USAGE OF ADDITIVE TECHNOLOGIES FOR ORTHOPEDIC FOOTWEAR MANUFACTURING

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Abstract. *In our times, the use of additive technologies has become very popular because of the ability to customize products, speed of manufacturing, save costs in production, simplify product development and launch into production, minimize of material waste. The production of orthopedic footwear components using FDM printing is very relevant because such footwear is custom-made and has numerous parameters that need to be considered during design and development: foot sizes and circumferences, type of deformity or foot condition, and sometimes associated diseases. The additive manufacturing of orthopedic insoles is particularly prevalent, because allows customize everyday footwear with minimal effort to enhance the comfort for patients and consumers with certain minor foot deformities and conditions (flat feet, minor limb shortening, varus or valgus foot alignment, increased foot load during pregnancy, etc.). In this study, we analyzed the latest global developments in 3D printing of orthopedic footwear parts, the used materials and printers, their advantages, and disadvantages. This work will be useful for specialists who want to implement additive technologies in the production of orthopedic footwear, as it will help evaluate the advanced experience of orthotic workshops, researchers, orthopedists and podiatrists, and make the right decisions.*

Keywords: *additive manufacturing, orthopedic footwear, FDM-printing, orthopedic insoles, orthotics*

Introduction

The structure and health of the feet affect a person's gait and posture. Negative impacts can come from injuries, innate deformities, bone and joint diseases, and central nervous system disorders. The most common pathological condition of the feet is innate or acquired abnormalities in the structure of the foot arches.

Three main states of the foot based on the height of the arches can be defined as follows:

- High-arched foot (or cavus foot)
- Normal-arched foot
- Low-arched foot (or flat foot) [1]

The height of the arches plays a significant role in the functioning of the lower limbs and can cause discomfort, pain, and even injuries to the lower extremities. For example, individuals with high arches may suffer from injuries due to reduced mobility of the foot joints. People with flat feet often experience pain in the feet, knees, and hips due to excessive foot mobility [2].

Optimizing gait and providing support for the feet can often be achieved through orthopedic footwear. In general, orthopedic footwear includes a special orthopedic insole and is made on an individual last that corresponds to the patient's foot parameters.

Recently, the technology of FDM printing has become increasingly widespread for manufacturing orthopedic elements of footwear. The main advantages of 3D printing include:

- Speed production
- Ability to create complex shapes

- Minimal material waste
- Ability to use materials with different properties and combine them
- Ability to provide the necessary characteristics to products (lightweight, durability, flexibility) through the design of the internal structure of the product.

The aim of the conducted research is to systematize the data obtained from scientific studies aimed at improving the manufacturing process and characteristics of insoles through the application of FDM printing technology.

Methodological part

The study analyzed 18 publications from scientists and manufacturers regarding 3D printing for orthopedic footwear production. Articles were searched for in the Scopus scientific database, the ResearchGate scientific portal, and the free scientific search engine Google Scholar. Keywords used during the search included: additive manufacturing, 3D printing, digital manufacturing, FDM printing, orthopedic footwear, orthopedic insoles, foot orthosis, flatfoot.

All analyzed articles can be classified into research directions as follows:

- Anthropometric, biomechanical, physiological studies of the condition of patients' feet using orthotic insoles
- Research on algorithms for designing orthopedic insoles
- Investigation of technical parameters of FDM printing.

Results and discussion

Traditional production of individual orthopedic insoles is a meticulous and labor-intensive process, and the quality of the resulting orthotics directly depends on the skills of the craftsman [3].

The advantages of using additive technologies in most spheres of material production have pushed for their implementation in the manufacturing of footwear and its components. However, the production of custom orthopedic insoles has its own specific requirements. This is because such products are expected to possess qualities such as elasticity, flexibility, compression resistance, and shock-absorbing properties [4].

3D printing of individual orthopedic insoles can offer several advantages, including reduced time costs and automation of production, potential cost reduction over the long term with continuous equipment use, and the ability to produce insoles that better conform to the contours of the foot [5, 6].

For 3D printing of orthopedic insoles, various materials can be used. Analyzed studies suggest the prospects of using materials such as TangoPlus and VeroClear in combination [7], PLA, TPU [8], Flex filament [9], Filaflex 60A, Filaflex 70A, Filaflex 82A, PolyFlex 90A, and VarioShore [10].

Patients who use orthopedic insoles notice a correlation between the stiffness of materials and the comfort of the orthoses [11]. Stiffer materials are used in the production of insoles for elevating the heel portion or supporting the arches of the foot, while softer materials are utilized to reduce pressure in the heel or forefoot area.

The printed surface of insoles is typically left open, but sometimes the top layer is made from sheet materials (such as Plastazote [12]), aiming to enhance comfort and aesthetic properties.

For designing the shape of an orthopedic insole, information about the bottom surface of the foot is required, presented in the form of a digital 3D model obtained through 3D scanning of the foot or its imprint on polymer foam. Additionally, information about the clinical condition of the foot, recommendations from the orthopedist, and the results of baropodometric or plantographic examinations are also necessary [9]. These methods allow obtaining information about the distribution of pressure on different areas of the foot, enabling the correct placement of orthopedic elements in the insole (metatarsal pad to support the transverse arch of the foot, cushioning materials in the heel or metatarsal areas, and, if necessary, a supinator or pronator).

The orthopedic insole, which is intended to simultaneously provide corrective, supportive, and cushioning functions, should have different physico-mechanical properties in various parts of the product. The filling of the inner space of the insole plays a significant role in achieving the desired characteristics of flexibility, cushioning degree, and durability. Slicing for 3D printing allows for selecting different patterns for filling, as well as varying density. The reviewed studies used uniform or variable infill density [9,10]. Variable infill density allows achieving varying stiffness using a single type of material [9]. The most common type of infill pattern is gyroid because it is sufficiently strong and it does not overly complicate the texture and does not unreasonably prolong printing time.

For many researchers and manufacturers, the question of using different 3D printing technologies and various 3D printers for implementing a 3D project of orthopedic insoles is relevant. Most of the publications analyzed in the study recommend using FDM printing as one of the most cost-effective and environmentally friendly additive manufacturing technologies. Such 3D printers as Ender 3 Pro (Creality) [10], Anet Prusa I3 [9], Bodyarch X1 printer [13, 14] provide a satisfactory result with minimal costs.

There are some preliminary studies indicating that orthopedic insoles manufactured using additive technologies are effective in reducing pain sensations in the heel area [15, 16] and in altering the biomechanics of the lower limb [17, 18].

Printed orthopedic insoles can reduce fatigue during walking. It has been demonstrated that both subtractive and additive insoles are equally comfortable, and both improve comfort compared to wearing shoes without individual orthopedic insoles [7].

Conclusions

Therefore, the use of FDM printing today is an important tool in customizing footwear and manufacturing orthopedic footwear and its components. With this method, orthopedic insoles that are not inferior in characteristics to milled ones can be created, while also reducing and simplifying the production process and decreasing the amount of material waste, which is crucial for environmental conservation in our time.

Based on the analysis results, it can be concluded that companies involved in orthopedic footwear production should pay attention to the Creality printer, as it has been researched for printing both orthopedic insoles and shoe lasts. For insoles, the best flexible materials are Filaflex, VarioShore, and TPU. Printed insoles perform the same functions as those made using CNC milling, but they may be more efficient and environmentally friendly CNC milling.

The use of 3D technologies for manufacturing orthopedic insoles raises several unresolved issues. For instance, it is necessary to conduct research aimed at improving the hygiene properties of custom orthopedic insoles.

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