Proceeding of the IEEE
International Conference on Robotics and Biomimetics
Dali, China, December 2019

Design of a Disposable Compliant Medical Forceps using Topology Optimization Techniques

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Abstract— **In this paper, we propose a novel disposable compliant forceps for general open surgical applications, developed using topology optimization techniques. Compliant mechanisms are much easier to sterilize than rigid-joint-based mechanisms, hence they are often used in the design of disposable medical forceps for preventing the spread of diseases from reusable medical devices. However, it is time consuming and inefficient to use empirical methods for designing compliant forceps. To simplify the design process, topology optimization techniques are employed in this paper to automatically synthesize the shape of compliant forceps. The entire design process was performed in Matlab. The designed forceps was quickly fabricated with selective laser sintering (SLS) and can be disposed of after single-use. The clamping capability of the proposed forceps was evaluated by a series of simulations and experiments. Results showed that the forceps is reliable and robust under different loads in open surgical tasks. With the work presented in this paper, we can achieve automatic synthesis of disposable compliant forceps with high performance.**

Index Terms— **Medical Robots and Systems; Mechanism Design; Surgical robotics; Topology Optimization**

I. Introduction

Forceps is one of the most basic surgical instruments for open surgical procedures, such as holding needles during suturing and stabilizing tissues during dissection [1], [2]. To prevent the spread of infectious diseases from re-used and poorly sterilized forceps, disposable forceps are widely used in various surgical applications [3]. In the conventional forceps, rigid joints are usually employed for realizing rotation and clamping movements. Despite of their stability and robustness, the complicated sterilization process of rigid-joint-based mechanisms makes them unsuitable for designing disposable medical forceps [4]. To cope with this problem, compliant mechanisms are often employed in the design of single-use forceps as they consist of fewer mechanical components and are thus easier to sterilize [4], [5]. Currently, a lot of research studies have been conducted to use compliant mechanisms for designing open surgical forceps. In [4], a disposable compliant forceps has been developed by Shuib *et al.* for HIV patients. Another disposable compliant forceps using U-shaped plastic hinge for realizing clamping movements, has been proposed by Eisenberg [6]. Other studies also tried to employ origami-based compliant mechanisms in the design of disposable forceps, as the Oriceps proposed by Edmondson *et al.* in [7]. However, most of the previous work used empirical methods for designing compliant forceps, which are time consuming and inefficient for achieving optimal clamping performance. Therefore, advanced methods for realizing disposable compliant forceps with optimal performance are highly desirable.

Fig. 1: Surface model of the proposed disposable compliant forceps.

In the past years, topology optimization has emerged as an efficient method for synthesizing compliant mechanisms with different functionalities [8]. Since then, many research efforts have also been made to explore the use of this methodology for designing medical devices. In [9], Frecker *et al.* realized a multi-functional compliant forceps for minimally invasive surgery (MIS) by using topology optimization techniques, which combines the clamping and cutting movements. In [10], Kota *et al.* also employed topology optimization method for designing a compliant kidney manipulator. Authors in [11] used the same methodology for optimizing the stability of the gripper of a compliant laparoscopic grasper. However, none of these previous work used topology optimization method for designing open surgical compliant forceps. On the other hand, most of the work mentioned above employed different software for performing the modeling, the finite element analysis (FEA) and the parameter modification process of the topology

This work is supported by the Department of Mechanical Engineering at Technical University of Munich.

978-1-7281-6321-5/19//$31.00 ©2019 IEEE

optimization algorithms. Such design frameworks require the implementation of additional interfaces between different developing environments, which are very inefficient. Besides, the solid modeling methods in the current topology optimization frameworks are very simple and can not construct complex geometries as initial design domain for the topology optimization process, which also limits the performance of the optimization method [12].

In this paper, we present the design of a novel disposable open surgical forceps by using topology optimization techniques. Compared to empirical methods, our design process is much more efficient as it can be automatically performed by providing initial design domain and boundary conditions. The entire design of the compliant forceps is performed in our automatic design platform in Matlab, the Solid Geometry (SG) Library [13]. We have integrated many powerful toolboxes from Matlab and also implemented a large number of functions for complex solid modeling in the SG Library so that no interface to other CAD software is required [14]–[16]. The proposed forceps can be directly fabricated with selective laser sintering (SLS) using biocompatible material PA2200 [17], which can be disposed of after single-use. The constructed forceps model in the SG Library is shown in Fig. 1.

