TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 67, Issue Special II, April, 2024

DESIGN AND ANALYSIS OF 3D MODELED SOFT PNEUMATIC ACTUATORS FOR USE IN HAND REHABILITATION DEVICES

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Abstract: *A challenge faced by soft robotics is the development of an actuator able to reproduce the specific motions conducted by the human anatomy. Starting from a thorough analysis of human hand anatomy and the motions that can be generated by it, the paper presents the successive stages of the design of a pneumatic actuator that mimics the motions of the fingers, manufactured by 3D printing. The thus obtained product will be used for hand rehabilitation device deploying continuous passive motion. The designed geometrical models were subject to a series of linear static and nonlinear finite element analyses aimed at predicting their behaviour. From several proposed constructive solutions eventually, the variant was selected that best meets the requirements of imposed motions and developed forces.*

Key words: *Soft robotics, finite element, finger actuator, deformation, pneumatic actuator*

1. INTRODUCTION

Stroke is a condition with a maximum incidence of 25‰ of the world's population, with a maximum recurrence risk of 40%. Thus, approximately 14 million such cases are registered annually [1]. Of these, depending on age or other comorbidities, up to 93% of affected people end up suffering from hemiparesis. Hemiparesis occurs opposite to the cerebral hemisphere where the stroke occurs involving partial or total loss of limb mobility on the affected side [2].

According to literature, the corner stone of rehabilitation is the controlled movement of the affected area according to the indications of a therapist, in his presence or individually by the patient. Movement of the affected area accelerates healing by restoring the neural networks of the brain, avoiding atrophy of the affected muscles and increasing the degree of mobility of the affected joints [3].

Superior results have been observed by supplementing conventional rehabilitation techniques with the use of specialized rehabilitation robots, particularly soft robots. [4,5]. Thus, the design of a device to perform passive rehabilitation movements is of particular interest to hemiparetic people and therapists [6].

The starting point in the design of a hand rehabilitation device is the understanding of the anatomy of the upper limb, starting with its skeleton, presented in fig. 1 [7].

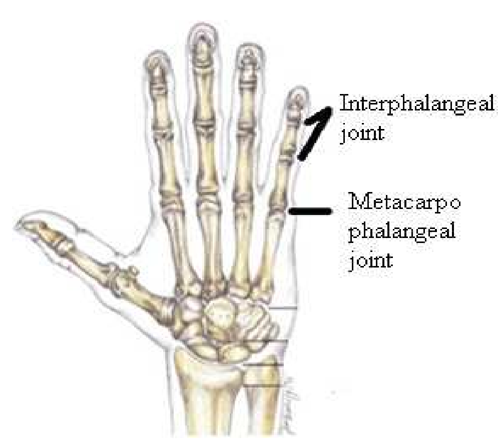

Fig.1. The skeleton of the human hand, the bones that structure it and the joints that they form

The structure of the hand includes three categories of bone segments of different lengths. The length of these segments differs according to age, gender and individual characteristics; therefore, in what follows, a statistical analysis of their sizes and proportions will be considered.

Previous studies have shown that the full flexion movement of the fingers (clenching the fist) follows the shape of a spiral that can be defined by the Fibonacci sequence [8].

$$x_n = x_{n-1} + x_{n-2}. \tag{1}$$

This equation has been confirmed by a team of researchers [9], who state that the interarticular distances between the distal, intermediate, proximal, and metacarpal phalanges abide to a Fibonacci sequence of the form 18; 26; 44; 70 in the case of a middle finger. The series of interarticular distances obtained is presented in fig. 2, which will be considered in the design of the soft robotic hand rehabilitation system.

Starting from a thorough analysis of human hand anatomy and the motions that can be generated by it, the paper presents the successive stages of the design of a pneumatic actuator that mimics the motions of the fingers, manufactured by 3D printing.

Using a CAD (computer aided design) program graphical representations of the desired object can be created. These representations can be used as models in performing analysis to predict the behaviour of the device in operation. Based on the results obtained, the geometry of the model can be easily modified enabling a trial by error optimization process. This process can be repeated until the expected result is obtained. Thus, the use of CAD processes offers a great advantage by reducing the time needed to design and test prototypes, also contributing to reducing the cost of product development [10,11].

