Development of a micro-scale soft gripper to be used in nerve repair surgery

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Abstract– Neurorrhaphy surgery is a nerve repair micro-surgery that is done by trimming damaged nerve and suturing the trimmed healthy one back to the nerve connected to it. The problem facing such surgery is the over gripping of the nerve by using the forceps in the surgery. The problem could be counteracted by replacing the rigid part, which in this case the forceps by an instrument which has soft parts. In this paper, a micro-scale trapezoid soft pneumatic gripper is designed to replace the forceps for the nerve repair application. Furthermore, Designing a more efficient fabrication process by implementing a mold made by SLA technology that will decrease the time of the soft gripper fabrication by half while ensuring high accuracy and quality of the soft gripper being manufactured, compared to the most used process for this application which is soft lithography. A finite element analysis is done in Abaqus to show the bending actuation of such gripper.

Keywords- Soft gripper, Neurorrhaphy, Soft pneumatic actuator

I. INTRODUCTION

End-to-end neurorrhaphy surgery is a microsurgery done to repair the nerves by trimming damaged nerve's end to reveal healthy ones, as seen in Fig.1. A forceps is then used to pull the nerve close to each other to stitch them [1].

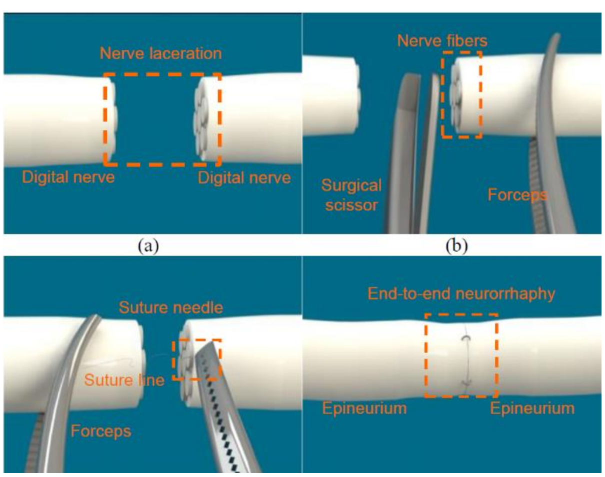

Fig. 1 Neurorrhaphy surgery [7]

The traditional forceps used presents a lot of challenges during the surgery itself. These challenges include over gripping nerve within the surgery which is undetectable within the surgery [2]. Due to such fear of damaging the nerve only specialized veteran surgeons are capable to carry out such operation. The over gripping is due to the forceps being made of rigid parts and the surgeons not being able to operate within the force range that prevents the nerve from being damaged. A solution to over gripping is to use a complaint soft material replacing the rigid forceps when manipulating the nerve. Thus, making the soft grippers applicable for the neurorrhaphy.

Soft grippers are divided into three technologies: controlled by adhesion, controlled by stiffness, and controlled by actuation.[3] Controlled by actuation is the technology that is chosen for this paper's gripper this due to its ability to grip object without excessive shear force applied on the nerve, and its ease of manufacturability in comparison to the other two technologies. Controlled by actuation includes electroactive polymer (EAP) which is actuated by electricity [4], passive structures which relies on motors for its actuation [5], shape memory material which uses stimulus such as temperature and light to actuate [6], and fluidic elastomer actuator (FEA) which uses fluids for its actuation. FEA is chosen for this application for its ease of use and fabrication in compared to EAP which requires voltage in the kilo voltage range and the smart material requiring specific material to achieve such function. Soft pneumatic actuator (SPA) gripper was used in this paper due to its fast response in compared to hydraulic actuator [3].

Soft pneumatic actuators were used for such application in other literature[7], [8]. Hybrid soft surgical gripper consist of soft inflatable actuator, stainless-steel gripper shell and a silicone air supply [7]. This method of gripping nerve showed promising results in gripping and manipulating the nerve. The problem remains that the gripper still has rigid parts for it to achieve such manipulation and grip of the nerve. Soft gripper bending actuation was also used for such application. This paper concentrates the shape engineering of the gripper for shape optimization [8]. The fabrication method used in this paper is soft lithography, which uses spin coating to layer the PDMS used above each other placing an insert for air passage in the second layer using a wire embed. It is then cut using a mask with exact dimension of the gripper. The soft lithography is relatively expensive process and using mask alignment while cutting using blade might produce inaccurate grippers. Furthermore, this paper proposed a trapezoid shape which gives 2 mm radius at 70 KPa which fully encloses the sciatic rabbit.