The remainder of the paper is organized as follows: Section II provides a detailed description of the employed topology optimization method and the design process of the disposable open surgical forceps. Experiments are conducted in section III to evaluate the clamping performance of the compliant forceps. Section IV discusses the automatic synthesis method, concludes the entire paper and also provides an outlook of the future work.

II. Forceps Design

A. Design Overview

The design process of the disposable compliant forceps starts by importing an initial design domain and the corresponding boundary conditions for defining the design problem. The initial design domain is a 2D geometry realized by the SG Library. The shape of the forceps is automatically synthesized by employing a topology optimization based method. During the optimization process, an objective function is defined to describe the pursued functionality of the forceps. The entire design domain is discretized into small elements, and the objective function can be calculated by using finite element analysis (FEA). The element density of the design domain is updated in each iteration according the sensitivity analysis result. The optimization process converges when the densities of the elements are either 0 (void) or 1 (solid) within a given tolerance. In the post-processing, the contour of the forceps is extracted from the optimized density distribution and smoothed for final fabrication. The entire design process is shown in the flowchart in Fig. 2.

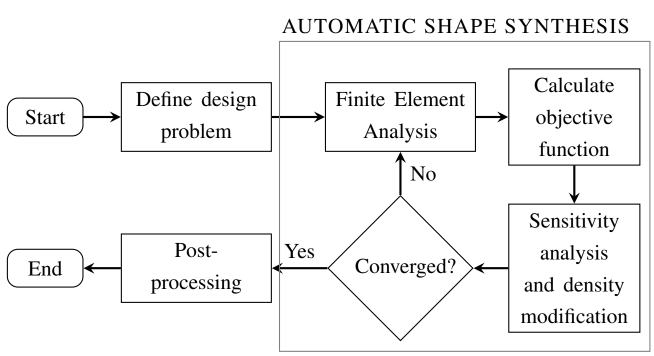

Fig. 2: Flowchart of the topology optimization based method for designing the disposable compliant forceps.

B. Design Problem

Fig. 3a) shows a 2D geometry constructed by the SG Library for modeling the initial design domain of the design problem. In our SG Library, the data structure Closed Polygon List (CPL) is used to describe a 2D geometry, which is a list composed of the coordinates of the points on the boundary of the 2D geometry [16], [18]. The points of the exterior boundary of CPL are listed counterclockwise while those of the interior boundary are listed clockwise. Since we want to realize a symmetrical forceps, the CPL in Fig. 3a) is defined as half of the initial design domain (see Fig. 3b).

A schematic diagram is presented in Fig. 3b) to illustrate the boundary conditions of the design problem. In the diagram, $\boldsymbol{\Omega_D}$ represents the design domain while $\boldsymbol{\Omega_C}$ (black region in the figure) is a constrained domain where the density is predefined as 1 (solid) and not to be modified during the automatic synthesis process. The $\boldsymbol{\Omega_C}$ is employed to construct a predefined handle for holding the forceps.

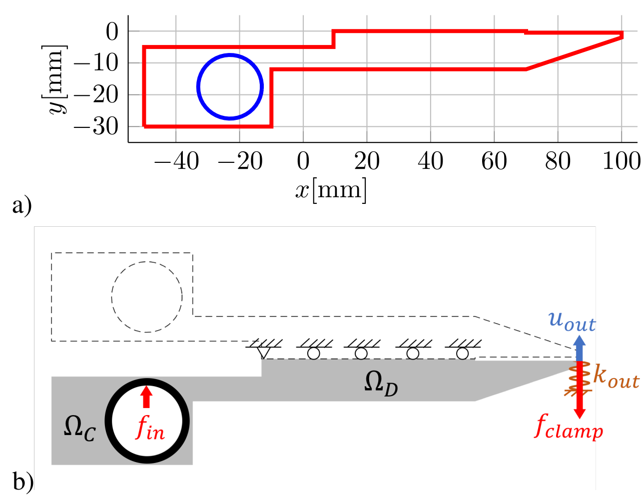

Fig. 3: Design problem of the proposed disposable compliant forceps: a) A 2D geometry realized by the SG Library as half of the design domain, b) Boundary conditions of the design problem.

f_{in} is the gripping force applied on the forceps handle while f_{clamp} simulates the clamping force on the forceps tip for grasping objects. The stiffness of the clamped tissue is modeled as a linear spring with spring constant k_{out} at the tip of the forceps. Since the forceps is SLS-printed by using the biocompatible polyamide PA2200, the elastic modulus E_0 and Poisson's ratio ν of PA2200 are used in the FE-Analysis. The objective of the design problem is to maximize the displacement u_{out} of the forceps tip in the positive y-direction with the predefined loading cases.