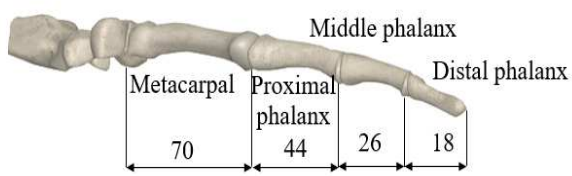

Fig.2. The distance between the joint of the hand in the case of the middle finger; the length of the distal phalanx is 18 mm[12]

2. METHODS

The design of the hand rehabilitation device was realized starting from its main functional element, namely the soft pneumatic actuator that mimics the movement of the finger. Once such a theoretically functional actuator has been designed for a finger, it can be scaled to the size of the other fingers allowing the final hand movement rehabilitation device to be assembled. This aspect requires a parametric design where every aspect of the geometry can be edited. For this reason, Autodesk Inventor Professional Student Version was used for the design.

The analysis of the performed models was carried out with the help of finite elements (FEM), using the aforementioned software in combination with the Autodesk Inventor Nastran Student Version extension. This extension is a solver that allows running linear and non-linear FEM analyses of higher complexity compared to the analysis module in Inventor.

Considering the future manufacturing of the designed model, a material suitable for the application was designated. NinjaFlex is a silicone-based polymer material developed specifically for 3D printing, marketed as filament rolls. The manufacturer recommends the optimal parameters for use in the manufacturing process, which are detailed in the table 1[13].

Table 1

The optimal 3D printing parameters using NinjaFlex.

Extruder temperature (°C)	222-235
Platform temperature (°C)	40
Print speed; top and bottom layer (mm/s)	10-20
Print speed; infill and shell (mm/s)	15-33
Spool cost ($) [wire diameter (mm); spool weight (kg)]	85 [1,75; 1]

The material presents a set of mechanical properties suitable for this purpose. These characteristics can be studied in table 2. The material input data for the analysis was taken from said table. An analysis of the parameters highlighted in table 2 [14] indicates an elastic behaviour of the material, therefore it was assumed that the value of the Poisson's ratio (coefficient) used during the research is ν = 0.49.

Table 2

Mechanichal parameters of NinjaFlex.

Youngs Modulus (MPa)	12
Ultimate tensile strength (MPa)	26
Yield strength (MPa)	4
Poisson ratio*	0,49
Density (g/cm^3)	1,19

The FEM analysis applied during the research started from the theory of negligible deformation[14], defined by the relationship:

$$\sin\alpha \cong \alpha \qquad (2)$$

here α represents the angle of deformation of the soft actuator. This relation applies only if α ≤ 10°. Therefore, the situation requires the use of a non-linear static FEM analysis, in which the deformation of the model is calculated in a predetermined number of increments (N), and at each increment the previously obtained deformation is inputted as the starting point for the new result. This process is graphically represented in fig. 3 was agreed upon to be performed until N=50.

Nonlinear static analysis also considers the direction of force application.
Non-linear static analysis also considers the direction of force application. At bends greater than 45°, the developers of the program state that non-linear analysis becomes necessary due to changes in the geometry of the model, thus considering not only the magnitude of the applied force, but also the direction in which it is applied. This phenomenon is detailed in fig. 4 [15].

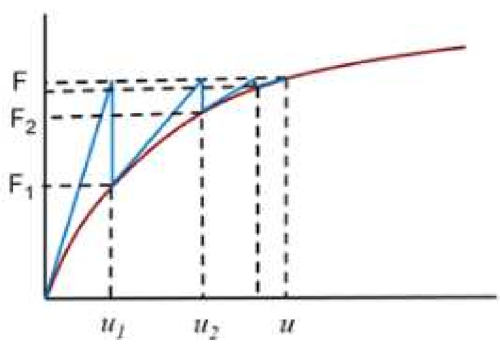

Fig.3. Application of the stress force in the nonlinear static analysis; F represents the force increment; u - deformation increment

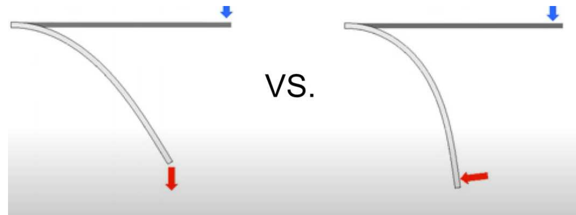

Fig.4. The difference between force application in the case of linear static analysis vs. non-linear statics

