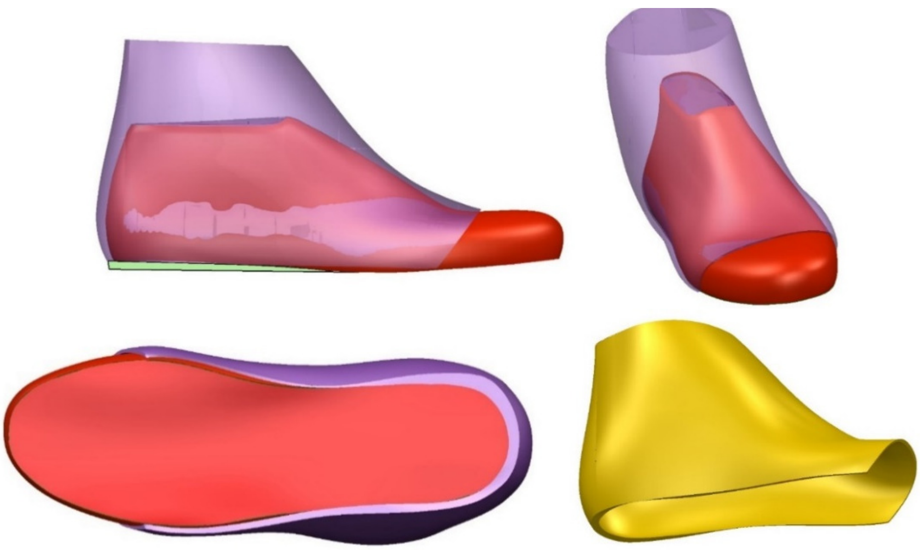


Fig. 11. Modeled pad with and without the last

When implementing the modeled shape through 3D printing, the choice of printing material is crucial. The most common filaments for rigid models made with FDM technology are PLA, ABS, and PETG [22]. A comparison of their main properties is presented in Table 4.

Table 4. Comparison of Key Material Properties for FDM Printing.

Property	**PLA**	**ABS**	**PETG**
Ease of printing	Easy; minimal shrinkage, does not require an enclosed chamber.	More difficult, higher shrinkage — an enclosed chamber/heated box is desirable.	Medium: requires a heated bed, but less warping than ABS.
Hardness Shore D (HShD) [23]	80	75	72
Temperature resistance (Glass transition temperature, T_g) [24]	~55–60 °C (low)	~90–105 °C (high)	~70–80 °C (medium)
Odor / Emissions (VOCs, particles) [25]	Lower emissions and less intense odor, but still emits some VOCs (e.g., formaldehyde)	Higher VOC and particle emissions; often the worst in terms of odor and toxicity.	Emissions are generally lower than ABS; studies show PETG usually emits fewer VOCs/particles, though some emissions are still present.

Thus, PLA is the strongest, most environmentally friendly, and safe material, as well as easy to print. A PLA-HS modification was chosen, which allows faster printing.
During print preparation, the main parameters were set in the slicer (Table 5).

Table 5. Main Parameters for Printing the Pad.

Parameter	**Value**
Support type	“Tree” for overhangs >30°, saving material and print time compared to standard supports
Wall loops	2
Top/bottom layer infill	Monotonic lines
Layer thickness	0,8 mm
Infill	Grid, 12 %
Printing speed	60 mm / s
Bed temperature	60^0C
Nozzle temperature	215^0C
Additional	Brim added

After preparing the pad model in the slicer, printing was attempted. However, the attempt to print the pad as a single piece was unsuccessful. Therefore, it was decided to split the model into several parts and print them separately. The finished parts were glued together using dichloroethane (for larger surface areas) and cyanoacrylate (for smaller monolithic areas). The printed pad model is shown in Fig. 12.

Fig. 12. Printed pad model.

The finished pad was fitted onto the last, with its edges slightly heated using an industrial footwear heat gun to better conform to the surface of the last (Fig. 13). Thanks to the use of digital technologies in the design process, the pad has a high geometric accuracy and can be easily positioned.

Fig. 13. Pad model on the base last.

A prototype shoe was manufactured on the adapted last, which the patient was able to put on and test in use (Fig. 14). After wearing the prototype shoe at home for a week, the decision was made to produce a pair of shoes according to this design.

Fig. 14. Manufactured orthopedic shoe.

Although the printed pad was not particularly strong, it fulfilled its intended function. For future applications, the infill percentage should be increased, as the pad may be subjected to significant impact loads.

The results obtained confirmed the effectiveness of using 3D printing to create individual pads for standard lasts. The use of PLA filament allowed for rapid fabrication and satisfactory dimensional accuracy, enabling the production of adapted prototype shoes with high comfort levels. This technological approach demonstrated potential for clinical use in the custom manufacturing of orthopedic footwear.

5. Conclusions

In this study, a methodology for adapting standard shoe lasts to the anatomical parameters of the foot was developed and tested by creating 3D-printed pads. The proposed technology combines 3D scanning, digital modeling, and additive manufacturing, ensuring accuracy, reproducibility, and the possibility of individualization. The use of the FLSUN printer and PLA-HS filament allowed for reduced production time, lower material consumption, and decreased energy use, which is a significant factor under manufacturing conditions in Ukraine. The resulting pads demonstrated sufficient strength for experimental applications.

The developed 3D-printed pads provided compensation for the asymmetry of the patient's right and left foot, who suffers from spastic tetraparesis and uses an orthosis. The use of pads improved comfort during the trial use of the footwear and reduced localized pressure on deformed areas. Unlike traditional shims, 3D-printed pads—when designed using prior 3D scanning and modeling—offer higher accuracy in reproducing foot shape, allow for local modifications, and enable automated correction as the patient's clinical condition changes. This expands the capabilities of orthopedic production without the need to manufacture new lasts. A combined approach that integrates SubD and parametric modeling proved to be effective for developing individualized orthopedic lasts with sufficient accuracy.

Future studies should explore the use of hybrid materials (PLA+PETG or fiber-reinforced composites) to increase pad strength, as well as the development of algorithms for automatic generation of correction zones based on 3D scanning data.

This work demonstrates that the integration of digital technologies—3D scanning, modeling, and printing—opens a new level of personalization in orthopedic footwear. Such an approach reduces manual operations, increases accuracy and comfort, and enables the rapid production of individualized solutions for patients with various foot pathologies.

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