Numerical Analysis of the Lower Limb Prosthesis Subjected to Various Load Conditions

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Abstract

This article presents the simulation of a prosthetic socket with an auxetic structure under typical loading cases. The designed model of prosthetic socket is dedicated to patients who have undergone transfemoral amputation and consists of four elements, among which can be distinguished an inner lining, a shock absorbing element, component with a honeycomb re-entrant structure, which has a negative Poisson's ratio an outer shell. The prosthetic socket was analysed by means of the finite element method. The simulations were used to evaluate the strength of the design and to check whether it is possible to avoid a problem of changing the circumference of the patient's stump, thanks to the use of an auxetic structure in the socket.

Keywords: prosthetic socket, FEM analysis, auxetic, negative Poisson's ratio

1. Introduction

The possibility of human movement is a very important factor that determines the quality of his life. People after lower limb amputation, in turn, are doomed to problems with independent locomotion. The solution for them is properly matched prosthetic supplies. However, for the prosthesis to perfectly replace the lost limb and the amputee could return to daily activities without restrictions, the prosthesis must have a well-fitting socket to the patient's stump.

It happens so, because the socket as the only component of the prosthesis, has direct contact with the new organ in the form stump and is responsible for the comfort and possibility of using the whole prosthetic equipment. Additionally, it is an element that is not universal, but it is manufactured individually for each patient. Its purpose is to accurately reproduce the shape created during the amputation of the stump and create a tight connection between the human body and the rest of the prosthetic device. In addition to fixing the prosthesis, the role of the socket is to transfer loads. Hence, the fit of the socket to the stump determines the extent to which the patient is able to use other elements of the prosthesis, such as the knee joint or prosthetic foot. Consequently, the prosthetic socket is an important element that ensures the safety and comfort of the patient [1].

A prosthetic socket should neither cause abrasions and mechanical injuries to the human body, nor lead to the patient's stump falling out. Moreover, almost every patient after amputation suffers from a serious problem which is the tendency of the stump to change in volume. For this reason, it is very difficult to design the proper attachment of the lower limb prosthesis to the human body. These challenges can be met by auxetic materials and structures, which allow the prosthetic application to properly adjust to the patient's body while ensuring sufficient deformability under the influence of external factors [2-4]. Numerical simulations included in this work may form the basis for further experimental research including the dynamics of human movement equipped with a lower limb prosthesis. Research of this kind in relation to the physiology of movement was presented in the works [5,6].

2. Auxetic materials and structures

Auxetic materials and structures constitute together a group of auxetic metamaterials. Characterized by negative Poisson's ratio. Additionally, auxetic materials and structures, compared to traditional components, exhibit a few specific mechanical properties, such as high indentation, shear, and crack resistance. These types of metamaterials are also characterized by synclastic behavior and variable permeability and show high energy absorption, i.e. amortization of various shocks [7].

There is a wide variety of both materials and auxetic structures. Considering the anatomy of animals and humans, it was found that cat and cow skin, as well as bone and tendon elements, are also characterized by negative Poisson's ratio [8]. When the macro scale is analysed, it can be seen that in terms of different geometries of the unit elements and their mutual relationship, auxetics are usually classified into several types of structures. Thus, there are structures with negative angles, such as honeycombs re-entrant, chiral and anti-chiral, rotating figures structures, double arrowhead, missing rib, or kagome structures [9].

Both the unconventional properties that characterize auxetics, as well as the variety of their materials and structures, cause that they can be used to develop various applications of everyday life. In addition to robotics and the aviation industry, auxetics have also found their place in the broadly understood biomedical [8-12] applications and in sports [13] in the production of various protective equipment. Medical applications characterized by a negative Poisson's ratio include e.g.: vascular implants, various medical filters, and drug-releasing bandages. Currently, the use of auxetics in the design of mechanical lungs, executive elements of upper limb prostheses, prosthetic inserts, or products used in orthotics is at the research stage [14-18].

3. Model of the prosthetic socket with an auxetic structure

The designed model with an auxetic structure is the most important element of the lower limb prosthesis, which is the prosthetic socket. This solution concerns a prosthetic socket that is used by a person, which was subjected to amputation of the lower limb running at thigh level. Due to the behavior of auxetic structures, the design is a prosthetic solution, which would allow for a slight growth of the socket, e.g. along with the development of the teenager after lower limb amputation or when edema occurs the prosthetic stump. The models presented in this chapter and later analyses are to show, that auxetics in the prosthetic socket can ensure both its sure fit with the human body, how and they react to the change in volume, which is the result of for example growth or swelling of the stump.