In the case of nonlinear analysis, the force is applied perpendicular to the model as specified, and after deformation it remains perpendicular to the model, even if its direction in the Cartesian frame of reference has changed. In the case of linear analysis, the direction of application is the same, however with the deformation, the force is no longer applied perpendicular to the model, preserving its orientation direction in the Cartesian system. Therefore, in the case of static analysis, a component of the force will stress the material in an undesired direction and the result will be an erroneous one.

3. RESULTS

The design process is based on an initial model, developed based on previous scientific documentation. This pneumatic actuator (soft finger) model was sketched, 3D designed, then analysed using the non-linear static FEM method. The sketch of the initial model can be seen in fig. 5. A tubular construction can be observed, the pneumatic actuator having a complex shape on the outside obtained by stringing together several crenelations. Their role is to direct and distribute the internal air pressure so that the resulting deformation mimics the anatomically correct movement of a human finger.

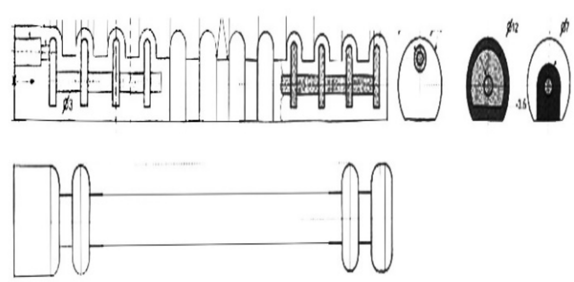

Fig.5. Bi-dimensional sketch of the initial pneumatic actuator model

Due to the short length of the actuator (11.5 cm) it was agreed that the internal pressure is evenly distributed over the entire surface of the actuator.

Special consideration was given to the Fibonacci sequence when developing the sketch. The total length of the actuator, 115 mm, approaches the sequence 12-20-32-52, the sum of which is 116 mm. Therefore, there is a deviation of 0.8% from the ideal ratio, which is considered acceptable.

To perform the FEM analysis, a network of 15662 nodes and 8202 elements was created, and in the representation of the results, the original shape of the actuator was preserved, i.e., the one before the pressure was applied. Also shown in each of the plots is a legend describing the colour scale used and the points where minimum and maximum material stress is observed. This stress is calculated with the von Mises criterion and represents the stress that develops inside the material due to pressurization. This value must not exceed 26 MPa, which is the ultimate tensile strength of the NinjaFlex material. If this value were exceeded, the actuator would fail. The maximum pressure applied to the model was 0.6 MPa.

The predicted behaviour of the actuator is presented, at different increments of the request, in fig. 6. The model in question behaves as expected, achieving a bend of about 180°. Also, bending is done gradually and constantly along the entire length of the actuator.

A graphic representation of the existing relationship between the load scale factor and the deformation obtained is presented in fig. 7. An in-depth analysis reveals that the relationship between the two quantities is not linear in nature. Therefore, as the model deforms, each calculated force increment has a different impact on the deformation. This phenomenon shows that nonlinear analysis is justified for determining the behaviour of the proposed models. If the model had behaved the same throughout the increments, then the relationship between the two quantities would have been linear and the use of a non-linear analysis would not have been justified.