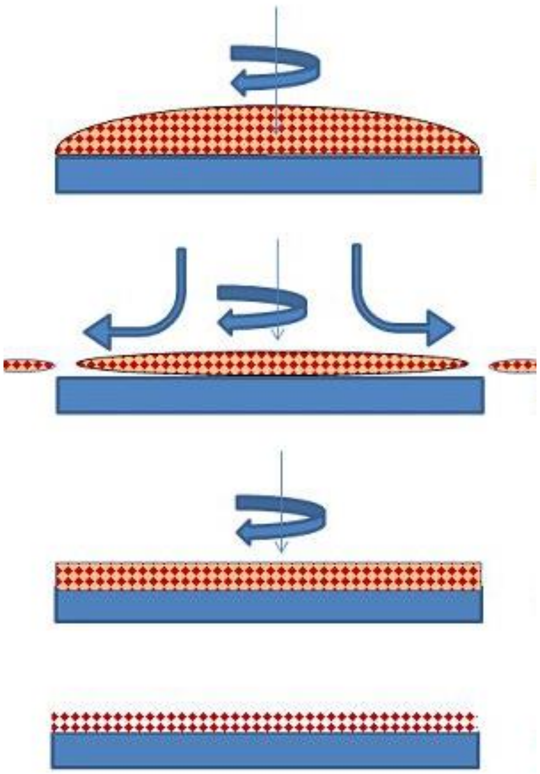

Fig. 2 Spin coating soft lithography [16]

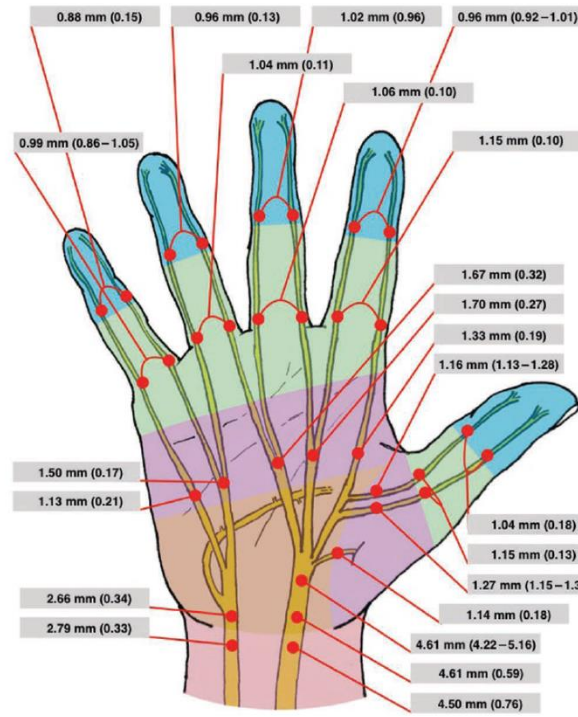

Fig. 3 Different measurement location of nerve diameter within wrist and hand.[9]

In this paper, a trapezoid profile will be designed for the neurorrhaphy surgery with a mold fabrication technique which will be used that will take less time to produce the trapezoid profile gripper.

II. Design and Material

A. Soft gripper design

The gripper design would need to abide to some design requirements. This design requirements are: 1) The incision workspace is about 20 mm and a working space of 10 mm, 2)The material used must have a low modulus to not over grip the nerve, 3) It must have a bending radius that is about the size the outer diameter of a human digital nerve [7]. Therefore, gripper designed must reach such diameter [9]. Furthermore, to achieve bending actuation the gripper must be asymmetric, the center of the air channel must have an offset distance from the center of the gripper's width[10]

The material used for the gripper is the Dragon skin 20 which is a silicon rubber with about 330 KPa young's modulus which is relatively low modulus. This feature makes it suitable for our application [11].

The following dimensions is for the designed gripper:

TABLE 1
Dimension for the soft gripper

Parameter	Dimension (mm)
b1	1
b2	2
L	20
e1	0.05
t	0.6
d	0.4

b1 is the dimension of the small width and b2 is the dimension of the large width. e1 is the distance from the channel center to the center of the thickness of the gripper. t is the thickness of the gripper. L is the length of the soft gripper.