The model of the prosthetic socket with elements with a negative Poisson's ratio consists of four parts. One of the most important elements of the designed structure is the inner lining, which is in direct contact with the patient's skin. This lining is responsible for the comfort of using the entire prosthetic socket. The dimensions of all design elements, including the inner lining, which is in direct contact with the patient's stump, have been matched to human anthropometric data contained in the literature [19]. Based on the average dimension of the thigh part of the human lower limb and assuming the fit of the designed prosthetic socket to a teenager, the inner padding is 250 mm long. In the proximal part, this element has an inner diameter of 140 mm. Due to the possibility of adapting the socket to the current external conditions and the dimensions of the stump, the second element of the model is a component with an auxetic structure on the macro scale. This part has a unit element in the form of a honeycomb re-entrant which is multiplied in a circular pattern and stretched out along the profiles in the shape of the socket tapering to the bottom. At the distal end of the prosthetic socket, there is an element adjusted in shape to both the inner funnel and the element with auxetic macrostructure, which is designed to cushion and compensate for the pressure of the stump on the socket. The last element of the proposed prosthetic solution in the form of an auxetic prosthetic socket is the outer shell. It is the part that brings together all the other elements of the analysed model.

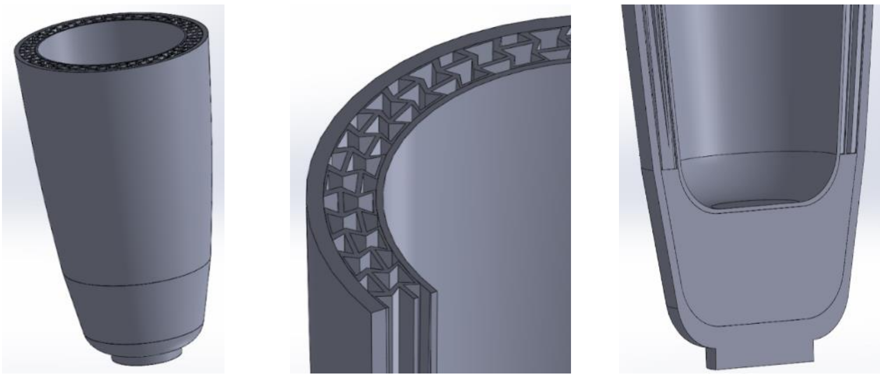

Figure 1. View of the prosthetic socket model with the auxetic structure.

The inner lining of the model, which is in direct contact with the patient's skin, is assumed to be made of thermoplastic polyurethane to ensure great comfort [20]. Polyurethane matching these characteristics was also used for the element which provide cushioning. As for the other two parts, which are part of the model, i.e. the outer shell and the honeycomb re-entrant macrostructure, in both cases, the assigned material was carbon fiber reinforced nylon. All materials used in simulation are isotropic and their properties are listed in Table 1.

Table 1. Properties of materials used in the socket model

Properties	Unit	TPU	Polyurethane	Nylon
Young's Modulus	N/mm^2	26	2409.9	8300
Density	kg/mm^3	1220	1260	1400
Poisson's Ratio	-	0.394	0.3897	0.28
Shear stress factor	N/mm^2	78.7	862.2	3200
Ultimate Tensile Strength	N/mm^2	39	40	139

In the numerical analysis, the model of the prosthetic socket was permanently fixed in its lower part. Such boundary condition reflects the place where the socket surface meets the rest of the prosthesis. In a further step, in order to analyse various situations related to the load of the auxetic prosthetic socket in various cases taken from e.g. from everyday life, for each analysis, external loads were applied separately and their values were determined. The solution of FEM problem is based on the Navier's equation of motion which could be written as:

$$\rho\frac{\partial^2\mathbf{u}}{\partial t^2} - \nabla\cdot\mathbf{S} = \mathbf{0}, \tag{1}$$

where ρ is the density, $\mathbf{u}$ is the vector of displacements and $\mathbf{S}$ is the stress tensor which, in this case, is linearly related to strain tensor. The mesh generated for the whole model exceeded 150000 elements and 800000 degrees of freedom.