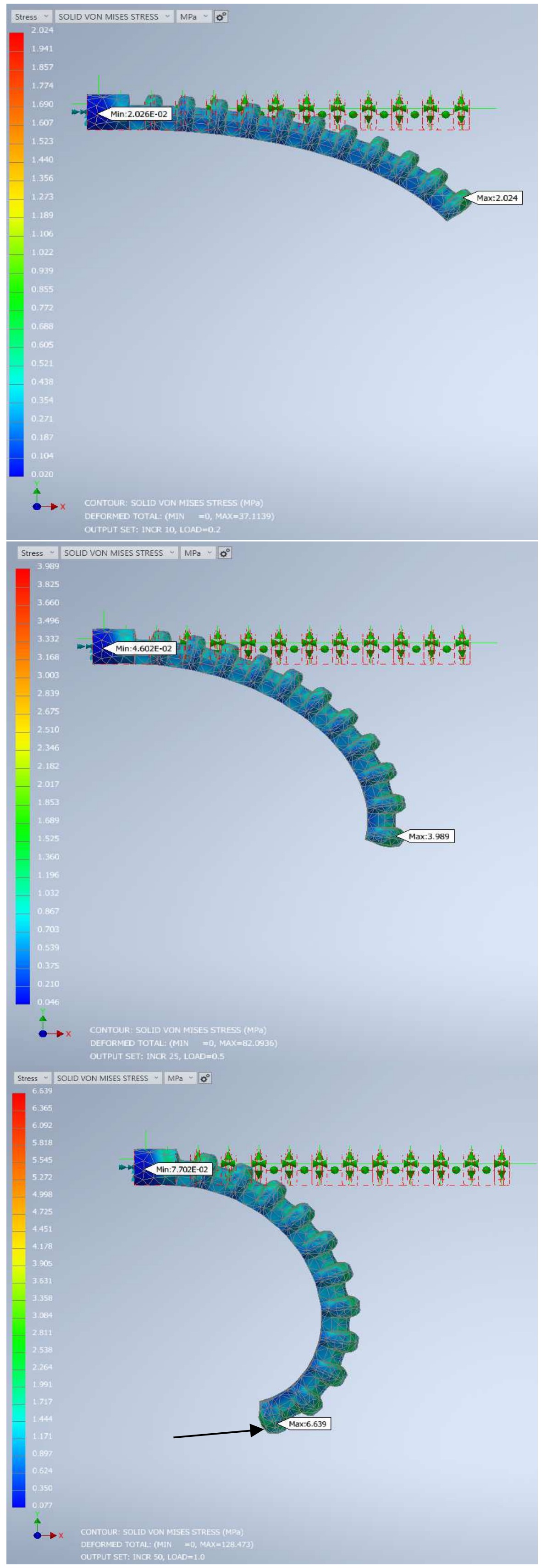

Fig.6. Predicted behaviour of initial pneumatic actuator; black arrow indicates maximum displacement point

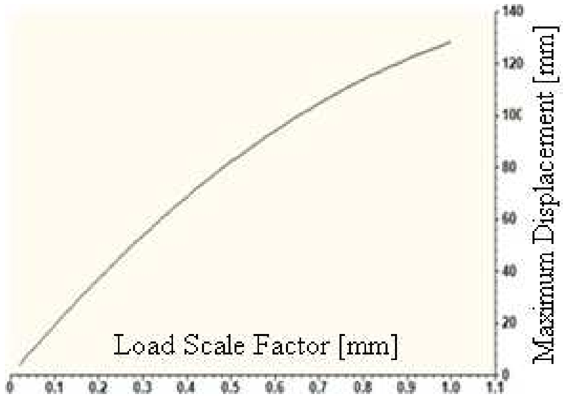

Fig.7. Load scale factor vs maximum displacement obtained

The maximum displacement referred to in fig. 6, marked by an arrow, in the amount of 128.473 mm, is determined using the equation:

$$DIS_{max}(A) = \sqrt{x_A^2 + y_A^2 + z_A^2} \qquad (3)$$

where x_A^2, y_A^2, z_A^2 represent the squares of the displacements on each axis, of the extreme point of the actuator. It represents the square root of the sum of the squares of the displacements recorded on each axis. In this case, the respective point has moved following the stress on each (x,y,z) axis by a distance of (-82.57;-102.9;-6.334) mm from its initial position.

Another model analysed maintains the number of crenelations constant, while presenting two particularities presented in fig.8.

The first of them is the thickening of the walls of the distal crenelation, and the second is the shortening of the distance between the last two crenelations. Their role is to achieve a lower stress in the material, in the hope of extending the life at the time of deployment and repeated use. The FEM analysis performed allowed obtaining a series of representations describing the behaviour of the actuator in use described in fig. 9. In this case, the pressure was applied uniformly on the inner surface of the model in 50 increments. The maximum applied pressure was 0.6 MPa. To perform the FEM analysis, a network of 12610 nodes and 6438 elements was generated.

