Journal of Visualized Experiments

Rapid Manufacturing of Thin Soft Pneumatic Actuators and Robots

--Manuscript Draft--

Article Type:	Invited Methods Article - JoVE Produced Video
Manuscript Number:	JoVE60595R2
Full Title:	Rapid Manufacturing of Thin Soft Pneumatic Actuators and Robots
Section/Category:	JoVE Engineering
Keywords:	Rapid Manufacturing; soft robotics; Thin Pneumatic Actuators; Thermoplastic Polyurethane; Laser Cutter; Two-dimensional to Three-dimensional actuation/transformation
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Additional Information:	
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TITLE:
Rapid Manufacturing of Thin Soft Pneumatic Actuators and Robots

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KEYWORDS:
rapid manufacturing, soft robotics, thin pneumatic actuators, thermoplastic polyurethane, laser cutter, two-dimensional to three-dimensional actuation/transformation

SUMMARY:
This protocol describes a method for rapid manufacturing of soft pneumatic actuators and robots with a thin form factor. The fabrication method starts with lamination of thermoplastic polyurethane (TPU) sheets followed by laser cutting/welding of a two-dimensional pattern to form actuators and robots.

ABSTRACT:
This protocol describes a method for rapid manufacturing of soft pneumatic actuators and robots with an ultrathin form factor using a heat press and a laser cutter machine. The method starts with the lamination of thermoplastic polyurethane (TPU) sheets using a heat press for 10 min at the temperature of ~93 °C. Next, the parameters of the laser cutter machine are optimized to produce a rectangular balloon with maximum burst pressure. Using the optimized parameters, the soft actuators are laser cut/welded three times sequentially. Next, a dispensing needle is attached to the actuator, allowing it to be inflated. The effect of geometrical parameters on the deflection of the actuator are studied systematically by varying the channel width and length. Finally, the performance of the actuator is characterized using an optical camera and a fluid dispenser. Conventional fabrication methods of soft pneumatic actuators based on silicone molding are time consuming (several hours). They also result in strong but bulky actuators, which limits the actuator's applications. Moreover, microfabrication of thin pneumatic actuators is both

time-consuming and expensive. The proposed manufacturing method in the current work resolves these issues by introducing a fast, simple, and cost-effective fabrication method of ultrathin pneumatic actuators.

INTRODUCTION:

As a step forward in manufacturing of soft pneumatic actuators, the proposed method illustrates rapid fabrication of ultrathin (~70 µm) pneumatic actuators made of thermoplastic polyurethane (TPU)[1]. These actuators are particularly useful in applications that require the robots to be lightweight and/or fit within small spaces. Such applications can be envisioned to be transcatheter surgical manipulators, wearable actuators, search and rescue robots, and flying or swimming robots.

The conventional manufacturing method of thin soft pneumatic actuators, which is based on silicone molding, is time consuming (several hours) and very challenging due to the low resolution of the 3D printed molds and difficulties in demolding of thin (less than 0.5 mm) actuators. In particular, fabrication of thin actuators requires the application of specialized tools and methods[2].

Microfabrication techniques can be adopted to fabricate thin actuators[3-7]. Alternatively, Ikeuchi et al. have developed thin pneumatic actuators using membrane micro-embossing[8]. These methods, although effective, require expensive tools and are time-consuming. Thus, they have limited applications.

Paek et al. demonstrated a simple method for fabrication of small-scale soft actuators using dip-coating of cylindrical templates[2]. Although effective, there are two issues with widespread application of this method: First, it is not easy to control the thickness of the dip-coated features, and secondly, its application is restricted to a limited number of three-dimensional (3D) designs.

Peano actuators[9,10] and pouch motors[11,12] have compact two-dimensional (2D) designs that result in thin form factors (i.e., large areas with small thickness). Veale et al. reported development of linear Peano actuators made of reinforced plastic and textile-silicone composites[1,8]. Niiyama et al. developed pouch motors using thermoplastic films manufactured by heat stamping and heat drawing systems[11,12].

While the 2D design of Peano actuators and pouch motors makes them very thin in their unactuated state, upon inflation their zero-volume chamber expands to a relatively large volume, thus limiting their application for operation in limited spaces such as transcatheter therapies or search and rescue missions[1]. In contrast to these designs, the proposed soft actuators in the current method can actuate with relatively small strains. Thus, even in the actuated state they occupy relatively small spaces[1].

PROTOCOL:

1. Smoothing the TPU sheets by heat pressing

1.1. Calibrate a force sensor to be used in the heat press.

1.1.1. Sandwich the force sensor between two layers of silicone (50 mm x 50 mm x 3 mm thick). Place the force sensor and silicone layers between the compression platens/anvils of the tensile machine. Decrease the distance between the platens by turning the knob of the heat press clockwise and write down the force and resistance of the sensor.

1.1.2. Measure the area of the sensor using a digital caliper and divide the force values by the measured area to obtain the pressure data. Fit a linear line to the pressure versus resistance data using a spreadsheet to calibrate the sensor.

1.2. Place the force sensor inside the heat press and turn the pressure knob until a pressure of ~200 kPa is read from the sensor.

1.3. Wear gloves to avoid any contamination of the TPU films.

1.4. Cut four layers of TPU with scissors or a laser cutter to fit the heat press plates (30 mm x 30 mm). Position the four sheets so all four edges are aligned.

1.5. Place the TPU sheets inside the heat press.

1.6. Set the temperature of the heat press to ~200 °F (~93 °C). Close the heat press fully.

1.7. Keep the films inside the heat press for 10 min. Open the heat press and remove the laminated TPU films to be laser cut in step 3.12.