C. Topology Optimization Based Method

This section presents the topology optimization based method used in this paper for automatically synthesizing the compliant forceps. The design problem described above can be formulated into an optimization problem:

$$\begin{aligned}\max_{\boldsymbol{\rho}}: \quad & u_{out} = \mathbf{L^T U} \\ \text{subject to}: \quad & V(\boldsymbol{\rho}) \leq cV_0 \\ : \quad & \mathbf{KU} = \mathbf{F} \quad \text{with} \quad \mathbf{K} = \sum_{e=1}^{N} \mathbf{K_e}(E_e) \\ : \quad & E_e = E_0 \rho_e^p \ , \ 0 < \rho_{min} \leq \rho_e \leq 1\end{aligned} \tag{1}$$

where the y-displacement u_{out} of the forceps tip is defined as objective function. A sparse vector $\mathbf{L}$ composed of 0 and 1 is employed to locate the u_{out} in the global displacement vector $\mathbf{U}$. The goal of the topology optimization based method is to maximize the output displacement by iteratively modifying the material density distribution $\boldsymbol{\rho} \in (\mathbf{0}, \mathbf{1}]$ until a fully void-or-solid (0 or 1) density distribution is achieved. In the FE-Analysis, the design domain is meshed into triangular elements and the displacement vector $\mathbf{U}$ is calculated by solving the system of linear equations $\mathbf{KU} = \mathbf{F}$ [16]. $\mathbf{K}$ and $\mathbf{F}$ are the global stiffness matrix and load vector respectively. $\mathbf{K_e}$ and E_e represent the stiffness matrix and elastic modulus of an element. E_e is interpolated by its element density ρ_e using the Solid Isotropic Material with Penalization (SIMP) method $E_e = E_0 \rho_e^p$ [19]. E_0 is the elastic modulus of the solid material, the polyamide PA2200, while p and ρ_{min} are respectively the penalty parameter and a prescribed minimum density used to avoid singularity problem in the FE-Analysis. An additional constraint function is provided by $V \leq cV_0$ to control the volume V of the final forceps, where V_0 and c are the volume of the initial design domain and a predefined volume fraction, respectively.

In this paper, we use the standard Optimality-Criteria (OC) method from [12] to solve the optimization problem in (1). According to the OC method, an updating algorithm for the design variables $\boldsymbol{\rho}$ can be formulated as:

$$\rho_e^{updated} = \begin{cases} \rho_e^-, & \text{if } \rho_e B_e^\eta \leq \rho_e^- \\ \rho_e B_e^\eta, & \text{if } \rho_e^- < \rho_e B_e^\eta < \rho_e^+ \\ \rho_e^+, & \text{if } \rho_e^+ \leq \rho_e B_e^\eta \end{cases} \tag{2}$$

$$\begin{aligned}\rho_e^- &= \max(\rho_{min}, \rho_e - m) \\ \rho_e^+ &= \min(1, \rho_e + m) \\ \rho_e^0 &= \begin{cases} c & \text{in } \boldsymbol{\Omega_D} \\ 1 & \text{in } \boldsymbol{\Omega_C} \end{cases}\end{aligned} \tag{3}$$

$$B_e = \frac{-\frac{\partial u_{out}}{\partial \rho_e}}{\lambda_1 \frac{\partial V}{\partial \rho_e}} \tag{4}$$

where $\rho_e^{updated}$ is the updated design variable in each iteration and η is a damping factor. A move limit m is employed to control the changing rate of the density distribution $\boldsymbol{\rho}$ in each step. The initial element density ρ_e^0 is set to the volume fraction c in the design domain $\boldsymbol{\Omega_D}$ and 1 (solid) in the constrained domain $\boldsymbol{\Omega_C}$. B_e can be calculated from the optimality condition problem as in (4), where λ_1 is a Lagrangian multiplier calculated by a bisection method [12]. The sensitivity of u_{out} can be obtained from:

$$\frac{\partial u_{out}}{\partial \rho_e} = \frac{\partial u_{out}}{\partial E_e} \frac{\partial E_e}{\partial \rho_e} = pE_0 \rho_e^{p-1} \frac{\partial u_{out}}{\partial E_e} \tag{5}$$

$$\frac{\partial u_{out}}{\partial \mathbf{E}} = -\boldsymbol{\lambda_2^T} \frac{\partial \mathbf{K}}{\partial \mathbf{E}} \mathbf{U} \tag{6}$$

$$\mathbf{K} \boldsymbol{\lambda_2} = \mathbf{L} \tag{7}$$

where $\boldsymbol{\lambda_2}$ is the solution of the adjoint problem in (7). $\mathbf{E}$ is a vector containing all E_e.

The convergence criterion of the topology optimization method is that the densities $\boldsymbol{\rho}$ of all elements in the design domain are either 0 (void) or 1 (solid) within a given tolerance ε. In the post-processing, we extract and smooth the final forceps boundary from the optimized density distribution by using the iso-contour method implemented in the SG Library. The obtained 2D contour (a CPL) is then extruded into a 3D surface model for the final fabrication with SLS printing.

D. Automatic Shape Synthesis

This section shows the automatic synthesis process of the proposed disposable compliant forceps. The value of the predefined parameters for the automatic synthesis are listed in Table I. The clamping force and spring constant on the

TABLE I: Predefined parameters for the automatic synthesis process

Parameter	Symbol	Value
Gripping force on the handle	f_{in}	2 N
Clamping force on the tip	f_{clamp}	2 N
Spring constant on the forceps tip	k_{out}	0.75 kg/s^2
Elastic modulus of PA2200	E_0	1700 MPa
Poisson's ratio of PA2200	ν	0.3
Maximum element size in FEA	h	0.4 mm
Volume fraction	c	0.45
Penalty parameter	p	3
Minimum density	ρ_{min}	0.001
Damping factor	η	0.3
Move limit	m	0.05
Convergence tolerance	ε	0.01

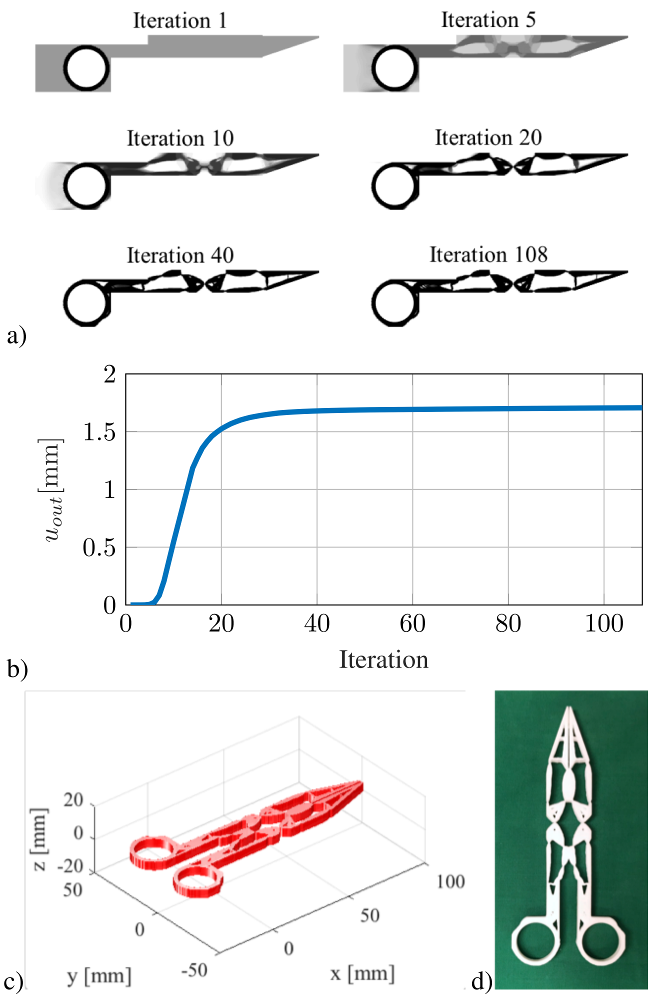

Fig. 4: Automatic shape synthesis of the proposed disposable compliant forceps: a) Evolutionary process of the density distribution in the design domain during the topology optimization, b) Value of the objective function u_{out} during the automatic synthesis process, c) Surface model of the forceps in the SG Library after post-processing, d) The SLS-printed disposable forceps.