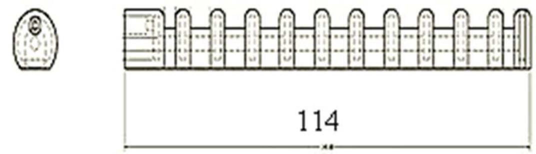

Fig.8. Bidimensional sketch of the M2 pneumatic actuator

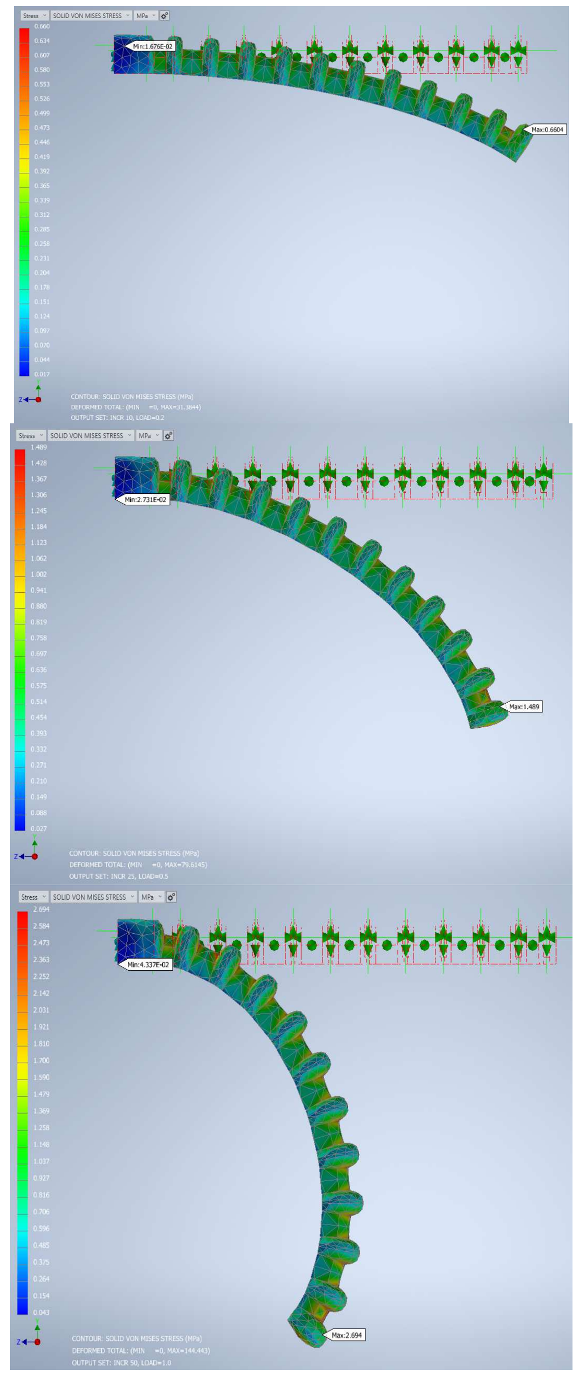

Fig.9. Predicted behaviour of the M2 pneumatic actuator

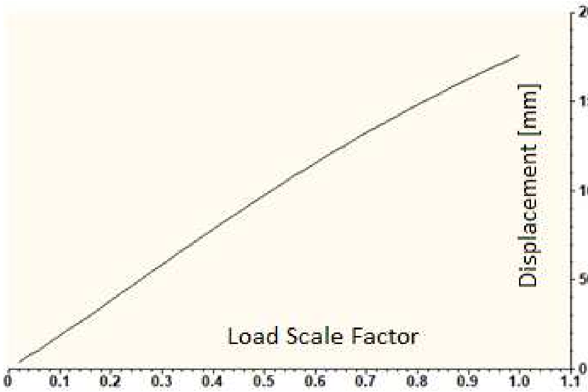

Fig.10. Load scale factor vs maximum displacement obtained

4. OPTIMIZATION

Following the previously observed results, the decision was made to take new approach, with the aim of obtaining a more efficient actuator. Thus, a series of principles were convened to allow easier iteration between models, hence facilitate the optimization process. From the analysis of the previous models, it emerged that a variation of the thickness of the air chamber walls does not provide higher performance of the actuator. Therefore, the new actuators will have a constant wall thickness of the air chamber, which makes the design process easier. In this way, one will start from a full cylinder, from which crenelations of different sizes will be extracted (fig. 11).