2. Finding the optimal laser parameters

2.1. As described in section 1, heat press two layers of TPU.

2.2. Using computer-aided design (CAD) software, design a square with 20 mm sides and a rectangle of 4 mm x 8 mm that will act as the inlet of the square balloon.

2.3. Laser cut/weld the square pattern from step 2.2 out of the TPU layers from step 2.1 using the following settings in the laser cutter software: set pulses per inch (PPI) to 500, vary the power from 10% to 100%, and for each value of power vary the speed from 10% to 100%.

2.4. Cut the end of the inlet of the square balloon with scissors.

2.5. Insert a needle inside the square balloon inlet, apply glue (**Table of Materials**) around it, and wrap the polytetrafluoroethene (PTFE) tape around the connection.

NOTE: After 5 min it is ready to use.

2.6. Identify the average burst pressure of the square balloon by inflating it with a precise fluid dispenser.

2.7. Increase the pressure of the balloon using the precise fluid dispenser until it bursts. Measure and write down the burst pressure. Repeat this step 5x and obtain the average burst pressure.

2.8. Repeat steps 2.1−2.7 for the full range of power and speed values and identify the maximum burst pressure of the square balloon and its associated power and speed values as the optimal parameters for the laser machine.

3. Fabricating the actuators by laser cutting/welding

3.1. Design the desired actuator pattern using CAD software.

NOTE: AutoCAD 2017 is used in this protocol.

3.2. Select the entire design in the CAD software by highlighting all segments of the design.

3.3. In the task bar under the **Properties** section, change the line weight to 0 mm for the software to print successfully to the laser cutter.

3.4. From the taskbar, select **Print**. Change the printer name to “VLS2.30” in the menu.

3.6. In the **Printer Settings**, choose the paper size as **User-defined Landscape**.

3.7. In the **Plot Scale** section, deselect the **Fit to Paper Option** and then scale the image size as 1 mm = one unit of length.

3.8. In the **Plot Offset (Origin Set to Printable Area)** check the **Center the Plot** option.

3.9. Turn on the air filter by pressing the power button.

3.10. Turn on the laser cutter by pressing the power button or by clicking on the power icon on the **Universal Laser System Control Panel** software.

3.11. In the **Setting** option, set the speed = 60%, PPI = 500, and power = 80%.

NOTE: These parameters may need to be changed based on the specific laser power of the system being used.

3.12. Using the **Focus View** tool, move the laser pointer to the left top corner and bottom right corner of the pattern to make sure the whole pattern fits inside the laminated TPU films (30 mm x 30 mm) made in step 1.10.

3.13. To focus the laser machine, move the lens carriage to the middle of the table. Place the focus tool on the table and move the table up until the top of the focus tool touches the front of the lens carriage. Then, move the table up slowly until the lens carriage hits the notch of the focus tool and bumps it forward.

NOTE: The laser is focused and ready for use with the parameters in 3.11.

3.14. Without changing the position of the TPU sheet, run the laser again, but decrease the speed = 55%, increase the power = 85%, and keep PPI = 500.

3.15. Perform a third run of the laser to ensure there are no leaks in the actuator. Set the speed = 50%, increase the power = 90%, and keep PPI = 500.

4. Bonding stainless steel dispensing needles with a Luer lock connection

4.1. Cut the end of the balloon actuator inlet with scissors.

4.2. Insert a needle inside the balloon actuator inlet, apply glue around it, and wrap the PTFE tape around the connection.

NOTE: After 5 min it is ready to use.

5. Characterization of the soft actuators

5.1. Mount a camera over the actuator with a sufficient distance so that the actuator is in full view within the camera in both its pressurized and unpressurized states.

5.2. Hold the actuator in an orientation such that its deflection upon pressurization is orthogonal to the camera.

5.3. Increase the pressure of the actuator with a precise fluid dispenser until it deflects into its full range without bursting. Assume the full range as the maximum deflection of the actuator without any plastic deformation or leakage or bursting due to overinflation.

5.4. Increase the actuator pressure until it reaches ~20% of its full range and write down the pressure.

5.5. Take a picture of the actuator using the camera from step 5.1, and then use an image processing software (e.g., imageJ) to measure the X- and Y-coordinates of the tip of the actuator in the image.

5.6. Repeat steps 5.4 and 5.5 until reaching the full range of actuator deflection.

5.7. Plot an X-Y graph of the actuator's deflection versus the inflation pressure using a plotting software.

REPRESENTATIVE RESULTS:

To demonstrate the proposed method, we show the fabrication of a single bending actuator. To fabricate this actuator, four sheets of TPU of dimension 25 cm x 25 cm were cut, stacked together, and then smoothed using a heat press (**Figure 1A**). Following the protocol, the heat press was applied for 10 min at a set temperature of 200 °F. Wrinkles in the laminated sheets can result in issues with bonding during the laser cutting step, therefore ensuring a perfectly smooth surface is critical for reproducible results. For example, **Figure 1B** shows a resulting lamination that contains wrinkles that will not produce desired results, while **Figure 1C** shows a resulting lamination that is sufficiently flat to produce the desired results.

The 2D design of the pneumatic actuator was drawn in AutoCAD. This actuator was made simply by drawing a rectangle of 8 mm x 150 mm. A linear pattern of eight lines, each 1.34 mm long, was added to the center of the design with a spacing of 10 mm (highlighted in red in **Figure 2**). Finally, the opening of the actuator (highlighted in blue in **Figure 2**) was designed by adding an open-ended rectangle of 4 mm x 8 mm. An AutoCAD file (.dwg) for this sample linear actuator is available in the **Supplemental Material**.

