2018 IEEE-RAS 18th International Conference on Humanoid Robots (Humanoids)
Beijing, China, November 6-9, 2018

Design, Fabrication, and Evaluation of Tendon-Driven Multi-Fingered Foam Hands

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***Abstract*— We present a novel class of tendon-actuated soft robots, which promise to be low-cost and accessible to non-experts. The primary structure of the robot consists of flexible foam, and so we term the robots created using our approach "foam robots." A foam robot moves by driving servo mounted winches that contract (or slacken) tendons routed through the robots textile skin. We provide a methodology for fabricating these types of robots and go on to fabricate several 'foam robots' in the form of multi-fingered hands and perform various experiments and demonstrations to illustrate the robust applications of these robots to tasks such as dexterous manipulation.**

***Index Terms*— Grasping and Manipulation, Novel mechanism design, Physical interaction**

I. Introduction

Soft robotics has shown great potential for producing versatile robots for a variety of tasks [1] that are inherently safe [2] due to their compliant nature, making them ideal systems for physical human interaction [3][4][5].

Over the years, there have been many interesting studies in soft robotics that explored variations in geometry [6], materials [7], fabrication techniques [8], and actuation [9][10][11]. These advances continue to improve the capabilities demonstrated by soft grippers [12][6]. However, completely soft multi-fingered hands capable of dexterous manipulation tasks remain largely out of reach.

Textiles, inflatables, and foams have been investigated as materials to make robots more suitable for human robot interaction scenarios including pediatric medicine [4] or elderly care [5], as well as for mobile robots [13]. However, most soft manipulators typically still rely on traditional rigid components, but with compliant exteriors, and so do not fully benefit from the aforementioned advantages of soft robots. We propose a fabrication and actuation methodology

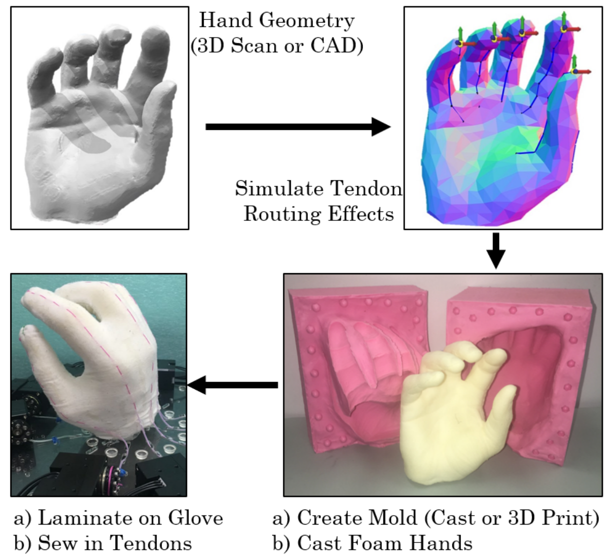

Fig. 1. Pipeline for creating foam robots (shown for a human hand design).

which produces soft robots with a fabric skin and a soft foam interior throughout. For the primary focus of this work, the foam robots of interest take the form of multi-fingered hands, demonstrating the robustness of our method by simultaneously achieving whole-body compliance as well as repeatable posing capable of dexterous manipulation. Our approach begins by choosing an initial hand pose, exploring different tendon routings in simulation (described in detail in [14], and fabricating the hand with appropriate casting methods; this approach is illustrated in Figure 1.

A benefit of using easy to mold bodies and even easier to cast foam, together with cheap and readily available materials for support and actuation, is that it promises to increase the accessibility of soft robotics. We draw on work from Bern et al. [15] who developed methods for designing tendon-driven plush robots. However, these robots are intended as toys for children, and are not suitable for dexterous manipulation. We move to use a cast foam interior, rather than stuffing, to improve deformation behavior and structure in more complex 3D geometries. Furthermore, we investigate new fabrication techniques that leverage well-developed practices from the artistic prop and textile industries.