forceps tip were chosen according to the study results in [20] and [21] respectively. All the calculations of the shape synthesis were performed on a personal computer with an Intel Core i7 CPU at 2.9 GHz and 16 GB of RAM.

Fig. 4a) presents the evolutionary process of the density distribution during the automatic shape synthesis. The topology optimization process reached its convergence at the 108$^{\text{th}}$ iteration. The entire process took 57.35 s. As can be seen in Fig. 4b), the maximum output displacement u_{out} (1.718 mm) was reached at the last iteration. Fig. 4c) shows the 3D model of the realized compliant forceps in the SG Library after post-processing. The thickness of the forceps in z direction was 5 mm. In our SG Library, the data structure of a 3D solid is a surface model called Solid Geometry (SG), which uses a list of oriented triangles to describe the boundary surface of a solid [16], [18]. We employ this type of surface model for 3D solid modeling since it has the same data structure as the STL-file, which can be directly 3D printed. Fig. 4d) shows the SLS-printed disposable forceps.

E. Simulation

In this section, two FE-Analyzes were performed to evaluate the opening and clamping capability of the disposable compliant forceps. The FE-simulation is based on the non-linear FE-method implemented in the SG Library [16]. A symmetrical load $F_1 = 2\,\mathrm{N}$ was applied on the forceps handle in Fig. 5a) to simulate the opening movement of the compliant forceps while a load with the same magnitude $F_1 = 2\,\mathrm{N}$ but the opposite direction was applied in Fig. 5b) to evaluate the clamping capability. The displacement and von Mises stress of the loaded forceps are shown in Fig. 5.

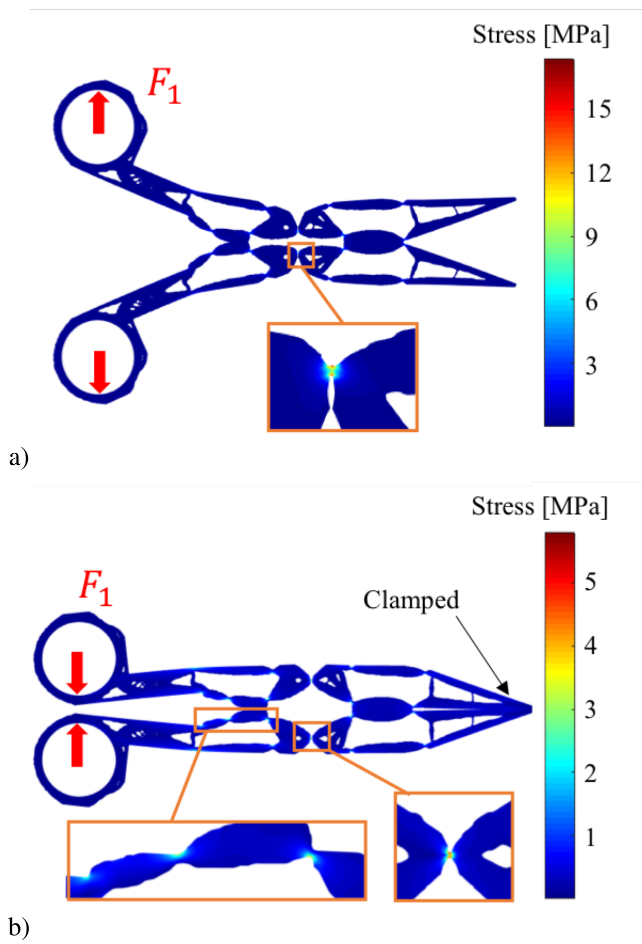

Fig. 5: FE-Analysis of the opening and clamping movements of the proposed compliant forceps: a) Displacement and stress of the compliant forceps when a symmetrical load F_1 (red arrow) was applied on the handle to open the forceps, b) Displacement and stress of the compliant forceps when a load with the same magnitude F_1 (red arrow) was applied to close the forceps tips.