The laminated four-layer stack of TPU was then placed in the laser cutting machine (**Figure 3A**) and the 2D design was imported using the software of the laser cutting machine. The **Focus** tool on the laser cutter verified the fit of the 2D drawing's position on the laminated TPU sheets. For a first run, the laser cut was set at speed = 60%, power = 80%, and PPI = 500. Once it was completed, without changing the position of the polyurethane sheets, a second run with new settings was started at speed = 55%, power = 85%, and PPI = 500. The same process was repeated with new settings for a third time at speed = 50%, power = 90%, and PPI = 500. Decreasing the speed and increasing the power exposes the pneumatic actuator to the heat source for a longer time and allows it to melt and bond to ensure a leak-free balloon that can separated from the rest of the TPU sheet easily (**Figure 3B**). It should be noted that the laser cutter is always simultaneously cutting and welding the TPU; the cutting and welding are not done in separate steps or achieved by different settings.

In order to couple the actuator to an air supply unit, the opening of the actuator was cut with scissors and a stainless steel needle (**Figure 4B**) was inserted between the second and third layers of the laser-cut actuator. To maintain a leak-free system, the outside of the needle was covered in glue beforehand (**Figure 4C**). Then the interface of the actuator and stainless steel needle was wrapped tightly with PTFE tape (**Figure 4D**).

Finally, using a digital fluid dispenser, the pneumatic actuator (**Figure 5A**) was inflated to a pressure of 5 psi to observe a deflection in the region where the array of lines was designed (**Figure 5B**).

FIGURE LEGENDS:

Figure 1: Heat pressing sheets. (**A**) Image of the heat press with the TPU sheets to be laminated. (**B**) Example image of poorly laminated sheets with excessive wrinkles. (**C**) Example image of successfully laminated sheets with a smooth surface.

Figure 2: Actuator design. Image of a CAD drawing used to form a single bending actuator. The bottom design shows the outline of the actuator, the middle design shows a single line added as a bending feature, and the top design shows a complete actuator. The red box highlights the features that form the bending region of the actuator. The blue box highlights the region for connecting a needle for pressurization.

Figure 3: Laser cutter. (**A**) Image of the laminated sheets in a laser cutter. (**B**,**C**) Image of the actuator to be removed after laser cutting. (**C**) Image of the actuator.

Figure 4: Needle connection. Images depicting the steps for connecting a blunt needle (**A**) to a balloon actuator using glue (**B**) as an adhesive. The needle is inserted into the narrow end of the actuator, which is opened using scissors (**C**) and sealed with PTFE tape (**D**).

Figure 5: Bending actuator. (**A**) Image of the actuator in an unpressurized state. (**B**) Image of the actuator in a pressurized state.

DISCUSSION:

The critical steps in the fabrication of the soft actuators include: i) The 2D CAD design. A proper 2D layout can dictate the deformation of the actuator (e.g. linear, biaxial, bending, and rotational motion). ii) Lamination of the TPU layers. The TPU films are heat pressed before laser cutting to make sure the layers are flat and in conformal contact everywhere. iii) Laser cut/weld. As the final step, the laminated TPU layers are laser cut/welded into soft actuators.

The success rate of the protocol can produce a 100% yield (for example, we have made 20 actuators simultaneously). The primary factor is the lamination step: to obtain the best results, the TPU should be flattened as much as possible before the heat press process. Examining different regions of the heat press plate with a force sensor may show that the pressure distribution is not uniform. Non-uniform pressure distribution can result in imperfect lamination of the TPU sheets, which in turn results in imperfect laser cutting/welding and leakage. Alternatively, non-uniform heat transfer due to small wrinkles in the TPU film during the laser cutting/welding can cause leakage.

In comparison to the conventional methods, the proposed method has several advantages including: i) Simple 2D design. While the current method only requires 2D CAD designs to laser cut/weld the actuators (various patterns are available[1]), the conventional fabrication methods based on silicone casting require a 3D mold design. ii) Rapid fabrication. Fabrication time from CAD design to lamination of TPU layers and laser cutting/welding can happen in several minutes, whereas the conventional fabrication method will take several hours. By allowing fabrication of soft devices and soft robots in a single step, without assembly, soft robots and devices can be designed from a combination of different types of actuators, and the CAD model can be laser cut/welded into the final product in a single step without requiring any assembly. For instance, a swimming robot, comprised of four legs each consisting of two types of bending actuators, is fabricated from a 2D CAD design in just a few minutes without requiring any assembly steps, as previously demonstrated[1].

As a future direction of this work, different types of thermoplastic materials can be adopted for fabrication of the soft actuators. Generally, these materials need to have elastic behavior to be used as actuators. Application of stiffer thermoplastic material will result in higher burst pressure and higher blocking force of the actuators compared to those previously characterized in Figure S6 of Moghadam et al.[1], showing forces up to 0.1 N. Thus, it can extend the application of the actuators to cases where higher blocking force is required, such as exoskeleton suites.

ACKNOWLEDGMENTS:

We thank the Dalio Institute of Cardiovascular Imaging for funding this work.

DISCLOSURES:

The authors have nothing to disclose.