Overall we make the following contributions:

- Fabrication methodology for *foam robots*, tendon actuated soft robots, using simple molding and casting techniques and driven by servo actuated tendons.
- Experiments and demonstrations that serve to illustrate the capabilities of these robots, such as complex ma-

This work was supported in part by the National Robotics Initiative grant NSF IIS-1637853 and in part by a NASA Space Technology Research Fellowship (award 80NSSC17K0140). Any opinions, figures, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Robotics Initiative or NASA.

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Fig. 2. 3D printed mold and cast foam planar gripper.

nipulations, sub-millimeter repeatability, and continuing functionality over 1-year later.

- Discussion of design challenges and methodology insights that shed light on the capabilities, drawbacks, and potential of this class of robot.
- A road-map of future goals that promises to greatly improve the scope and quality of these class of robots.

We show examples of power grasps, precision grasps, and precision in-hand manipulations. We show that different tendon arrangements for the thumb produce different sets of capabilities, and that the rest pose of the robot is important to consider. We demonstrate our approach on both humanlike and non-humanlike hands. We believe that this approach has great potential to produce highly capable manipulators, and hope this work provides a proof of concept that will open the door to large scale exploration of design and optimization of completely soft multi-fingered hands for dexterous manipulation.

II. Fabrication

We present in this section a set of fabrication techniques and mechanisms used to create a soft multi-fingered hand, with capabilities to be adapted for the creation of a wide variety of foam robots. The general goal of designing foam robots is that they should be truly soft, while still able to perform a diverse set of tasks. Hence, a foam robot dexterous manipulator capable of complex poses and actions is an ideal candidate to showcase the potential of such systems. To achieve the goal of 'true' softness, the robot is constructed of only soft foams, knitted textile skins, fibrous tendons, and flexible PTFE tubes for cable routing. All rigid mechanical components are housed away from the hand, and in the future systems can be embedded inside the foam to a degree that their hardness is unnoticed, or even replaced by soft actuators such as the cost effective artificial muscles explored in [16].

A secondary goal of our work was to develop a fabrication methodology which was easily accessible to non-experts. For this reason, the fabrication methodology was chosen to be low-cost ($<$ \$100), and relies on easy to follow casting techniques that can be readily found in step by step internet video tutorials. The mechanical devices we use consist of off-the-shelf components, 3D-printed parts, and laser cut acrylic, and so should also be accessible to the novice user.

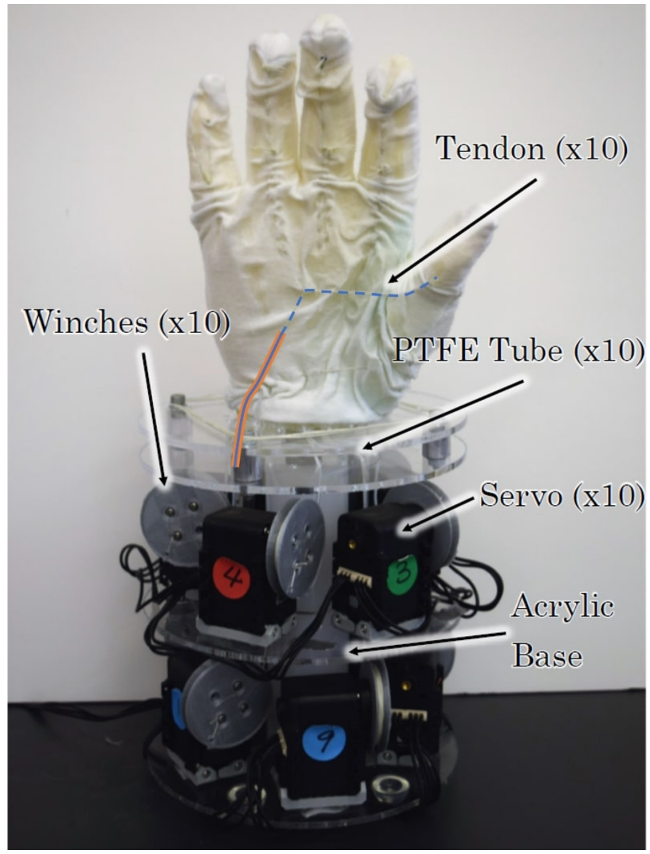

Fig. 3. Annotated assembly of a foam hand. A single tendon is highlighted in blue, with a dash line representing the porting sewn into the glove. The associated PTFE routing tube is highlighted in orange.

