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3D printing technology for the prototyping of prosthesis construction and exoskeletons

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ABSTRACT:
The article discusses the manufacturing a limb prosthesis and exoskeleton using 3D printing technology. Hand prostheses available on the market and the direction of development in the construction of exoskeletons have been characterized. An example of a prosthesis made using incremental technology by the FFF/FDM method using a Zortrax M200 printer is presented. The mechanism of prosthesis work and elements of exoskeleton construction as well as the general characteristics of materials used are described. Attention was paid to the low cost of printing the components of the prototype structures.

KEYWORDS:
hand prosthesis; exoskeleton; 3D printing; mechanical prosthesis; biomedical engineering

1. Introduction

Upper limb prostheses and exoprostheses are an important and complex medical-scientific challenge requiring interdisciplinary cooperation in the fields of medical, material, IT, and electrotechnical knowledge as well as knowledge in the field of biotechnology. In medicine, the term prosthesis means an artificial complement to the biological part of the body [1]. Within the scope of orthopedics there are prostheses that completely replace a given part of the body, or so-called orthoses, which improve the function of a weak joint or are used to restore functional abilities. Since prehistory, the missing parts of the body have been replaced by complementary or even mechanical constructions. The oldest surviving prosthesis leg dates back to around 300 BC and was made of the following materials: wood, leather, bronze and iron [1]. The legendary Ruppin's hand comes from 1400 and is often described in the literature [1, 2], used by the German knight Goetz von Berlichinger, the fingers could be bent and blocked in the desired position. The design of prostheses has changed over the centuries depending on the technology available: material, mechanical, electronic and IT technology. Technological solutions still take on new functions and functional features. Artificial hand construction and its control system must assume the possibility of capturing various objects. Improvements in the design of prostheses are associated with the use and application of scientific achievements in order to increase their durability, reliability and effectiveness, assuming widespread availability [3]. Exoprostheses are these days an opportunity to quickly solve problems and to help in the functioning of a society whose average age increases year by year. Contemporary biomedical engineering solves the issue of combining and using for this purpose electronics, information technology and technological

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possibilities related to the use of materials, especially bioneutral materials, with the orientation of new compositions for filaments used in 3D printing technology [4, 5].

2. Analysis of the hand prosthesis structure made using 3D printing technology

The upper limb prosthesis was made for the E-Nable Polska project [6], using incremental technology. The design of the prosthesis was adapted from the E-Nable platform [7], which was adapted to the needs of the patient under the care of dr. Krzysztof Grandys.

The prosthesis was printed based on the experience described in the literature [5, 8-10]. A Zortrax M200 3D printer was used to print the model. Due to the complexity of the design and the need for thermal forming of the individual prosthesis components, a Noctuo type PET-G filament was selected for printing. This material, using relatively low temperatures, becomes plastic, allowing for precise thermoforming of the prosthesis elements, taking into account the anatomic-geometric parameters of the patient. Other elements not requiring thermal forming were printed from an ABS filament from the same company. The materials used allowed a rigid and durable construction to be achieved. During the printing of the elements, excessive cooling of the top layers of the model was noticed. This led to excessive shrinkage of the material, which caused peeling of the printed element from the printer's work table. It was advisable to print each element individually on the work table, as it would reduce the shrinkage, improve the adhesion of the printed element with the platform and improve the quality of the printed model.

The printout of all prosthesis elements yielded 30 man-hours of printing, with a total consumption of 290 g filaments. This is a relatively low financial outlay in relation to the industrial production of prostheses. An imitation-like element for a given design task during printing is shown in Figure 1 [11].

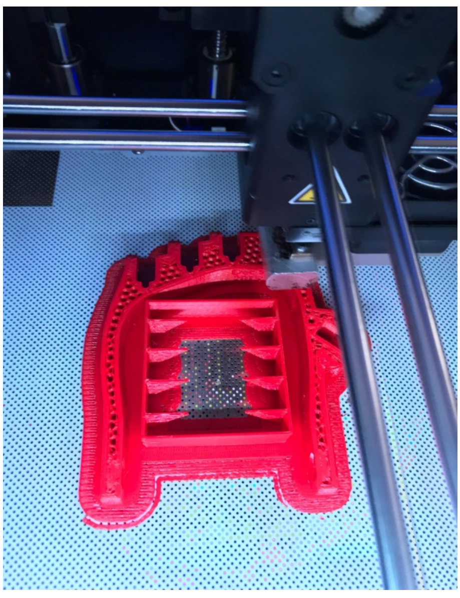

Fig. 1. Mink imitation during incremental printing [11]

An important element in any prosthesis is its movement mechanism. It is evident from the literature [1, 12-14] that for outer prostheses a tensile and electro-mechanical mechanism is used. For the implementation of the aforementioned prosthesis, a tensile mechanism was used, which is illustrated in Figure 2.