4. Numerical results

Four cases of an endurance test of the auxetic prosthetic socket have been studied with the use of Solidworks FEM module. Two of the considered load analysis concerned the typical strength of the designed structure to a given load. The second of these analyses concerned the effect of the maximum load that occurs during the patient's gait with a stump socket adapted to the femoral amputation of the lower limb. The other two analyses performed were aimed at checking the auxetic effects that are characteristic of the structure with a negative Poisson's ratio, that contained in the prosthetic socket. One of them was aimed to show what happens to the socket after the occurrence of peripheral edema thigh. The second example was supposed to present, what will happen at the external adjustment of the circumference of the hopper after the swelling patient's stump has stopped.

In the first conducted research, an analysis related to the effect of the stump on the entire inner surface of the inner lining of the socket for the patient leaning on a lower limb prosthesis with all your body weight. The patient characteristics used in the simulation of the prosthetic socket is assumed to be an adolescent teenager with a body weight of 70 kg. Due to the static nature of the case, the assumed force acting on the analysed structure in this study takes a value of 700 N. The results of this simulation presented below show the von Mises stress distribution, displacement, and deformations in the tested model. The highest reduced stress that occurs in the object in this case is equal to 1.695 MPa and is located in the lower part of the socket. At the proximal end of the model under consideration only small stresses running along the axis of the funnel can be seen, and their highest value is around 0.5 MPa. The exact place where one of the greatest stresses is located at the junction of the inner lining of the prosthetic socket and the parts with auxetic macrostructure in their fragments lying closer to the top of the entire socket. Significantly high values, compared to the rest of the model, are also found at the rounding in the flexible liner and in the lower part of the auxetic structure (see Fig. 2). Outer shell of the modelled prosthetic socket and its component, which is to act as a shock absorber, are in turn the elements on which in the considered load system, there are all zero or close to zero stress values. Considering the limit of strength and plasticity for all three materials used in the model, it can be concluded that the stress values present in this analysis do not exceed these permissible values. By analysing the resulting displacement distribution it can be observed that their maximum value is around 3.5 mm. This is a relatively large value, but it only applies to a small part of the inner lining of the socket. The largest displacement can therefore be observed centrally, at the very end of the recess through which the orthopedic equipment contacts the patient's stump. In all other elements and places on the model, the displacements are negligible, as they correspond to a value below 0.5 mm. The greatest values of deformations, which occur when the total internal surface of the funnel is loaded with a force of 700 N, are only about 1.42mm (see Fig. 3). As in the case of displacements, the only element of the prosthetic socket on which all the deformations are concentrated is its internal, very flexible lining. Also in this case the largest deformations are located in the center of its distal part, which is in contact with element with the characteristics of a shock absorber. Additionally, in this distribution, several deformations can be observed that occur on the circumference of the inside of the funnel and are stretched along its length. However, these strain values do not exceed 0.005 (see Fig. 3).

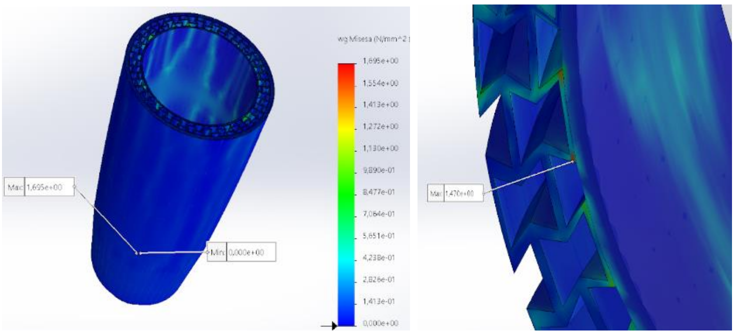

Figure 2. View of the von Mises stress distribution when standing on one leg.

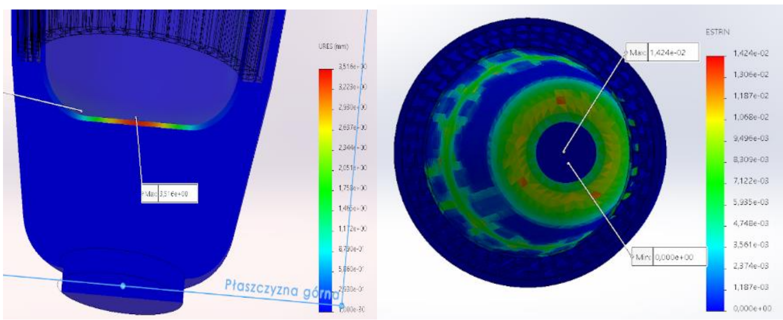

Figure 3. View of the simulation results for the patient standing on one leg: displacement distribution on the left and deformation distribution on the right