A. Creating the Mold

An initial hand pose is chosen and evaluated in simulation to find tendon networks that result in the ability to achieve desired poses. If necessary, the user iteratively changes the hand geometry to better suit their tasks. Using the hand geometry the user can either use CAD software or automatic mold generation methods [17][18] to yield models that can be 3D-printed or machined. Additionally, the mold can be made by casting physical objects, such as a real human hand.

B. Casting Foam Hands

A two-part urethane foam compound is used to cast the final foam hand, a mold and cast of a planar two-fingered gripper is shown in Figure 2. A variety of densities are available to choose from that best match the user's application, we most preferred *FlexFoam-iT! X*, finding it a good balance of strength and compliance. The behavior of the foam is not always intuitive: while casting humanlike hands we found that slightly thicker sections of the palm were much stiffer, and slightly thinner sections of the fingers were much softer. Therefore, the hand geometry should be carefully considered to avoid unwanted behavior. While not necessary, the use of a laboratory mixing machine guarantees very consistent results from cast to cast.

Of great benefit is the ability to go from a chosen rest pose or model to a cast foam hand in under 24 hours for a cost of a approximately $50 for the mold and only a few dollars for each foam hand afterward. The ability to make a large supply of foam hands in a time and cost efficient manner is very important for lowering the barrier to entry for researchers desiring to experiment with soft robots.

C. Gloves and Sewing Tendons

A textile exterior, e.g. a glove, is used as a skin for the foam hand, acting as a layer conducive to sewing in tendons for actuation. For anthropomorphic hands, off the shelf gloves can be used, but for general soft robots, sewn skins from cut felt can be used. In our case, gloves were custom knit for each hand geometry by way of automatic processes [19]. The custom gloves can be knit in under an hour with many choices of materials, greatly complementing our rapid prototyping approach. Whatever choice of skin is selected, it is then laminated to the foam core to prevent slip using spray-on upholstery adhesive [1].

Tendons are realized in practice with PTFE coated braided fishing line, and are sewn into the glove with a typical sewing needle, and fixed at the ends with finishing knots.

D. Robot Chassis

The gloved hand is fixtured to a laser-cut acrylic base with hot-melt glue. The tendons are routed through PTFE tubes along the base of the hand to minimize friction where they then interface with servo driven winches. Additional mounting points are placed on the acrylic base so that the PTFE tubes can be fixtured with cable ties. The assembly is detailed in Figure 3.