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Figure 1

Click here to access/download;Figure;Figure 1.psd

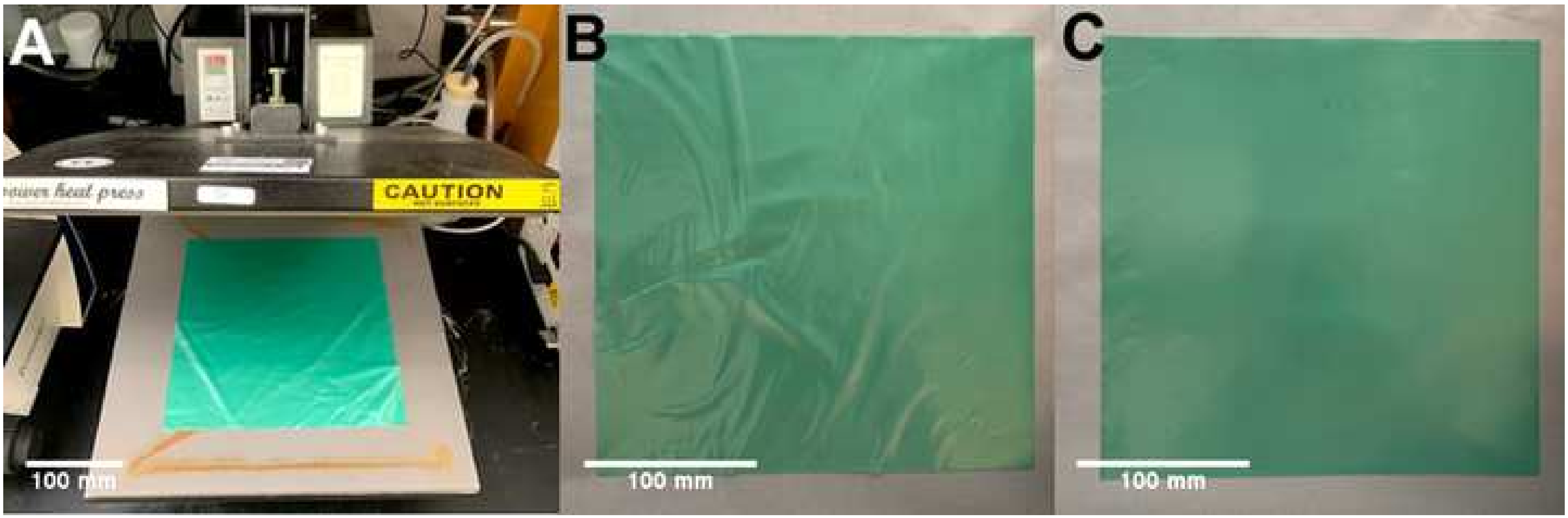

Figure 2

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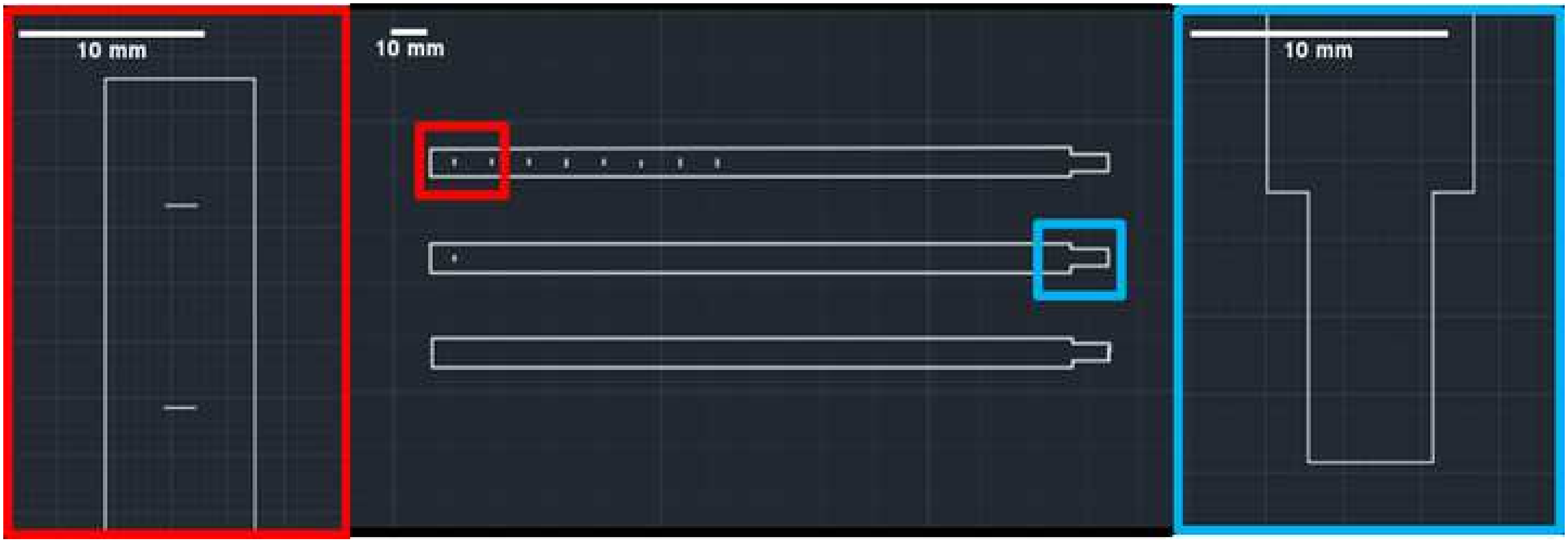