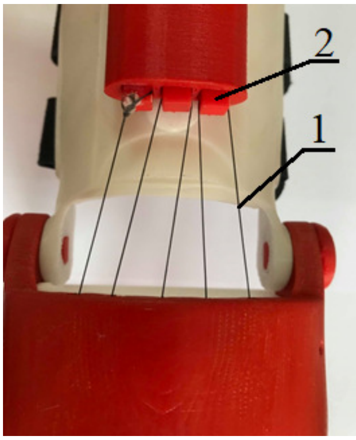

Fig. 2. Mechanism of prosthesis: 1 – tendon from high-strength fishing line; 2 – tensioning system of tendons [11]

In the given task, the tensile mechanism is one of the simplest mechanisms allowing the prosthesis to work, because it does not require complex structures. The tie rods were made of high-strength fishing line, which thanks to its mechanical properties does not stretch. This ensures the quality of work, reliability and durability of the prosthesis mechanism. The tendons were formed by channels modelled inside the metacarpal structure, which was why a flawless print and supports were so important. This was because a printout with supports would make it difficult to insert the tendons. The presented prosthesis has a series of lines running along each finger at the end of which there is a resistant attachment and, converging in the main part of the prosthesis, is a tension mechanism, where stresses are generated due to the work of the muscles of the upper hand joint. This in turn causes the fingers to bend. As a result, the prosthesis causes the hand to squeeze, and when the stress of the muscles is released, the fingers return to their normal position. The patient in practice using the prosthesis showed good finger grip and ease of movement.

In the construction, it was noticed that the tendons directly rest on the individual elements of the prosthesis, which may result in the rubbing of the components. It is advisable to hide the cables in casings, for example, thermocoating or teflon, to reduce damaging of the prosthesis components. An important modification that should be used in this type of process is the remodelling of the first finger - adding an additional joint, which will improve the bending of the thumb and thus allow you to model a hand close to a natural one.

A part of the metacarpal imitation with the fingers was set at an angle of –30° to the plane in order to reduce energy expenditure and to make it easier to control during operation of the prosthesis. As an additional improvement – to improve the grip of the prosthesis with the elements manipulated by it, a silicone finger coating was used to improve adhesion.

In the presented mechanical construction of the hand prosthesis, the following effects were obtained:

– the prosthesis has been adapted to the anthropometric conditions of the patient by mapping the shape of a healthy hand,
– simple construction guaranteed reliability of the work at a low price,
– a low total weight of the prosthesis was obtained at 320 g.

The prosthesis presented in Figure 3 using 3D printing technology for the patient in order to improve everyday functioning.

Target selection of materials and improvement of performance, e.g. application of protective or biologically inert coatings in vacuum technology on the components of the prosthesis is important in order to increase usability.

Fig. 3. Prosthesis made using 3D printing technology – view from outside [11]

The introduction of high-strength materials and coatings will increase the characteristics of the prostheses and improve the quality of life of patients. It is advisable that the constructions made by 3D printing technology are ultimately complemented with surface treatment from specially selected metallic, biologically inert coatings and silicone materials. As a result of analysing the knowledge in the field of prosthesis prototyping, it should be noted that advancement in this work remains largely bordering on the fields of medicine, engineering and materials sciences.

3. Design of exoskeleton prototypes using 3D printing technology

A device called an exoskeleton allows individuals to free stand and walk. Exoskeletons were created for people with motor dysfunctions of the lower limbs, and who have not lost the ability to control the device using EMG signals. Design assumptions that the exoskeleton should comply with include: the maximum possible lightweight construction (4 to 6 kg weight is estimated), battery supply with the possibility to regulate and use EMG sensors to control the device, and mobility using rapid prototyping methods to perform selected device elements on the condition of low cost of prototype implementation.

The device consists of two parts. Each of them is placed on the lower limb, the structure has one degree of freedom (knee joint). The knee joint consists of two elements cooperating with each other. The first element of the joint is connected by a multi-line with the main drive wheel of a toothed gear. The second element is both a joint and a mounting of the engine gear. A bearing gear was used, consisting of 3 large gears and 3 small gears. The gearing has 3 stages of reduction with ratios of 1: 4, 1: 5 and 1: 6. Silent slide bearings have also been used, which ensure quiet operation with a low friction coefficient. Limit switches have also been mounted on the joint, which limit the swing angle.