III. Results

A. Repeatability

A planar two-fingered hand, shown in Figure 2 was fitted with a glove and 4 tendons, 2 flexors and 2 extensors per finger. Using a camera, the trajectories for 6 different grasps were recorded for 800 trials each. The first 50 trials were discarded as a 'break-in' period. From the remaining 750 trials, 50 random trials for each of the 6 grasps were selected (due to limited video processing power and time constraints) for analysis. Seven black dots 6*mm* in diameter were adhered along the gripper before testing to be used for motion tracking. The dots were tracked by applying a *Grayscale Conversion*, *Gaussian Blur*, *Prewitt Edge Filter*, and *Hough Circle Transform*, in sequence, to each frame. Then the circles were sorted using *Nearest Neighbors* .Three of the grasp poses are shown in Figure 4 with the splines formed by the tracking dots superimposed for all 50 trials and at 6 different intervals (300 splines/grasp) along the pose trajectories. For repeatability analysis, the fingertip tracking dots at the final stage of the grasp trajectories were considered, as they undergo the most significant displacements. The final fingertip positions, p_{g_t}, were recorded for each grasp, $g \in \{1,2,\dots,6\}$, and trial, $t \in \{1,2,\dots,50\}$. The nominal positions for each grasp were taken as the mean over the trials, $\overline{p_g} = (\sum_{i\in t} p_{g_i})/50$. The error was computed as the L^2 distance of the fingertips from their nominal positions, $e_{g_t} = \|\overline{p_g} - p_{g_t}\|_2$. The histogram of errors for all 600 trials is shown in Figure 5. Upon inspection there appears to be several outliers in the data; we believe that these correspond to the rare instance that motor commands are not delivered due to a faulty serial connection, and that in the future this can be avoided with a simple program loop to verify motor command delivery. The distribution metrics for the complete data and inlier data (computed with the very conservative $\mu \pm 3\sigma$ filter) are given below in Table I. In the future, higher resolution motion capture should be used, as many of the error measurements were sub-pixel in length. Finally, by plotting the fingertip locations in order, we notice some drift across the 800 trials, on the order of tenths of millimeters as shown in Figure 6. We believe that this is due to some yield, i.e. stretch, in the textile components, and can be reduced in the future by using stronger yarn in the glove knitting process.

TABLE I

Repeatability statistics for planar gripper.

Values in [mm]	μ	σ	median	max
All Trials	0.1738	0.2293	0.1307	3.6360
Inlier Trials	0.1576	0.1210	0.1296	0.8160

B. Strength

Caging grasps were performed on a tennis ball with two separate hands. The pullout force was measured to be 3.2N and 5.8N, respectively, test setup is shown in Figure 7. The difference in strength is primarily due to the hand geometries, indicating that a more 'opposable' thumb is important for power grasps.

C. Comments on Longevity and Durability

Several of the grippers presented have been in use for over one year and thousands of trials, additionally they have been transported transcontinentally in checked luggage and exposed to harsh weather conditions, all without a noticeable lack in performance. While this information is anecdotal, it is the opinion of the authors that these grippers demonstrate good longevity and ruggedness overall.

D. Manipulation Showcase

A variety of manipulations were chosen to showcase the abilities of these hands. In Figure 8 several static grasps are shown. In Figures 9 to 10 several in-hand manipulations are shown. The in hand manipulations are are achieved by selecting several transition poses as key frames, and interpolating between them to achieve smooth motions. The supplemental video for this paper better illustrates these, and more, manipulations.

IV. Discussion

Several of the showcased manipulations were performed with the first prototype ever made, before improving designs; still the robot is capable of achieving robust motions and in-hand manipulations right-away without the need to worry

[1] *3M Adhesive 23*

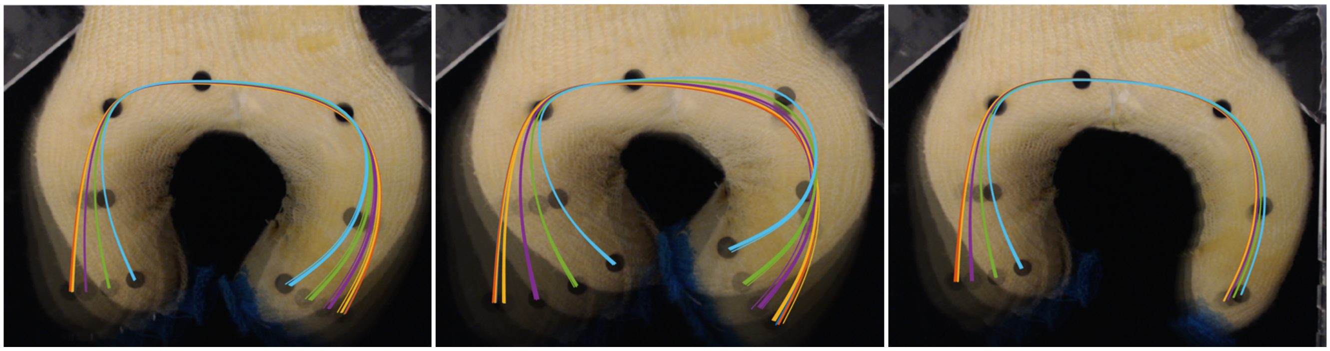

Fig. 4. Three example poses measured for repeatability. Shown are splines for 50 trials per pose, shown at 6 steps along the trajectory.