Figure 3

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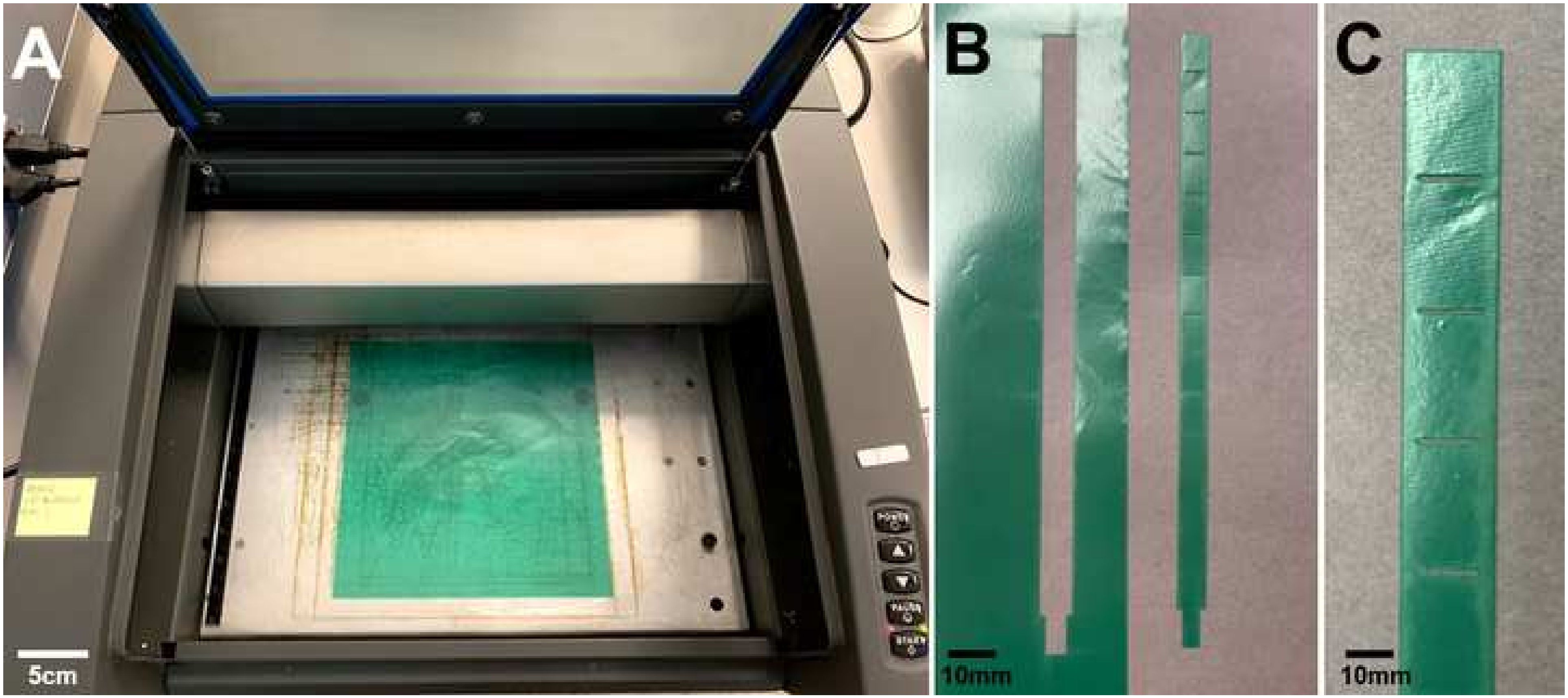