The second endurance study is based on the analysis of the pressures that occur when the patient is walking. This has been done in a simplified case of quasistatic analysis of the impact force that occur during the patient's gait cycle with a prosthetic lower limb. By analysing the individual phases of gait and considering the forces that occur in it, it can be stated that that their maximum value is usually in the middle of the patient's gait cycle. According to the literature data, the maximum value of muscle strength during movement is on average, about 1.4 times the patient's body weight [21]. This maximum value is related primarily to amortization when the foot hits the ground during the overload phase. When considering a 70 kg patient, the force that allows to show the pressure that is exerted on the socket while walking with the lower limb will take a value equal to 980N. Just like it did in the first case, also in this case the force is evenly distributed in the form of the pressure acting over the entire inner surface of the hopper liner. Such load allows to state that the maximum stresses when walking with the prosthesis may reach a value slightly exceeding 2 MPa. It can therefore be concluded that this value is still much lower than the strength of the materials used in the designed model. Due to the analogous nature of the loads, the locations of the highest stress values are in a similar location as it was in the first of the analyses (see Fig. 4A). Mentioned maximum stress value is therefore located at the bottom of the socket (see Fig. 4B) and the displacement, does not exceed 4.2 mm. Despite the fairly large value of this parameter it should be noted that it concerns a small fragment of the top of the inner lining, which is made of a very flexible material. In other components included in the prosthetic socket maximum displacements does not exceed 1 mm on the inner circumference of the funnel. In the results of the deformation distribution obtained in the analysis, one can also see an analogy to those obtained when standing on one leg. In this case, however, there is a slightly higher value of the maximum displacement, which is located in the center of the distal part of the lining. To be precise, it is the very top of the cavity which forms the nest of the stump. Apart from these maximum displacements one can also observe little deformations on the peripheral inner surface of the model, but their order of magnitude is negligible (see Fig. 4C).

Another analysis that was considered for the modelled prosthetic socket was the situation of the force acting from the stump on the inner circumferential surface of the elastic lining of the model. It is a load model that has the character of stretching the walls of the modelled prosthetic socket. Due to the load acting only on the circumferential surface, this situation may reflect a circumferential swelling of the e stump patient after amputation. In the case under consideration, the load indirectly affects the macrostructure contained in the socket, which is characterized by the properties typical of auxetics. The user of the prosthesis weighs 70 kg, therefore it can be concluded that the force acting on the socket from the entire human body is about 700N. However, it can be stated that if we analyse the swelling on the stump after amputation, the force acting and stretching its structure is much lower. For this reason, assuming a force of 700 N in this case already has a significant safety factor. The lateral surfaces of the inner lining of the designed auxetic prosthetic socket at the point of contact with the auxetic structure, which is located around the perimeter of the socket, were taken into account as the places where the force specified above acts directly. The first of the obtained results of this simulation show the stresses that occur in the prosthetic socket, amounting to a maximum of 1.578 MPa (see Fig. 5A). It can be concluded that this is a value that is negligible compared to the yield point of the materials used. The maximum stresses occurring in this consideration are mainly found in the macrostructure element characterized by a negative Poisson's ratio. Their peak value is in the upper part of the honeycomb re-entrant structures in cut-outs that lie closer to the inside of the hopper. In addition, slight stresses can also be observed in the circumferential interior of the lining to which the external load assumed in the analysis was applied.

A) B) C)

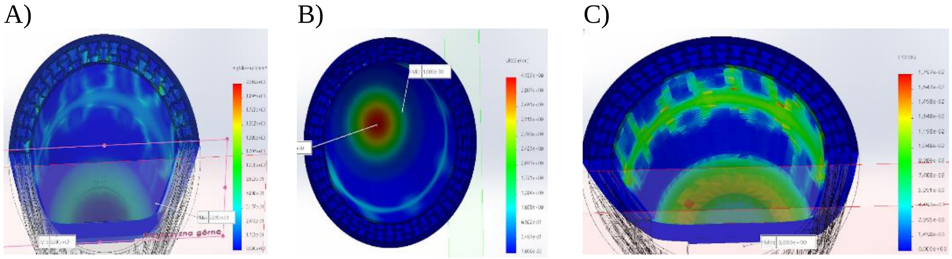

Figure 4. View of the simulation results of the patient's gait with the prosthesis: A) stresses; B) displacement; C) deformation.