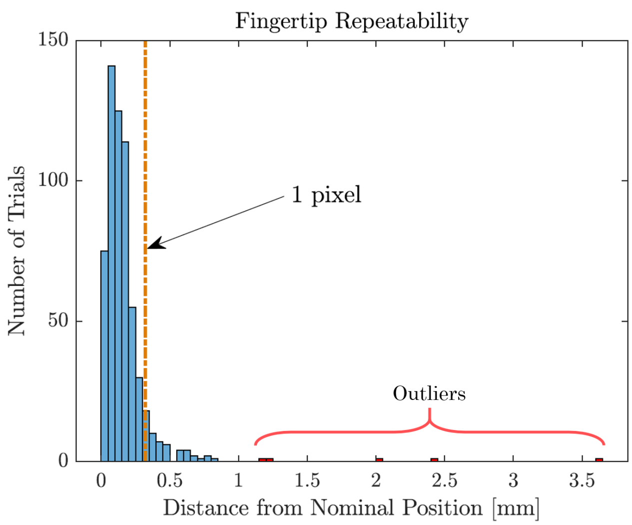

Fig. 5. Histogram of fingertip repeatability over 600 trials.

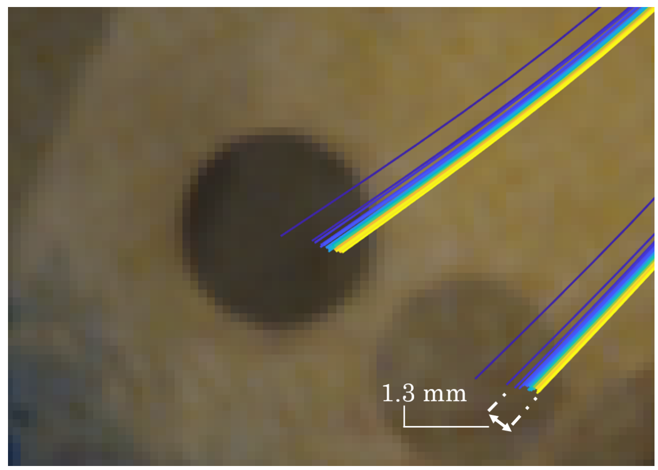

Fig. 6. The fingertip position was observed to drift (shown as blue to yellow) over 8000 grasps.

about self-collisions, a capability not yet seen in truly soft robotic hands.

A. Effects of Different Tendon Routings

Since soft robots do not have any joints, the variety and complexity of achievable poses largely depends on the tendon routing. We explore the effects of different routings in simulation by utilizing FEM tuned to match the behavior of the foam (detailed in [14]) and apply them on the physical hand. A major weakness of our initial design is the inability of the thumb to abduct and oppose the palm. This is mainly caused by an inefficient tendon routing with two antagonistic tendons as shown in the left column of Figure 11. Changing the routing increased the complexity of feasible motions of the thumb significantly. Figure 11 visualizes how different tendon activations enable either lateral or opposing grasps.

Depending on the task, multi-fingered hands are required to achieve certain grasps and motions. The motions of the hand are most importantly determined by the tendon routing. This feature highlights an important advantage of our tendon driven approach, compared to e.g. pneumatically actuated designs, because of the ability to change the kinematics any time by switching to another tendon routing by re-sewing the tendons or swapping gloves, a $\sim$1 hour process.