Figure 4

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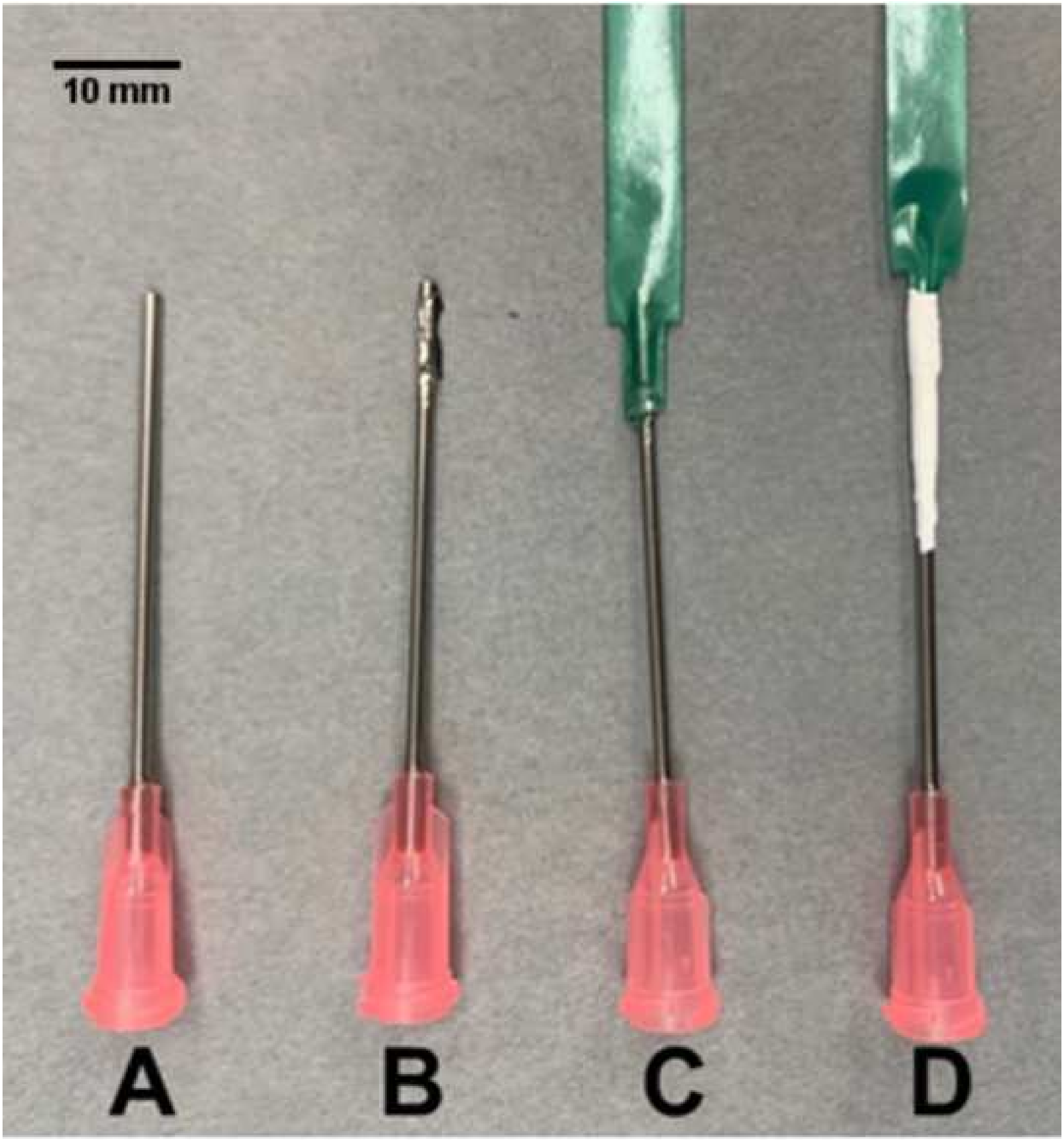
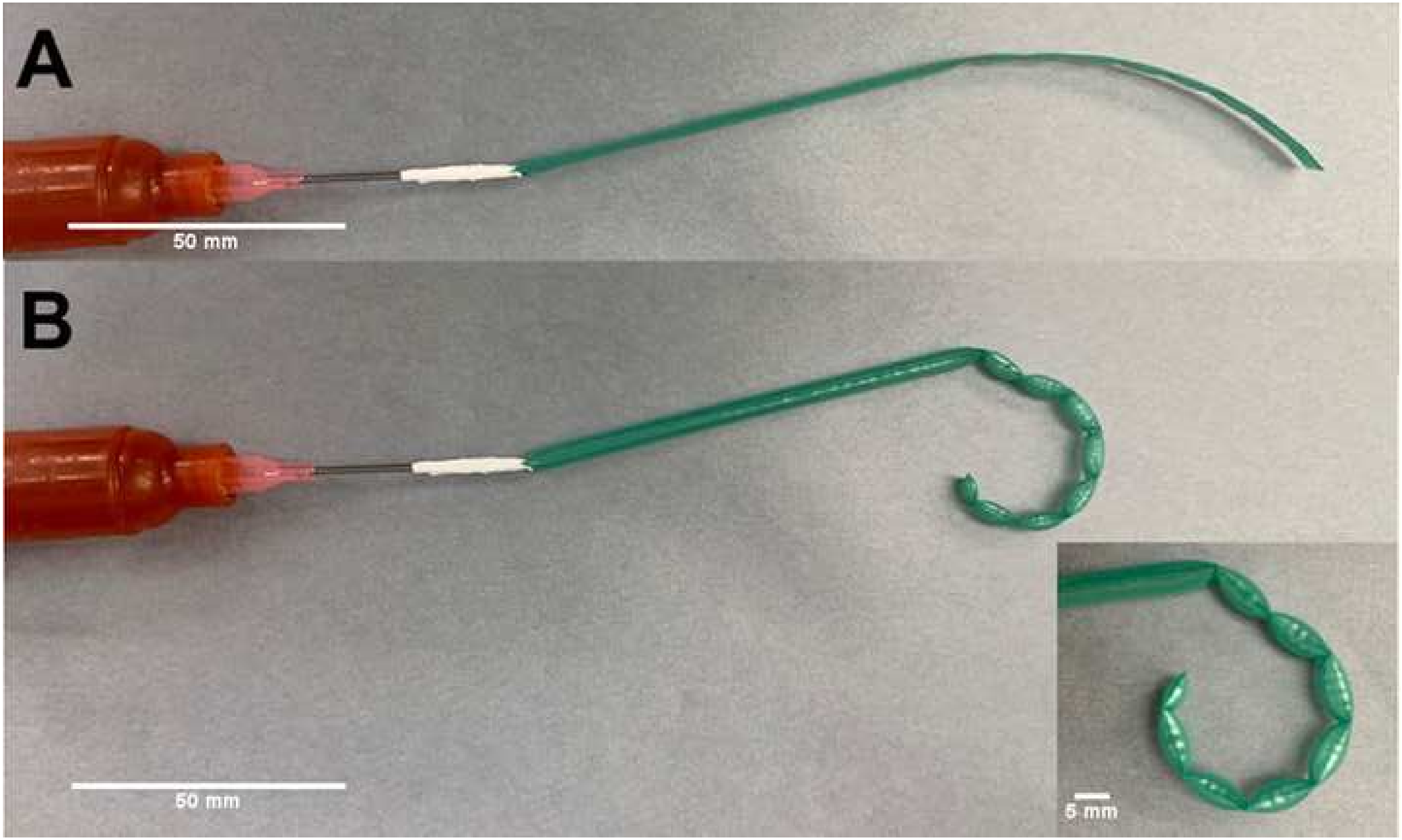