The FEA results in Fig. 5 demonstrated that the proposed compliant forceps could successfully achieve opening and clamping movements with the the given load F_1. In Fig. 5b), the distance between the two pairs of the forceps handle was shortened to close the tips. The calculated clamping force on the forceps tip was $2.45\,\mathrm{N}$. From the stress distribution, it can be noticed that, in both loading cases the stress was not equally distributed in the entire forceps but concentrated in some parts of thin flexure hinges. During the clamping movement, the maximum stress in the forceps was lower than that in the opening position. This can be attributed to the boundary conditions employed in the topology optimization process, which was specifically designed for the clamping movement (see Fig. 3b).

III. EXPERIMENTS

In this section, a series of experiments were conducted to validate the clamping capability of the proposed disposable compliant forceps.

A. Tests of Clamping Capability

As is shown in Fig. 5b), the clamping force on the forceps tip is correlated to the gripping force on the handle, while the deformation of the two handle pairs can be used to characterize the gripping force. Hence, we measured the deformation of the forceps handle pairs as well as the resulting clamping force in a series of loading tests, to experimentally evaluate the clamping capability of the proposed forceps. The experimental setup is shown in Fig 6. A weight F_G was employed to pull the two forceps tips apart through cables, which emulated the clamping resistance. At the same time,

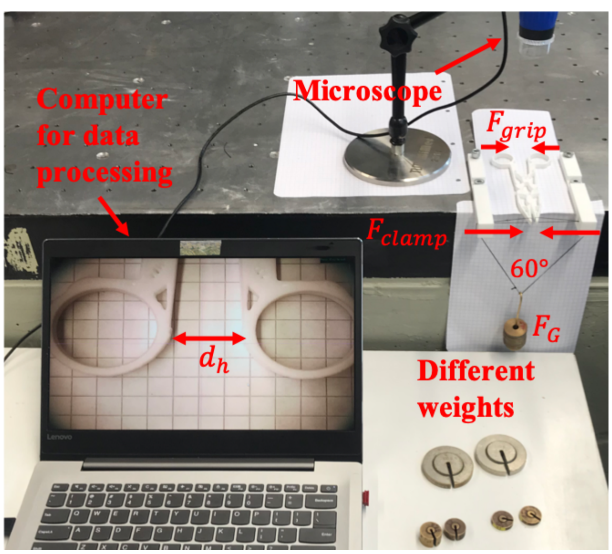

Fig. 6: Experimental setup for testing the clamping capability of the proposed forceps. A microscope was used to determine the deformation of the forceps handle while different weights were used to emulate the clamping resistance.

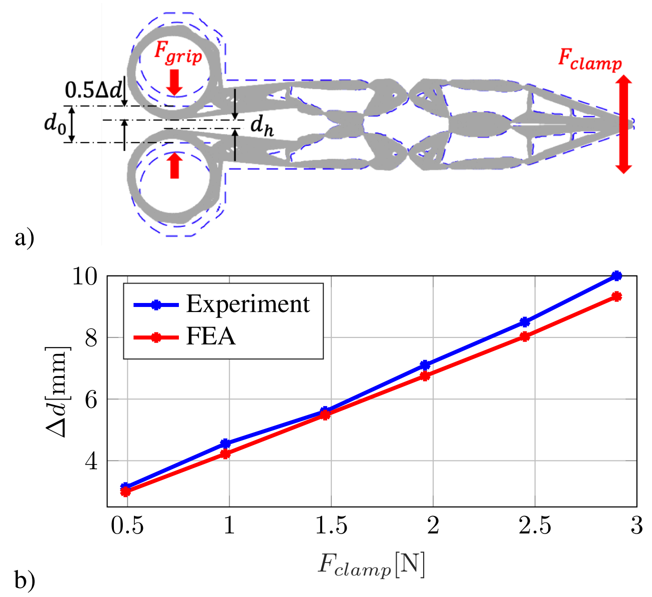

Fig. 7: Schematic representation and results of the experiments: a) A schematic diagram which illustrates the loading cases of the forceps in the experiments, b) Diagrams of the relationship between F_{clamp} and Δd. The blue one was measured by experiments while the red one was calculated by FEA.