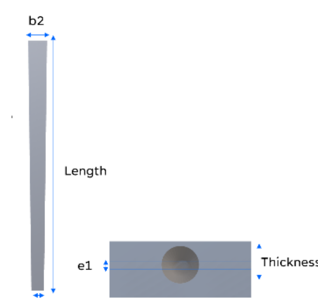

Fig. 4 Top view (on the left) and Front view (on the right) of the soft gripper

B. Material Characterization

Hyperelastic materials is a non-linear elastic model that uses strain energy density function to derive stress-strain to accurately describe the material behavior [12]

Their mechanical behaviour is derived for the strain energy function (W) based on three strain invariants being I_1, I_2, I_3 from green deformation tensor based on the energy restored in the material per unit of reference of volume in the initial configuration as a function of strain at that of the material,as in (1).[13]

$$W = f(I_1, I_2, I_3) \quad (1)$$

The three variants are defined in terms principal stretch ratio λ_1 , λ_2 and λ_3 , as in (2)-(4).

$$I_1 = {\lambda_1}^2 + {\lambda_2}^2 + {\lambda_3}^2 \quad (2)$$

$$I_1 = {\lambda_1}^2{\lambda_2}^2 + {\lambda_2}^2{\lambda_3}^2 + {\lambda_3}^2{\lambda_1}^2 \quad (3)$$

$$I_1 = {\lambda_1}^2{\lambda_2}^2{\lambda_3}^2 \quad (4)$$

For incompressibility, I_3 =1 therefore W is a function of I_1 and I_2 only, as in (5).

$$W = W(I_1 - 3, I_2 - 3) \quad (5)$$

Hyperelastic models used for such application are:

1) The Mooney-Rivlin model is considered the simplest model of the complete polynomial models and it is well suited for 100% strain and 30% compressive strain. This model the main drawbacks is that its parameters must be obtained experimentally, and the fitting procedure can be complicated if the number of parameters is large [14].

$$W = C_1(I_1 - 3) + C_2(I_2 - 3) \quad (6)$$

2) The Yeoh model is proposed By Yeoh in 1993 in the form of a third order polynomial based on the first invariant of I_1.[13] The model used is beneficial in much wider range of deformation, at 400% or above [14] and to predict the stress-strain behaviour from the uniaxial extension [14]

$$W = C_1(I_1 - 3) + C_2(I_1 - 3)^2 + C_3(I_1 - 3)^2 \quad (7)$$

3) Ogden Model model is proposed by Ogden in 1972 and it is based on the stretch ratios instead of the invariants [13]. This model is commonly used for large strain problems at 400 % [14] and up to 700%.[13] The model allows up to N=6 terms and I_2 is ignored. Not recommended to be used with limited data.

$$W = \sum_{n=1}^{N} \frac{\mu_n}{\alpha_n}({\lambda_1}^{\alpha_n} + {\lambda_2}^{\alpha_n} + {\lambda_3}^{\alpha_n} - 3 \quad (7)$$

The model that will be used for such application is the Ogden due to it being relatively more accurate that other models in large strain ranges [15]. The material coefficient Ogden through experimental data of Uniaxial Test are obtained from this paper [15]: μ1 = 1.3077, α1 = 1.1087, μ2 = -2.3497, α2 =-0.0317, μ3 = 1.2075, α3 = -1.6291, D1 = 0.4900, D2 = 0, D3 = 0.

III. Mold Design and Fabrication

The curing time for the dragon skin 20 is 4 hours. If the soft gripper is to be made using the spin coating method with 4 layers [8] it would take in total 16 hours to cure and there the time that it will take for the preparation and degassing. The preparation needs to be done before placing it on the substrate, that will be placed in the spin coater, within its 25 minutes pot life.

Fig. 5 Part A and Part B of DragonSkin 20

This paper purposes a mold design instead that will take a total of 8 hours to make the soft gripper, which is its curing time. The mold is made using SLA technology for its accuracy of its layer thickness, which is 0.05 mm per layer. This especially useful for the air inlet offset of 0.05 mm.

A. *Mold design*

The mold consists of three parts which are the mold base, dog bone placement (DBP) and the dog bone replacement (DBR). Mold base is made in two halves to enclose the whole at which the wire will be placed, for the air inlet. Mold base is made to take the perimeter of the gripper, its thickness, and the air inlet offset. DBP is used to ensure the straightness of the wire fixing it from two points, therefore it is also made into two parts. DBR is used for the fabrication of the full gripper. All the molds are printed using SLA. The SLA machine used is a .Form3B from Formlabs.

