Low-Cost Open-Source Mechanical Tester for Soft Robotics*

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***Abstract*— Current setups for testing soft robotic actuators are neither open-source nor automated, and tend to be expensive. In this paper, we present a versatile and accurate mechanical tester that measures the force output of soft pneumatic actuators. The tester uses an automated stage to autonomously run measurements of characteristics such as blocked tip force. We developed a design that used 3D printing, laser cutting, and pre-machined components to make the mechanical tester low-cost, easy to assemble, and easily modified. We present a comparison of our mechanical tester to a more traditional approach to demonstrate the tester's accuracy. We designed the tester to be open-source and accessible to all soft roboticists including academics and hobbyists.**

I. INTRODUCTION

Soft robotics is an emerging field that is giving rise to a diverse plethora of robots and devices [1], [2], [3], all of which rely on novel actuation methods to interact with their environment. Such actuators include dielectric elastomer actuators [5], pneumatic artificial muscles [6], pneumatic network actuators [7], and fiber reinforced actuators [8]. These soft actuators make soft robotic devices well suited to a variety of applications such as hand rehabilitation [9], food handling [10], and as general robotic manipulators [11]. To be useful in a practical setting, the behavior of an actuator must be understood through modeling and characterization [9], [13]. One primary parameter is actuation force. Establishing a relationship between actuator geometry, input power, and output force will allow roboticists to design soft robots with better grip force, allowing them to handle objects with dexterity. To this end, previous work has developed a number of characterization procedures and setups [9], [13], [14]. However, these setups are either closed-source, expensive, or completely manually operated.

In this paper, we present a low cost actuator testing platform that is easy to assemble and open source. In addition, we are releasing the hardware and software files that allow anyone to make a copy of this tester (i.e. making making it open-source). We also show that, despite its simplicity, the testing platform enables accurate evaluations of tip force for various actuator morphologies. The following sections describe the open-source design of the tester (Section II), the fabrication and assembly process (Section III), a discussion of our experiences using the tester and a comparison with manual testing methods (Section IV), conclusions and future directions (Section V).

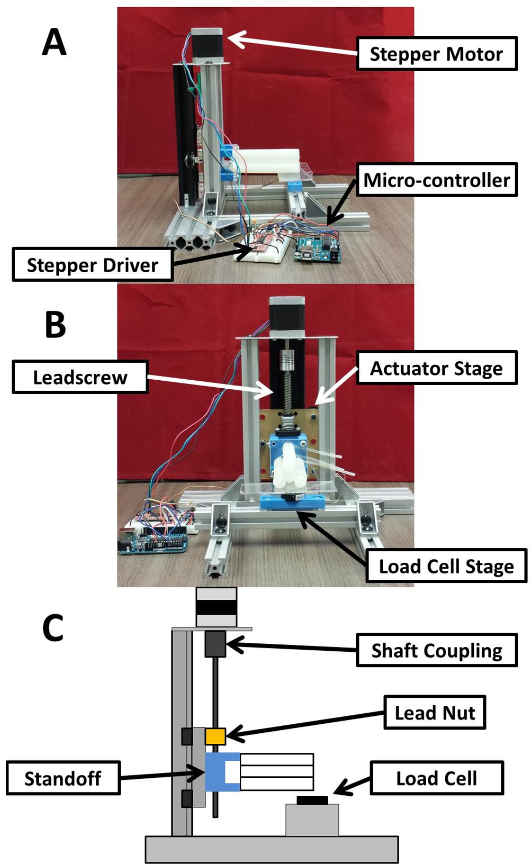

Fig. 1. A) Side view of mechanical tester and major components. B) Front view of mechanical tester, C) Diagram of linear motion system.

II. Open-Source Mechanical Tester Design

The functional requirements of the mechanical tester were to measure the blocked force output at the tip of a soft pneumatic actuator and to automatically position the actuator so that the force sensor blocks the actuator's motion. The blocked force of a soft actuator is the force exerted when its displacement from resting is zero. This is typically when a soft actuator outputs the greatest force because the more an actuator deflects, the more the elasticity of its material applies a restoring force. In order to keep the distance between the actuator and the force sensor constant between tests, we employed a motorized vertical axis so that the apparatus

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could automatically position the actuator right above the force sensor. The force sensor was a commercially available compression load cell (FX1901, Measurement Specialties, Inc.).

Our goal was to make the mechanical tester open-source and adaptable, to make it useful to makers and academics alike. With minor modifications, the mechanical tester could be used to conduct tensile or 3 point bend tests of soft materials.