Click here to access/download;Figure;Figure 5.psd



 Click here to access/download;Table of Materials;JoVE_Table_of_Materials.xlsx

Name of Material/Equipment	Company	Catalog Number	Comments/Description
Force Sensor	Omega	KHLVA-102	https://www.omega.co.uk/pp
High Precision Dispensers Ultimus I	Nordson		http://www.nordsonefd.com/
Laser Cutter VLS2.30	Universal Laser System		https://www.ulsinc.com/prod
PowerPress Heat Press	Power Heat Press	OX-A1	https://www.howtoheatpress
PTFE Thread Sealant tape	McMaster-Carr	4934A11	https://www.mcmaster.com/
Stainless Steel Dispensing Needle	McMaster-Carr	75165A754	https://www.mcmaster.com/
Super Glue Loctite 409	Henkel	229654	https://www.henkel-adhesive
Thermoplastic polyurethane Airtech's Stretchlon 200	ACP Composites	v-11A	https://store.acpsales.com/pr
Universal Testing Systems	Instron	5943	

otst/KHRA-KHLVA-KHA-SERIES.html

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lucts/platforms/vls2-30

s.com/power-press-15x15-heat-press-review/

ptfe-tape

75165a754

es.com/us/en/product/instant-adhesives/loctite_409.html

roducts/3321/stretchlon-200-high-stretch-bag-film-60

Mk_choCJIgQAvD_BwE

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Dear Editor,

We thank you and the reviewers for very useful comments/edits that have improved our manuscript significantly. We have addressed each of the reviewer comments thoroughly, as shown below:

Reviewer #1:

1. Line 2: Please change the paper title to "Rapid Manufacturing of Thin Soft Pneumatic Actuators and Robots" as the current title suggests too much generality.

We have changed the title accordingly.

2. Line 36: Please define the term "form factor" (e.g., in dashes) or just use "ultrathin" instead.

We have changed the text to “ultrathin”.

3. Lines 38/39: The sentence "Next, the parameters of the laser cutter machine will be optimized to result in the maximum burst pressure of a rectangular balloon." is logically not quite correct. I would rather say: "Next, the parameters of the laser cutter machine will be optimized to produce a rectangular balloon with maximum burst pressure."

We have changed the text accordingly.

4. Lines 44/45: Please change "Conventional fabrication method of soft pneumatic actuators..." to "Conventional fabrication method of thin soft pneumatic actuators...".

This text is specific to non-thin actuators and therefore should not be changed.

5. Here also a general aspect, which also arises in the introduction section: The comparison of the presented method with the classical casting method gives the impression that the manufactured actuators are comparable in their mechanical behavior. Is this really the case? I would assume that the more massive cast actuators can transmit much greater forces. This compensates for the disadvantage of more complex production with the advantage of better mechanical properties.

The review is correct, that non-thin actuators are inherently stronger, and therefore the text has been modified to address this fact, by adding the text “(albeit stronger)”.

Introduction:

6. Line 54: Please change "ultrathin (~70 µm) pneumatic actuators [1]." to "ultrathin (~70 µm) pneumatic actuators of thermoplastic polyurethane (TPU) [1]", as the abbreviation TPU is later used in the protocol, bus was nowhere defined in the main text.

We have changed the text accordingly.

7. Line 59: Please change "of soft pneumatic actuators" to "of thin soft pneumatic actuators".

We have changed the text accordingly.

8. Line 61: To "very challenging due to low resolution of 3D printed molds": There are, however, 3D printers on the market that can produce even nanosized molds with high resolution, see https://www.nanoscribe.com/en/.

Nanoscribe is small in all dimensions and can't practically fabricate large area actuators with thin form factors. Also, Nanoscribe is not a conventional manufacturing method as described in our text.

9. Line 77: Please change "thin form factors" to "small form factors" and also define this term.

The term does refer to thin, and not small, since they can be large areas. We have modified the text to define this term as, "(i.e., large areas with small thickness)".

10. Line 78: Please change "Niiyama et al. has" to "Niiyama et al. have".

We have changed the text accordingly.

11. Lines 83/84: Please change "relatively large volume [1]. Thus, limiting their" to "relatively large volume, thus limiting their", as the second sentence doesn't have a predicate.

We have changed the text accordingly.

Protocol:

12. Line 90: I would suggest changing the title to "Smoothing the TPU sheets by heat pressing" as the current title doesn't describe the purpose of the step.

We have changed the text accordingly.

13. Line 92: One can also use a laser cutter to exactly cut the TPU layers, if necessary.

We have added the laser cutter as another method for cutting the TPU layers.

14. Line 96: Please change "sensitive resistor using" to "sensitive resistor later to be used in the heat press using".

We have changed the text accordingly.

15. Line 104: There is an error in °F.

We have fixed the error.

16. Line 109: I would suggest changing the title to "Finding the optimal laser parameters" as the current title is logically not correct.

We have changed the text accordingly.

17. Line 115: How is the fluid dispenser connected to the balloon and how does the connection seal? Maybe, refer to step 4?

We have referred to step 4 accordingly.

18. Line 120: Please change "parameter" to "parameters".

We have changed the text accordingly.

19. Line 123: I would suggest changing the title to "Fabricating the actuators by laser cutting/welding".

We have changed the text accordingly.

20. Line 124: is the specification of the CAD software really necessary?

We have changed the text to a generic CAD term.

21. Line 126: Do you mean "line width"?

We have updated the text to explain the need for this step.