The reason for the cylindrical shape is to increase the air contact surface at the bottom of the actuator in hope of obtaining a uniform bend within the defined pressure range (1 - 6 MPa) while decreasing the number of sharp angles which can become stress concentrators. Hopefully this will also increase the operating safety of the actuator and its lifespan.

The next step is to define the air circuit inside the actuator.

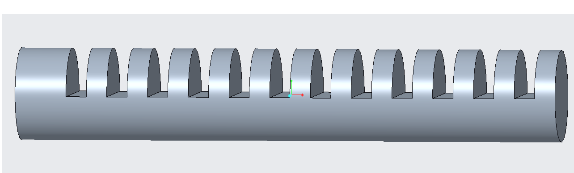

Fig.11. The second step in the new design approach

Another design program was used in the optimization process. This is Creo Direct 7.0, similar to Autodesk Inventor used in previous models. This decision was made because files in Creo Direct can also be imported into Inventor. Thus, the results obtained from the analysis with each of the two programs can be compared.

The pressure was uniformly applied to the inner surface of the model. In the case of Creo Direct, the number of increments in which the pressure is applied is no longer defined, this is done automatically by the software when it is static non-linear analysis is selected and large deformations are expected ($\sin(\alpha) \approx \alpha$ does not apply). The applied pressure was 0.6 MPa, the maximum the compressor can provide.

Under these conditions, the new model presents the most appropriate bending. It is uniform, with a maximum amplitude of almost 360°, and the maximum deformation obtained is 123 mm. It seems that these performances are influenced by a specific behaviour of this actuator. The inner part of the inter-crenelated space deforms semi circularly due to the pressurization. This semicircle in turn pushes into the adjacent semicircle resulting in an increased bending movement.

The problem with this model is that in real life it would not withstand pressurization to 0.6 MPa. The maximum stress of the material after pressurization is 40.11 MPa, and the ultimate strength of the material is 26 MPa. Therefore, the analysis must be repeated to see if a lower pressure achieves the desired bending motion without overstressing the actuator beyond its endurance limit.

Pressurization to 0.3 MPa was attempted to reduce the stress exerted on the material. The results can be seen in fig. 12. In this case, the deformation is uniform, with a maximum amplitude of nearly 180°.

The maximum deformation achieved is 136 mm, the largest yet. The reason why this value is higher than for pressurizing at 0.6 MPa is because the strain on the Oy axis is smaller, influencing the sum of squares.

Due to the satisfactory results of the new model, it was decided that this actuator lends itself to use in the prototyping stage of the hand rehabilitation device.

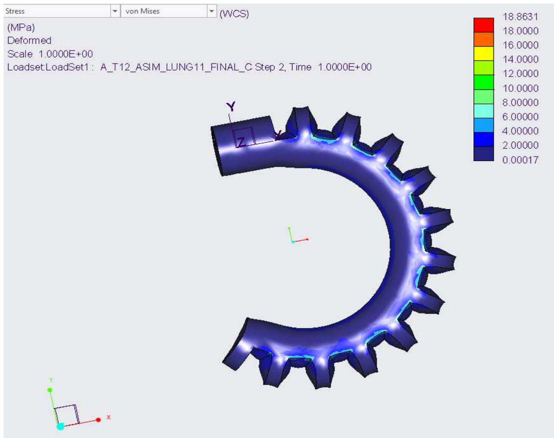

Fig.12. Predicted behaviour of the pneumatic actuator

Therefore, the question was raised about the technical solution for attaching the actuator to the glove that will be worn by the user. To this end a series of flanges have been designed which will be fixed to the glove either by a strap or by sewing or using an adhesive, this to be determined later.

The flanges are an integral part of the actuator, they will be 3D printed from the same material as the rest of the device. Thus, it is desired that the flanges do not influence the behaviour of the actuator. An analysis of the flanged model was deemed necessary to find out if the flanges somehow influence the behaviour of the actuator. The applied pressure is 0.4 MPa. All other parameters remained constant, and the result can be seen in fig. 13.