The testing device, shown in Figure 1, consisted of three sets of t-slotted aluminum bars arranged orthogonal to each other. The vertical bar acted as a linear guide for the actuator stage while the horizontal bars constrained the position of the load cell. A lead screw turned by a stepper motor moved the actuator stage along the vertical bar. The stepper motor was mounted at the top of the assembly with a metal bracket. A shaft coupling handled misalignment between the mounting bracket and the lead nut on the slider stage. The load cell snapped into a carriage which allowed for its repositioning. An anti-backlash lead nut transferred the motion of the lead screw to the linear stage and eliminated slack in the stage's position. A pressure plate attached to the load cell to increase the sensor surface area. Since soft actuators deform readily when making contact with a flat surface, the area that the actuator pushed against had to be sufficiently large to ensure that it made contact with the load cell only. We designed the pressure plate itself to be just large enough to support a thin piece of acrylic. This piece of acrylic served as the target for the actuator. For each actuator morphology, a mounting plate was made so that the actuator could attach to the tester. This actuator plate was attached to a standoff so that there was room for pneumatic tubes attached at the base of the actuator. An Arduino received data from the load cell through an instrument amplifier and controlled the stepper motor with a stepper motor driver circuit.

As mentioned earlier, the mechanical tester was designed with the intent of making its design freely available in an open-source format. We designed the testing frame while keeping in mind the needs of other experimenters who may use our device. For this reason, the load cell could occupy a wide range of positions relative to the actuator to accommodate actuators of varying lengths and the frame was made from t-slotted aluminum bars to facilitate additions to the design. We will upload the plans for our tester to the Soft Robotics Toolkit website for distribution. These plans would include a full bill of materials of all parts used, CAD files, step by step pictures of the assembly process, and starter code for the micro-controller. We hope that by explaining how our tester works, others may modify and improve upon our design as they adapt it to their particular needs.

III. Fabrication of Testing Device

The t-slotted aluminum frame (Misumi Group Inc.) of the mechanical tester was cut to size by the manufacturer so only a screwdriver and allen key were needed to construct the frame.

Due to the standardization and generous tolerances of t-slotted aluminum bars, parts from different manufacturers (e.g. Misumi Group Inc., Inventables, Inc.) were easily integrated with each other. A specialized aluminum extrusion (Inventables, Inc.) served as both a linear guide rail and a support for the stepper motor. The linear guide had rails that allowed a cart with v-shaped wheels to traverse across it, but also had the t-slots of normal t-slotted aluminum.

We designed the testing device to require minimal machining. Only two parts required machining: the mounting plate for the stepper motor and the lead screw. We formed the mounting plate with a metal shear for the shape, a drill for the mounting holes, and a CNC-controlled mill for the large central hole. We used a band saw to cut the lead screw to the correct length and a lathe to create a smooth stepped portion that would fit into the shaft coupling.

To save time and reduce complexity, we used a laser cutter (PLSM6W, Universal Laser Systems) to make some of the parts that were unique to our design. Although prefabricated linear stages exist, we used laser-cut acrylic to make a linear stage that was appropriately sized and had the required hole pattern. Commercially available stages were expensive, larger than what our tester could accommodate, and did not have appropriate mounting hole patterns. To attach an actuator to the linear stage, we laser-cut a piece of acrylic that contained an outline of the actuator's base and four screw holes for attaching to the linear stage. In addition to using a laser cutter, we made use of a 3D printer (Robo R1+, Robo3D, Inc.) to create parts that integrated the load cell with the rest of our hardware. The 3D printer fabricated the pressure plate so that it could attach to the recessed button of the load cell. In the interests of avoiding adhesive in our design, we made an adapter with two mounting holes and which snap-fitted onto the load cell. We also fabricated the standoff bracket with a 3d printer to allow us to connect the linear stage, the lead nut, and the actuator mounting plate together with a single part.

A micro-controller (Arduino, LLC) controlled the motion of the linear slide. Custom code acquired, filtered, and processed data from the load cell. The micro-controller used a low-pass digital filter to reduce noise in the voltage signal from the load cell's amplifier. A function converted the filtered signal to force (Newtons).