22. Line 136: Please change "pattern" to "actuator pattern".

We have changed the text accordingly.

23. Line 142: Here, you write that the laser is run again, but the laser hasn't been run yet; it was only focused.

The laser has been run using the parameters in step 3.11. Step 3.13 has been updated to clarify this fact.

24. Lines 142/145: The middle lines in the actuator design are welded and the outer contour is cut out. This is not clear in the description. This also applies to finding the optimal laser cutting parameters.

There is no separate welding condition. We have updated the text in 3.15 to be consistent.

25. To steps 3.11, 3.14, and 3.15: If you define the laser cutter parameters here, why should the reader identify them in step 2 in the first place?

These are representative numbers for our exact system. We have provided this text to clarify this fact, "(these parameters work for our system, but depending on your laser power and system, it may need to be changed)".

26. Line 158: Please change "over inflation" to "overinflation".

We have changed the text accordingly.

27. Line 161: Please change "using" to "use".

We have changed the text accordingly.

28. Line 185: Please delete the "and".

We have changed the text accordingly.

29. Line 199: Please change "will be" to "was".

We have changed the text accordingly.

30. Lines 198-200: See comment 24.

There is no difference between cutting and welding. The term edges has been removed to avoid confusion.

31. Line 208: Please change "is cut" to "was cut".

We have changed the text accordingly.

32. Line 209: Please change "steel needle" to "steel needle (Fig. 4B)".

We have changed the text accordingly.

33. Line 211: Please change "(Loctite 409)" to "(Loctite 409), Fig. 4C".

We have changed the text accordingly.

34. Line 212: Please change "(Fig. 4)" to "(Fig. 4D)".

We have changed the text accordingly.

35. Lines 240-242: Please reformulate this description as it grammatically incorrect.

We have changed the text to the following, "Figure 4. Needle Connection. Images depicting the steps for connecting a blunt needle (A) to a balloon actuator using glue (B) as an adhesive. The needle is inserted into the narrow end of the actuator, which is opened using scissors (C), and sealed with PTFE tape (D).".

36. Line 265: Please change "requires" to "require".

We have changed the text accordingly.

37. Line 276: Please change "used actuators" to "used as actuators".

We have changed the text accordingly.

38. Line 278: Please delete the comma.

The comma has been deleted.

Reviewer #2:

Manuscript Summary:

This method article is an extension of the author's previous paper. The manuscript demonstrate the method of rapidly manufacturing thermoplastic polyurethane soft pneumatic actuators in detail.

Minor Concerns:

1. Since the linear pattern of 8 lines are stressed in the Representative Result section and in Figure 2, the reviewer suggests that the author should clearly demonstrate this pattern in the fabricated actuator in Figure 3B.

Figure 3 has been updated to include the described linear pattern.

2. The descriptions in several steps in the Protocol section need to be expressed more clearly. The commercial information of the force sensor in 1.5 and 1.6 should be sufficiently referenced in the Table of Materials and Reagents. The thickness of the silicone layer should be clearly stated.

The details of the force sensor have been added to the Table of Materials and the thickness of the silicone layer has been clarified, as (~3 mm thick) in step 1.6.

Reviewer #3:

This work presents a method to rapid Manufacture of soft pneumatic actuators and robots with a thin form factor using a laser cutter machine to weld/cut. This manuscript is suitable for this journal. But before publication, there is something need to be modified.

1. During the process of heat pressing, were the TPU films stamped by the heat press? Or they were just flattened. That should be clarified to avoid the confusion from readers.

The title of this section has been updated to, "1. Smoothing the TPU sheets by heat pressing", in order to avoid confusion.

2. During the process of Laser Cutting the TPU sheets, were the films cut first or welded

first? And when were they cut or welded? These information should be provided to help reader to understand the aims and details of the process.

There are no separate cutting and welding steps. We have updated the document with consistent terminology to clarify this. In addition, we now specifically state this fact in the Representative Results section, "It should be noted that the laser cutter always is simultaneously cutting and welding the TPU, the cutting and welding are not done in separate steps or achieved by different settings."

3. Except for the bending pattern, are there some other deformation patterns, such as spiral, twist or axial contraction, realizable in this method? If yes, these designs are suggested to be included in this manuscript.

There are several other deformations that are achievable by changing the cutting pattern. Those have been shown in a previous publication and are cited accordingly, "(various patterns can be seen in reference [1])".

4. The output force of the actuator is also a significantly important property for soft actuators. But in the part of characterization of the soft actuators, only the deflection of the actuator was measured. The authors need characterize the output force/moment under different pressure and deflection conditions to give readers more information about the performance of the actuator presented in this work.

The performance of these actuators has been thoroughly characterized in reference [1]. For convenience of the reader, we add this information to this manuscript to give some context for the force of these thin actuators, "(as compared to those previously characterized in Fig S6 of [1], showing forces up to 0.1 N)".

5. In this manuscript, it was mentioned that a swimming robot, comprised from four legs where each leg consists from two types of bending actuators is fabricated just in few minutes with the method shown in this work. However, there is no other information provided about the swimming robot. More detail information is suggested to be added in this manuscript.

The details of the swimming robot are described in our previous manuscript, but clarified with this added text, "as previously demonstrated [1]".

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Title of Article:	Rapid Manufacturing of Soft Pneumatic Actuators and Robots
Author(s):	Amir Ali Amiri Moghadam, Alexandre Caprio, Seyedhamidreza Alaie, James K. Min, Simon Dunham, Bobak Mosadegh

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