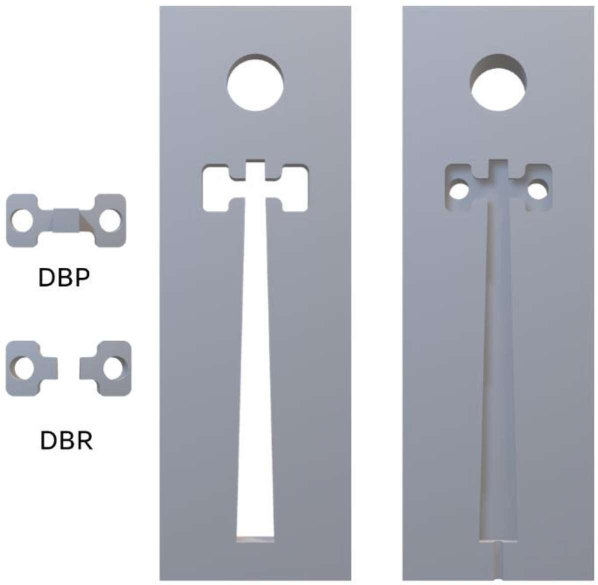

Fig. 7 Mold of the soft gripper with DBP and DBR on the right

B. *Fabrication process*

First, the Dragon skin 20’s part A and part B are stirred within the containers. Then part A and part B are mixed with a ratio 1:1 for 3 minutes. The DBP is placed in the mold base. Release agent is sprayed on the mold and is left for 5 minutes. The top half is placed on the mold then the mixture is poured

on it. A sharp tool is used to moving above the surface to ensure the levelling of the surface. The mixture is then left to cure for 4 hours. After 4 hours, DBP is removed replaced by DBR then a new mixture with a lower volume is made and poured in the place where the DBR was placed and then left to cure for 4 hours.

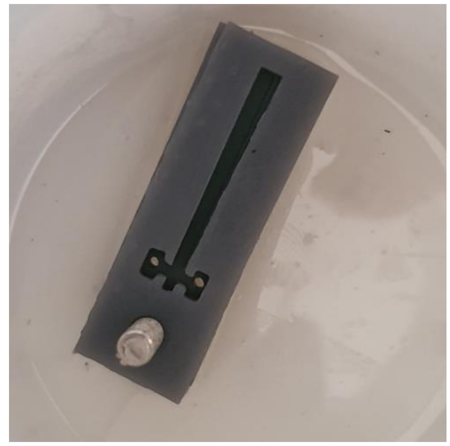

Fig. 6 mold with silicone poured into

Fig. 8 Soft gripper out of the mold

IV. Finite element analysis

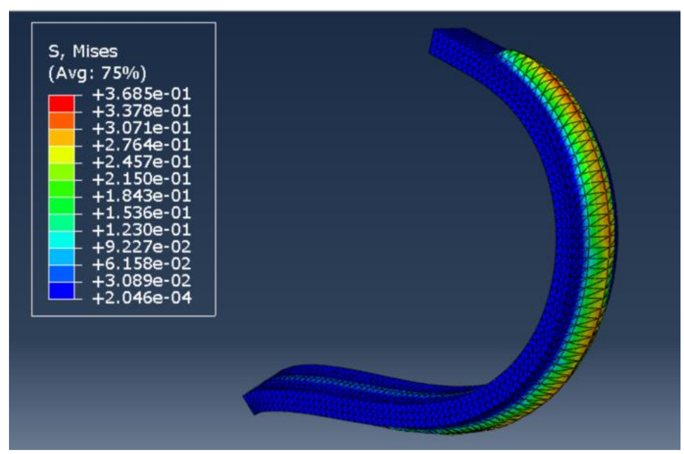

Fig. 9 Finite element analysis using Abaqus

Finite element analysis was done on 150 KPa for the material showing its bending potential with maximum stress of 368000 KPa at 150KPa. This shows the safety of the gripper since its maximum stress is about 3.5 MPa.[11]

V. Conclusion

The nerve gripping trapezoid shaped gripper would be better be suited to be fabricated by the mold made by SLA is it is relatively not expensive and reusable. The Trapezoid shape would be better suited for such application of nerve gripping due to its ability to have a high bending radius using the dragon skin 20 it shows its applicable for its bending actuation.

VI. References

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