Elements were made of PLA type filaments or high-strength filaments using the rapid prototyping method on a 3D printer. This technology was used to make, among other parts, the knee joint and the attachment of the exoskeleton to the limb. The skeleton frame was made of a pair of aluminium angles. In order to attach the exoskeleton to the user's body, a set of adjustable length jaws and a harness at pelvic belt height were designed for the thigh and lower leg of the assisted limb.

The electronics together with the power system were placed in the lumbar belt clamp, which can be seen in Figure 5. Figure 4 shows the exoskeleton construction.

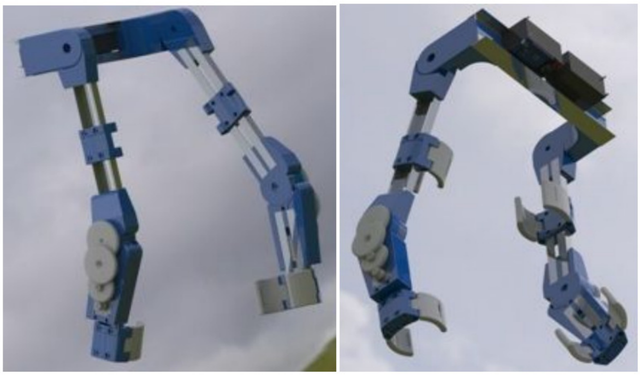

Fig. 4. TransforME exoskeleton design [15]

The aim of the project is to reduce the weight of the exoskeleton as much as possible. The elements of the electrical system of the device for supporting the walking process include: An Arduino Mega, potentiometer, battery, stepper motor, StepStick, EMG Advanced Technologies sensor, and limit switches. Figure 5 shows an exemplary electrical diagram of the device.

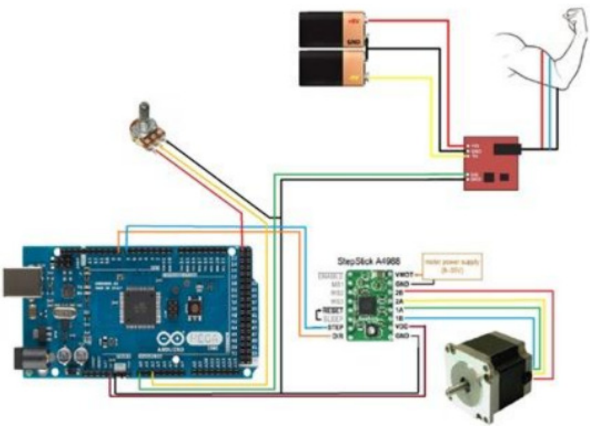

Fig. 5. Electrical scheme of the device [15]

4. Conclusions

It is advisable to refine the design of the prosthesis, especially the first finger – the thumb, which thanks to the introduced modification of the additional joint, allows the patient to perform natural movements.

The technology and materials used in the project means it is possible to make a prosthesis with low financial expenditure compared to industrial prosthesis constructions, and also to be manufactured by workers with lower specialist qualifications.

Practical monitoring of the exploitation and subsequent analysis of the work of tendons and operating elements of the prosthesis will be useful in order to improve the structure and verify the materials used in making it.

The applied tensile mechanism in the hand prosthesis allows the wearer to easily perform basic activities, similar to the work of a natural hand.

When designing exoskeletons, the basic construction aim is to minimize the mass by developing filament compositions and to develop high-strength joints and drive mechanisms with minimal friction. The latest battery solutions should be used and must be characterized by low weight and high capacity. It is expected on the basis of recent publications regarding batteries that in the coming years a product will appear in the form of a light-weight and very high-capacity battery.

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Technologia druku 3D do prototypowania konstrukcji protezy oraz egzoszkieletu

STRESZCZENIE:
Artykuł omawia problematykę wytworzenia protezy kończyny górnej oraz egzoszkieletu z użyciem technologii druku 3D. Scharakteryzowano dostępne na rynku rodzaje protez ręki oraz kierunek rozwoju w zakresie konstruowania egzoszkieletu. Przedstawiono przykład wykonania protezy przy użyciu technologii przyrostowej w metodzie FFF/FDM z wykorzystaniem drukarki Zortrax M200. Opisano mechanizm pracy protezy oraz elementy konstrukcji egzoszkieletu z ogólną charakterystyką materiałów wykorzystanych do ich wytworzenia. Zwrócono uwagę na niski koszt wydruku wszystkich składowych konstrukcji prototypowych.

SŁOWA KLUCZOWE:
proteza ręki; egzoszkielet; druk 3D; protezy mechaniczne; inżynieria biomedyczna