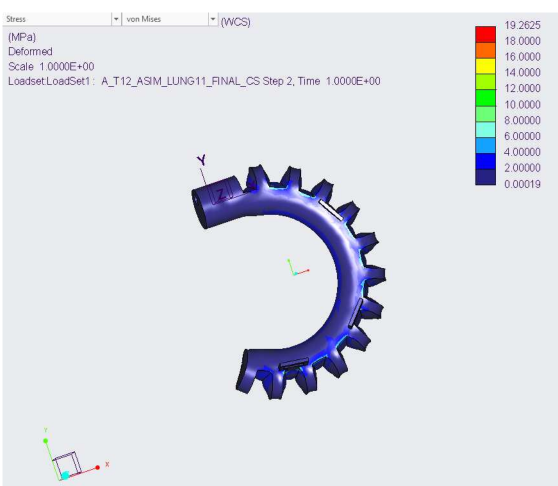

Fig.13. Predicted behaviour of the pneumatic actuator with flanges. Applied pressure is 0,4 MPa

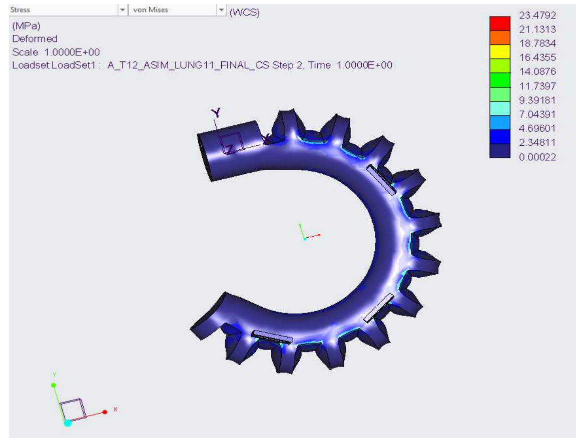

Fig.14. Predicted behaviour of the pneumatic actuator with build-in flanges; Applied pressure is 0.45MPa

It emerged that the clamping flanges have a stiffening effect on the actuator. The deformation is less, and the maximum material stress was 19.26 MPa.

Another analysis was carried out at a pressure of 0.45 MPa, the result being shown in fig. 14. The deformation of 137 mm is more than satisfactory, at an angle of 180°, and the maximum material stress is 23.5 MPa, which is about 10% below the permissible limit. Therefore, this model is the best performing result from this study.

5. CONCLUSIONS

The aim of this paper was to present the design process of a pneumatically actuated actuator, manufactured by 3D printing capable of imitating the movements of the hand fingers. Thus, a series of models were presented, analysed, and optimized. Following this process, it was possible to obtain an optimized model that, in the future, can be 3D printed and integrated into the final rehabilitation device.

The optimization decisions considered the nature of the problem, the end use of the device, and the knowledge gathered in the field of hand anatomy and techniques for rehabilitating mobility lost as a result of hemiparesis.

The FEM analysis run on the models was carefully studied to ensure accuracy. It has also been thoroughly checked whether the type of FEM analysis run can describe the expected behaviour of the studied models. Great care has been taken with the input and output parameters to ensure smooth, error-free running of the analysis.

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Proiectarea și analizarea 3D a unor modele de actuator pneumatic soft utilizat pentru realizarea unui dispozitiv de reabilitare a mișcărilor mâinii

O provocare întâlnită în domeniul roboticii soft este dezvoltarea unui actuator care poate reproduce mișcările specifice anatomiei umane. Pornindu-se de la cunoașterea în profunzime a anatomiei mâinii și a mișcărilor pe care aceasta le poate executa, această lucrare prezintă etapele proiectării și realizării unui actuator acționat pneumatic, realizat prin tipărire 3D și care imită mișcările degetelor mâinii. Produsul astfel obținut urmează să fie folosit pentru realizarea unui dispozitiv de reabilitare a mobilității mâinii prin mișcare continuă pasivă. Asupra modelelor geometrice proiectate au fost făcute mai multe analize cu elemente finite liniare statice și neliniare, scopul fiind acela de a predetermina comportamentul acestora. S-au propus mai multe soluții constructive, în final alegându-se varianta care răspunde cel mai bine la mișcările și solicitările impuse.

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