we applied gripping force F_{grip} on the two handle pairs to achieve closure of the forceps tips. The digital microscope of Conrad was used to measure the distance d_h between the two handle pairs (see Fig. 6) at the moment when the two forceps tips just touched each other. In this case, the clamping force F_{clamp} was equal to the dragging force F_{cable} in the cable. The deformation Δd of the two handle pairs and the clamping force F_{clamp} can be formulated as:

$$\begin{aligned} \Delta d &= d_0 - d_h \\ F_{clamp} &= F_{cable} = \frac{\sqrt{3}}{3} F_G \end{aligned} \tag{8}$$

where $d_0 = 10\,\mathrm{mm}$ is the original distance between the two handle pairs. F_{clamp} in (8) is determined according to the law of sines. The schematic diagram in Fig. 7a) illustrates the loading cases and deformation of the forceps in the experiments. Apart from the experimental measurements, a series of FE-simulations were also performed to evaluate the handle deformation Δd. The same set of clamping forces as in the experiments were applied in the FEA for calculation. The experimental and FEA results are presented in Fig 7b). It can be noticed that, the experimental results were very close to those of the simulations, which shows the plausibility of our design. On the other hand, Δd and F_{clamp} showed almost linear correlations in both experimental and FEA results. The maximum clamping force measured in the experiments was $2.90\,\mathrm{N}$, which was achieved at $\Delta d = d_0 = 10\,\mathrm{mm}$ when the the two forceps handle pairs were completely closed. The maximum clamping force of the proposed forceps is already sufficient for the most clamping tasks in cardiovascular surgery according to [20].

B. Clamping in Open Surgical Dissection

To test the clamping performance of the proposed forceps in open surgical tasks, an experiment of surgical dissection was performed in this section on a silicone heart. The surgical instruments and the silicone heart used in the experiment are shown in Fig. 8a). The disposable compliant forceps was used for stabilizing the phantom tissue while conventional surgical scissors were used for cutting the tissue. As can be seen Fig. 8b), the forceps could successfully clamp and stabilize the phantom tissue during the dissection task, which shows the reliability of the proposed forceps.

a) b)

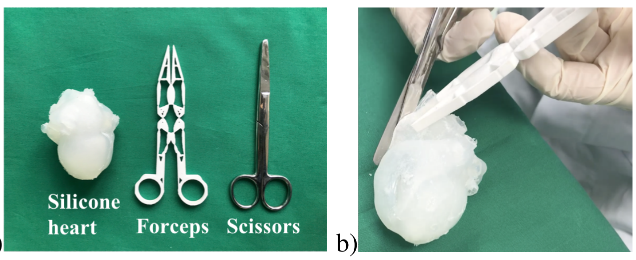

Fig. 8: Open surgical dissection on a silicone heart: a) The disposable forceps, the conventional scissors and the silicone heart for the dissection experiment, b) Dissection on the phantom tissue.

IV. Conclusion and Future Work

In this paper, we presented the design of a disposable compliant forceps for open surgery by using a topology optimization based method. The shape of the forceps was automatically synthesized by providing an initial design domain and the corresponding boundary conditions. Compared to the empirical methods, the automatic synthesis method can achieve optimal design more efficiently, as the algorithm behind the topology optimization method is based on the biological evolution process, in which the animals always try to modify their shape to adapt to the living environment. The entire synthesis process was performed in our design platform in Matlab, the SG Library. The forceps was SLS-printed and can be disposed of after single use, which prevents the spread of diseases from reusable medical devices. Simulations and experiments were conducted to validate the clamping capability of the forceps. Results showed that the proposed compliant forceps can achieve robust clamping in general open surgical tasks, such as dissection.

Nevertheless, the work in this paper can still be improved by introducing a stress constraint into the optimization problem to reduce the high stress in the thin flexure hinges of the forceps. Moreover, we also plan to conduct other complex surgical experiments, such as suturing, to further evaluate the clamping performance of the proposed forceps.

References

[1] S. Sheikh, I. Ganesaratnam, and H. Jan, "The birth of forceps," *JRSM Short Reports*, vol. 4, no. 7, pp. 1–4, 2013.