B. Robot Rest Pose

Our experiments show that the rest pose of the hand design pre-defines the range of motion independently of the tendon arrangement. Since the shape of the foam is fixed and cannot be changed (unlike the tendons), evaluating the geometry in simulation is an important step before fabricating the actual foam model. Depending on the underlying task, certain poses are identified to be more suitable than others. This especially applies to human-like hand geometries. We discovered that human-like hands with flat rest poses have a problem grasping large objects such as tennis balls. This is due to the inability of the fingers to curl around the object and oppose the palm. An advantage of flat rest poses over curled rest poses is that they don't need tendons that run on the back of the hand, because the geometry and the compliance of the foam itself restores the hand to it's original shape. This makes it possible to add more tendons to the front of the fingers increasing the overall dexterity of the design.

Additionally, aspects of the robot geometry are important to consider. It was observed that relatively thick palms and fingers lead to (possibly undesired) localized stiffening. These undesired features can be mitigated by iteratively changing the hand designs and testing them in simulation, reducing the need for iteration of the physical prototypes.

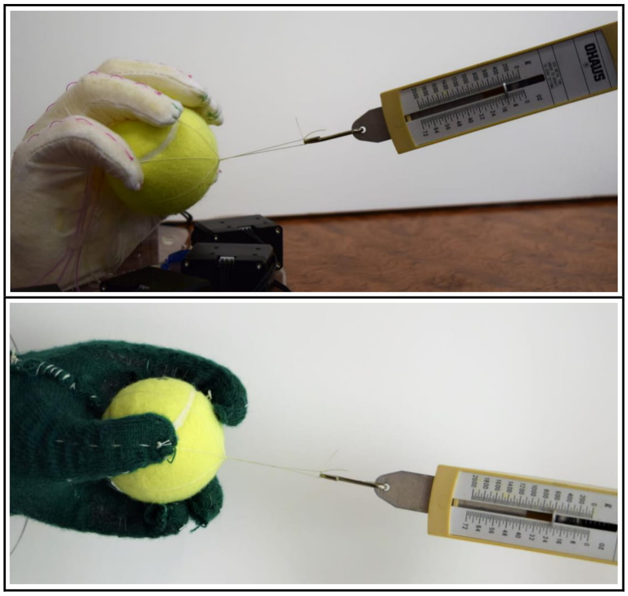

Fig. 7. The strength of caging grasps was measured by pulling on a grasped tennis ball until failure.

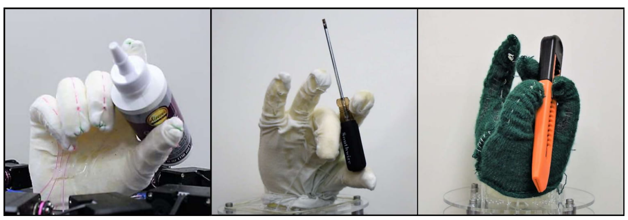

Fig. 8. Demonstration of static grasping with a glue bottle (left), a screwdriver (middle) and a box cutter (right).

C. Weaknesses and Current Limitations

A limitation of the current design is the low stiffness of the foam, which limits the forces we can apply during manipulation, especially while performing ‘pushing’ or ‘pressing’ actions. Our goal is to address this issue in future work by embedding controllable stiffness elements. Additionally, the foam has some hysteresis when returning to the rest pose which we postulate to be caused by tendon-glove friction, this can likely be mitigated with a corrective maneuver, i.e. extending beyond the rest pose in the opposite direction.

The current method of routing tendons along the glove limits the possibilities of these hands two-fold. 1) Geometrically: routing tendons through the foam body would allow for more motions and increased forces by the hands. Initial attempts to route tendons through the foam caused tearing, we would like to explore improved methods to accomplish this in future work. 2) Mechanically: the tendons pull on the gloves, straining the adhesive layer, limiting the maximum tendon forces that can be applied without failure. First attempts at using gloves had no adhesive, causing the gloves to slip. We also experimented with cyanoacrylate, which caused foam hardening. As for the foam itself, it was chosen for being easy to work with. Nevertheless, there are many high performance textiles, adhesives, and specifically engineered foams which could be used instead, and these will likely further improve the longevity, durability, and performance of these soft multi-fingered hands.