The micro-controller also communicated with a computer through a serial port to allow the user to see force data from the load cell. We programmed the Arduino to default to printing data from the load cell while waiting for user input. We controlled the mechanical tester with commands in a number-letter format where the letter denoted the type of command and the number was an argument required by the action. This code allowed the mechanical tester to accept the following commands:

- Move up: moves actuator stage upwards by an amount specified by the user
- Move down: moves actuator stage downwards by an amount specified by the user
- Zero load cell: samples load cell output over five

seconds and defines the average of measurements as zero Newtons.
- Home actuator: moves the linear stage downwards until the actuator makes contact with the load cell, then moves upwards a small predefined amount.

On start-up, the micro-controller automatically zeroed the load cell and provided the user with a summary of the above commands. After 3 seconds (enough time for the user to read the command summary), the micro-controller began to print data from the load cell and wait for user commands.

The cost of the mechanical tester was kept relatively low in order to make it feasible as an open source design. Parts were purchased from hobbyist retailers when possible as they tend to be less expensive than professional grade equipment. Some parts were even made by members of the maker community such as the stepper motor driver. Price was also reduced by fabricating parts using laser cutters and 3D printers. The price breakdown by part type or system is given in Table I. In terms of labor in fabrication and assembly, the mechanical tester was low cost as well thanks to its use of 3D printing. As can be seen in Table II, fabricating the 3D printed parts took the most time but required no supervision and thus could be made in parallel to the rest of the system.

TABLE I
PRICE BREAKDOWN OF MECHANICAL TESTER

Part Category	Price
Extruded Aluminum Frame	$65.68
Stepper Motor and Lead Screw	$64.52
Linear Slide Mechanism	$36.42
Sensors and Electronics	$70.66
Total	$237.28

TABLE II
ESTIMATED TIME OF FABRICATION AND ASSEMBLY

Task	Time to Complete
3D Printing	4 hours
Machining	1 hour
Laser Cutting	10 minutes
Soldering and Wiring	30 minutes
Assembly	30 minutes
Total	6 hours and 10 minutes

IV. DISCUSSION

We used our mechanical tester to aid in the characterization of molded silicone pneumatic actuators, of varying material and wall thicknesses, based on blocked tip force. These actuators had 3 radially arranged silicone air chambers and were used to make a dexterous soft robotic gripper [12]. The goal of the characterizations was to determine how the material and wall thickness of the actuator's air chambers affected their agility and strength. This required the load cell to be immediately adjacent to the actuator in its resting position. When tested, each actuator was pressed into the mounting plate where it was held in by friction. We then fixed the combined actuator and mounting plate to the linear stage and adjusted the position of the load cell to align with the tip of the actuator. Next, we used the homing routine to vertically position the actuator for a blocked tip force measurement, i.e. immediately adjacent to the load cell. While activating the actuator with a pressure valve, we recorded the data returned by the testing device's micro-controller with a MATLAB script. In addition to evaluating blocked tip force, we also measured the maximum displacement of the tip when unconstrained while the actuator was in the testing frame. To do this, we simply moved the actuator away from the load cell and pressurized the actuator while taking a video of it. The video was later processed by a MATLAB script which tracked the actuator's boundary to determine tip displacement.

To verify the accuracy of our mechanical tester, we compared its data with an alternate method. This method, depicted in Figure 2, held the actuator in place with a fixed mount and used a commercial scale as a force sensor. The relative position of the scale to the actuator had to be set manually. In this comparison, we inflated a soft pneumatic actuator at 20, 40, 60, 80, and 100 kPa for both the mechanical tester and the scale setups. The same actuator was used for each system. The data returned by each system, in Figure 3, correlated well with each other and showed that the tester can automatically do the job of positioning the actuator for a force test with minimal losses in accuracy.

In our testing, we found that the mechanical tester was ca-

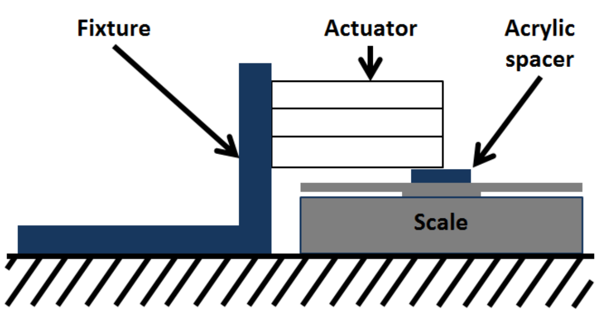

Fig. 2. Diagram of testing setup using manual positioning and a scale.