[2] M. A. Talamini and E. J. Hanly, "Technology in the operating suite," *JAMA*, vol. 293, no. 7, pp. 863–866, 2005.

[3] W. Sopwith, T. Hart, and P. Garner, "Preventing infection from reusable medical equipment: a systematic review," *BMC infectious diseases*, vol. 2, no. 1, p. 4, 2002.

[4] S. Shuib, R. Yusoff, A. Hassan, M. Ridzwan, and M. Ibrahim, "A disposable compliant-forceps for hiv patients," *Journalof Medical Science*, vol. 7, no. 4, pp. 591–596, 2007.

[5] L. L. Howell, *Compliant mechanisms*. John Wiley & Sons, 2001.

[6] E. Arthur, "Disposable medical forceps," Feb. 6 1968. US Patent 3,367,336.

[7] B. J. Edmondson, L. A. Bowen, C. L. Grames, S. P. Magleby, L. L. Howell, and T. C. Bateman, "Oriceps: Origami-inspired forceps," in *ASME 2013 conference on smart materials, adaptive structures and intelligent systems*, American Society of Mechanical Engineers Digital Collection, 2014.

[8] J. A. Gallego and J. Herder, "Synthesis methods in compliant mechanisms: An overview," in *ASME 2009 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, pp. 193–214, American Society of Mechanical Engineers Digital Collection, 2010.

[9] M. I. Frecker, R. Dziedzic, and R. Haluck, "Design of multifunctional compliant mechanisms for minimally invasive surgery," *Minimally Invasive Therapy & Allied Technologies*, vol. 11, no. 5-6, pp. 311–319, 2002.

[10] S. Kota, K.-J. Lu, Z. Kreiner, B. Trease, J. Arenas, and J. Geiger, "Design and application of compliant mechanisms for surgical tools," *Journal of biomechanical engineering*, vol. 127, no. 6, pp. 981–989, 2005.

[11] D. J. de Lange, M. Langelaar, and J. L. Herder, "Towards the design of a statically balanced compliant laparoscopic grasper using topology optimization," in *ASME 2008 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, pp. 293–305, American Society of Mechanical Engineers, 2008.

[12] O. Sigmund, "A 99 line topology optimization code written in matlab," *Structural and multidisciplinary optimization*, vol. 21, no. 2, pp. 120–127, 2001.

[13] "Sg-lib: Solid geometry library toolbox." `http://www.sg-lib.org`. Accessed: 2019-09-05.

[14] Y. Sun and T. C. Lueth, "Extension of the fem analysis using the pdetoolbox of matlab with regard to point loads, line loads, and freeform surface loads: Feature surface concept," in *2018 IEEE International Conference on Robotics and Biomimetics (ROBIO)*, pp. 1151–1158, IEEE, 2018.

[15] Y. Sun and T. C. Lueth, "Extension of matlabs pde toolbox for developing bionic structural optimization methods: Overlapping region concept," in *International Conference on Robotics in Alpe-Adria Danube Region*, pp. 357–364, Springer, 2019.

[16] Y. Sun, Y. Liu, and T. C. Lueth, "Fe-analysis of bio-inspired compliant mechanisms in matlab for medical applications," in *2019 IEEE International Conference on Cyborg and Bionic Systems (CBS)*, IEEE, 2019.

[17] EOS GmBH - Electrical Optical Systems, *PA 2200*, 12 2008. Rev. 1.

[18] T. C. Lueth, "Sg-library: Entwicklung einer konstruktiven matlabtoolbox zur räumlichen modellierung von körpern, gelenken und getrieben," in *11. Kolloquium Getriebetechnik*, pp. 183–203, 2015.

[19] M. P. Bendsøe and O. Sigmund, "Material interpolation schemes in topology optimization," *Archive of applied mechanics*, vol. 69, no. 9-10, pp. 635–654, 1999.

[20] R. Trobec and B. Gersak, "Direct measurement of clamping forces in cardiovascular surgery," *Medical and Biological Engineering and Computing*, vol. 35, no. 1, pp. 17–20, 1997.

[21] C.-C. Wei, S.-W. Huang, and C.-T. Bau, "Using the spring constant method to analyze arterial elasticity in type 2 diabeticpatients," *Cardiovascular diabetology*, vol. 11, no. 1, p. 39, 2012.