A) B) C)

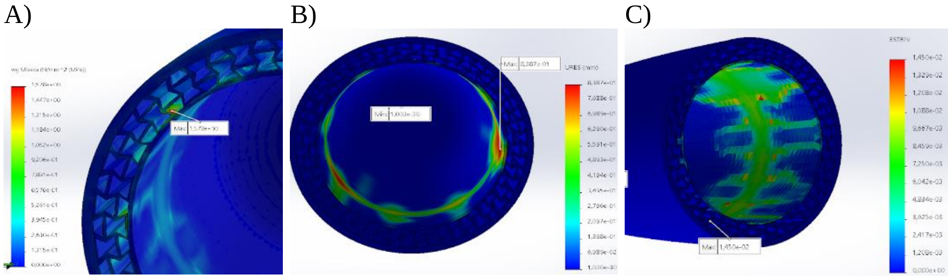

Figure 5. View of the results obtained when analyzing the situation with the occurrence of swelling of the patient's stump: A) stresses; B) displacement; C) deformation.

The second analysis shows what happens with the prosthetic socket during the occurrence of edema, when the maximum displacements value is about 0.8 mm (see Fig. 5B). This type of displacement appears only in small fragments of the upper part of the inner lining of the funnel, which is the element that is mainly subject to displacement in this case. The strain distribution which values are also relatively small are presented in Fig. 5C. The maximum deformations, which are the only deformations occurring on the inner lining, are found in its upper part. Only a slight, axial spread of deformations along the funnel is visible. All these deformations are insignificant because their greatest value is 0.015.

A) B)

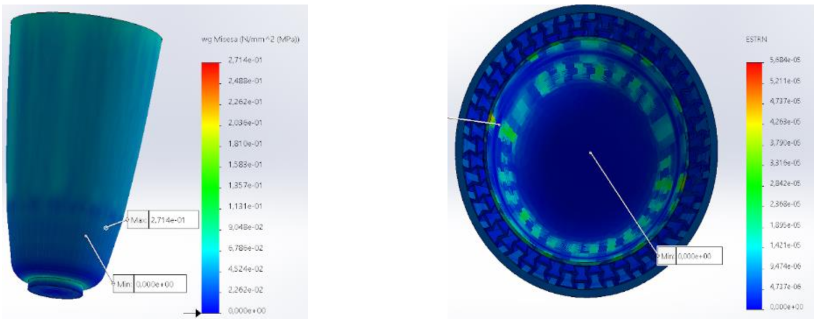

Figure 6. View of the test results, that showing the external two-handed compression of the socket: A) stresses; B) deformation.

The last considered case of the socket strength test is loading the model with a force that acts from the outside on the surface of the outer shell. This is a situation that may occur the patient, after inserting the stump into a slightly loose prosthetic socket, tries to press it against his body. Due to the fact that in this case the force comes from the hands of the patient, for this purpose, according to the literature data, the value of the applied load that acts on the outer peripheral surface of the socket was 500 N. It is related to that the average force from one patient's hand is equal to 250 N [22]. From the stress distribution obtained in this case, it can be read that the maximum value of the occurring stress is approximately 0.27MPa (see Fig. 7). Due to the fact that the load assumed in the study was evenly distributed on the outer surface of the socket model, in the place where the outer shell directly contacts the auxetic structure, most of the stresses occur on these two components of the funnel. The exact location of the maximum stresses is the boundary between the two components, especially at the bottom of this contact. The displacements as well as its maximum value are very small so it can is negligible, as it assumes a value of the order of thousandths of a millimetre. These values are at the top of the socket and apply to both the outer shell and the auxetic structure as well as the inner lining of the model. It can be concluded that the influence of an external force on the auxetic structure may directly lead to a slight reduction of the inner circumference of the funnel, which will allow it to be adapted to the frequently changing volume of the patient's stump. The last of the parameters that define the results of the analysis is the deformation, the maximum value is a very small. These deformations mainly concern the inner lining of the prosthetic socket and its contact with the auxetic structure. The highest loads are located in places on the elastic lining, which have a cut-out in their vicinity, belonging to the auxetic honeycomb re-entrant structure.