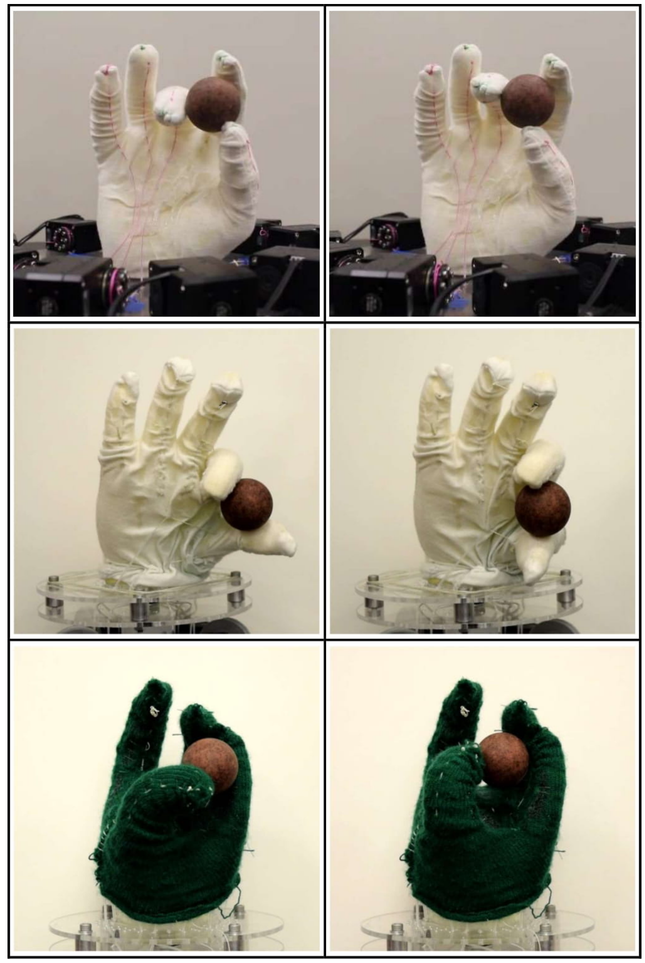

Fig. 9. Three distinct robot hands performing precision in-hand manipulation (twisting a ball).

V. Conclusions

We presented multi-fingered foam hands, a novel class of tendon-actuated soft robots fabricated from easily accessible materials and methods. The fabrication techniques we introduced promise to be inexpensive and help democratize the process of creating soft robots. We utilize a simulation model to aid in choosing robot geometries and tendon routings. Results and select demonstrations from four foam robots of differing morphology were described. A discussion of the results and lessons learned sheds light on the capabilities, strengths, and weaknesses of these systems. The presented robots yield promising potential for many applications such as general use home robotics, industrial applications such as picking, and a variety of human robot interaction scenarios.

Future work will focus on improved designs and models, including contact models for simulating manipulation. We will also continue to develop other types of foam robots such as mobile systems that can walk, slither, and roll. On the physical systems we would like to use better motion capture and embedded sensors to close the loop on our controllers.

Acknowledgements

The authors thank James McCann for knitting our gloves.