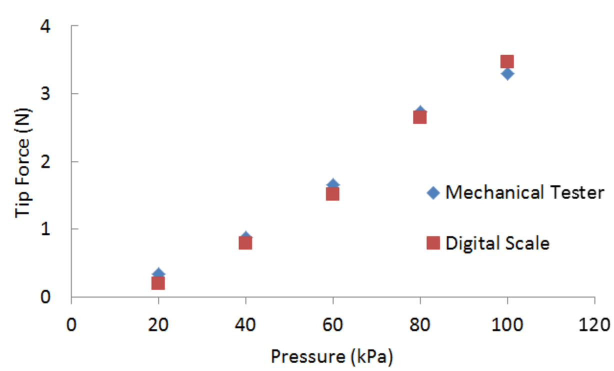

Fig. 3. Comparison of two actuator evaluation methods: mechanical tester and commercially available scale.

pable of evaluating tip force in a variety of actuator designs. In addition to the molded silicone actuator described above, we tested a 3D printed three-chambered soft actuator (Figure 4a) and a pneu-net style actuator (Figure 4b). The only modifications to the testing frame that we needed to make were to the actuator mounting plate, and these modifications simply involved laser-cutting a new mounting plate from acrylic and screwing it onto the linear stage standoff.

V. Conclusion

In this paper, we presented a testing apparatus that measures tip force for a variety of soft actuators. Its low cost, quick assembly, and versatility make it useful for labs that want a reliable method for gathering data about their actuator designs. The mechanical tester also made use of components used or created by hobbyists.

The testing device's cost, simplicity, and use of readily available parts make it suitable for those maker hobbyists that want to do perform tests on their creations. Currently, hobbyists in the maker community rarely make quantitative measurements in their work, although there have been some exceptions. By making our testing device open source, we may encourage members of the maker community to perform more experiments and to use quantitative measurements to shape their design process, and possibly build testing devices of their own.

During actuator characterization, pressure sensing was handled by the pressure source's instruments. In order to make the mechanical tester more convenient, we plan to integrate a pressure sensor into the hardware so that the microcontroller can record pressure and force data simultaneously.

The tester was designed to be able to test soft materials, which allowed for a compact, inexpensive design. Since the applied load and lead nut are arranged alongside each other (rather than in-line), the testing of rigid materials may jam the linear stage. Future work would include the design of a specialized linear stage for stress testing. The stage would be designed to closely align the point of loading with the lead nut. To improve the mechanical tester's functionality as a stress tester, a later iteration would use position feedback of the stage to allow for accurate measurement of strain in the test specimen.

In a future version of the mechanical tester, we will eliminate machining from the build process in order to avoid the need for access to expensive machinery such as mills and lathes. To do this, the aluminum mounting plate, which required the use of a mill, would be replaced by laser-cut acrylic. The machining required to integrate the lead screw would be eliminated by purchasing a customizable pre-machined lead screw.

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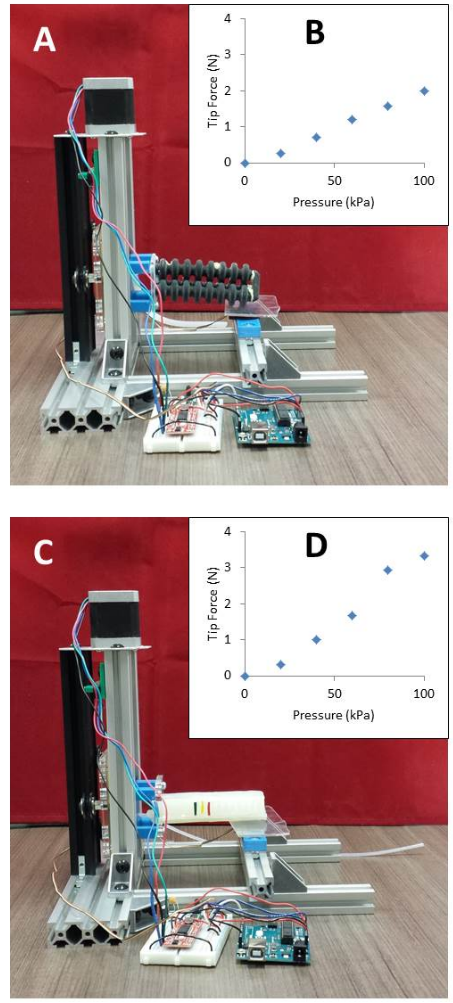

Fig. 4. A) Testing frame with 3D printed multi-chamber actuator. B) force-pressure data of 3D printed actuator obtained with mechanical tester. C) Testing frame with pneunet actuator. D) force-pressure data of pneunet actuator obtained with mechanical tester.

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