A) B)

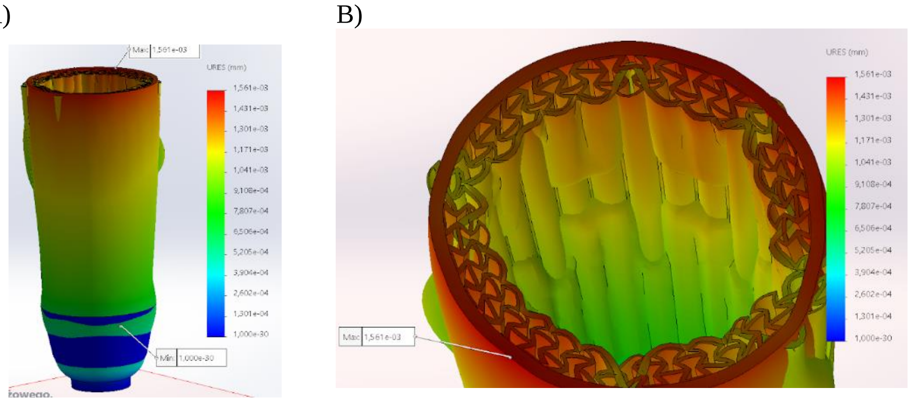

Figure 7. An exaggerated view of the displacement distribution with the effect of narrowing the circumference of the prosthetic socket.

Table 2 above presents the key results of all four strength analysis of the prosthetic socket. The results obtained and presented in this paper concern the loads of the lower limb prosthesis. In this study, the dynamic real forces were modelled as quasi-static interactions. Further research on strictly dynamic properties is planned.

Table 2. Strength simulation results of a prosthetic socket

Analysed situation	Maximum von Mises stresses [N/mm^2]	Maximum displacements [mm]	Maximum strain [-]
Standing on an amputated limb	1.695	3.516	0.0142
Occurrence of peripheral swelling of the stump	1.578	0.8387	0.0145
Pressure while walking	2.069	4.153	0.018
Reducing the circumference of the stump	0.2714	0.016	0.00006

5. Conclusions

During the direct contact between the stump and the socket of the prosthetic socket, there are numerous changes in the circumference or shape of the stump, which leads, for example, to the loosening all prosthetic equipment. For this purpose, in this article, was performed modelling and strength analysis of the prosthetic socket, which constitutes the application of materials and structures showing a negative Poisson's ratio in medicine. This is to increase the comfort and safety of the use of such a thigh socket for an adolescent and intensively developing patient after the removal of the lower limb.

Consisting of four interconnected independent components, the prosthetic socket model was subjected to four different load cases. The simulations carried out in this way allowed to check the stresses, displacements and deformations of the model under consideration, in a variety of external conditions to which it may be this exposed. Based on the results of the strength tests carried out, it can be concluded that the modelled prosthetic socket fulfils its assumed functions. In any situation, there were negligible values of the maximum reduced stresses, therefore it can be concluded that they do not exceed strength of the materials used in it in the form of polyurethanes and nylon. This type of prosthetic socket does not pose a threat to the safety of its user, because the presented situations, both while standing and while walking, do not constitute a reason for any cracks or damage to the modelled prosthetic equipment. Most of the deformations and displacements that had their maximum values were located within the inner lining of the project under consideration. It therefore represents a premise to be stated, that mentioned inner element is flexible enough to be comfortable for the patient and be able to adapt to the current volume and shape of its stump. Additionally, based on the conducted analyses, it can be stated that the shock-absorbing element used in the project, due to the fact that in any test there was no concentration of stresses, displacements or deformations in it, fulfils its intended tasks.

Considering showing of auxetic effects, it can be stated that the designed prosthetic socket, due to the honeycomb re-entrant structure contained in its construction, shows partially the desired properties changes in the internal circumference of the funnel with the action of a specific external load. Based on the research, it can be shown that the burden on the peripheral surface of the inside lining of the model allows for a slight radial compression of the auxetic structure, which in turn leads to a slight increased circumference of the thigh hopper. The second situation in the study of the auxetic structure showed that without a major problem by action simultaneously with both hands on the outer surface of the funnel, can lead to slight reduction in the circumference of the stump seat in the socket. Summarizing, all these conclusions allow us to state that the designed prosthetic socket with an auxetic structure states both safe and comfortable and minimally adjusting to the current circumference of the stump, a solution for fixing the lower limb thigh prosthesis to the patient's body.

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