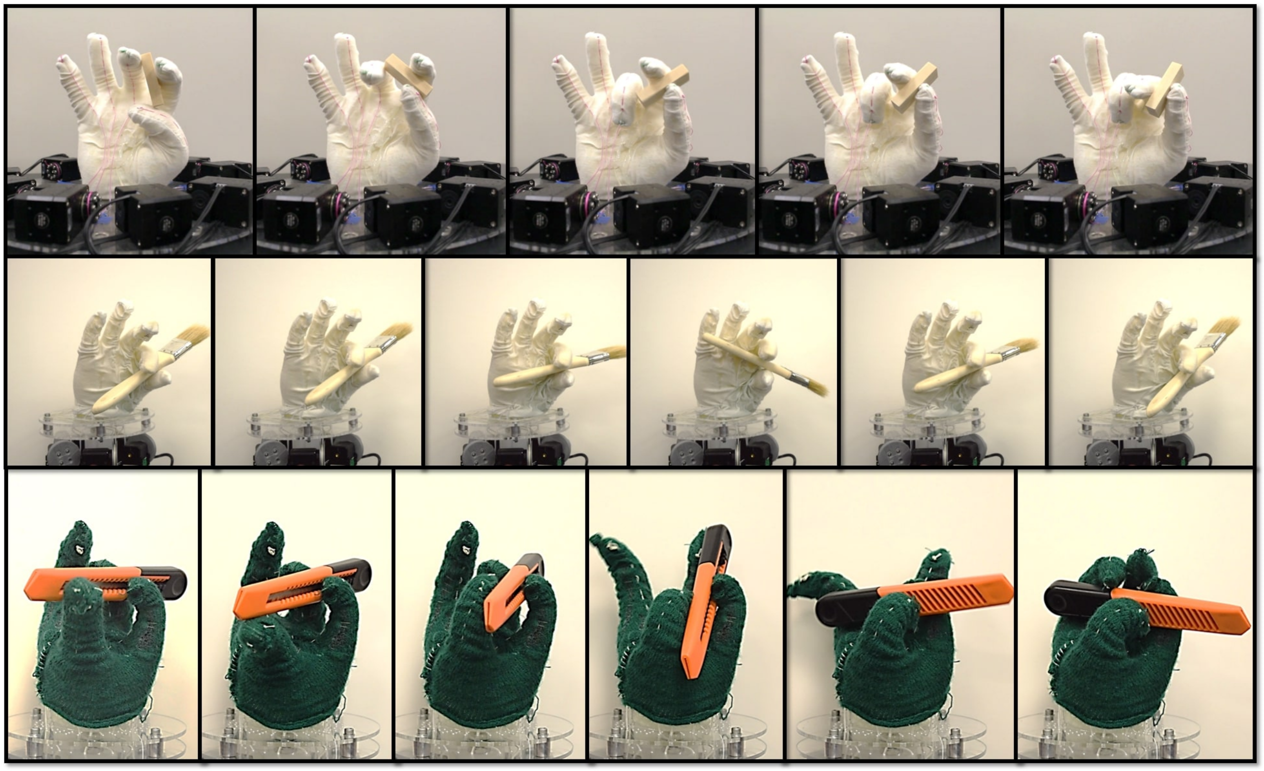

Fig. 10. In-hand manipulation sequences of three foam robots. Top) Lateral Grasp Transition. Middle) Rocking Motion. Bottom) Utility Knife Spinning.

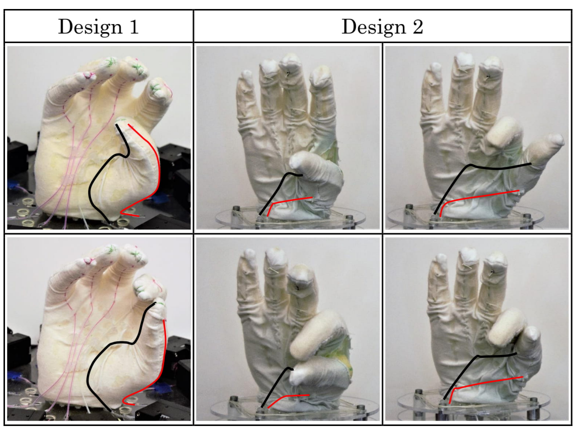

Fig. 11. The effect of tendon configuration impacts the realizable hand poses. In the designs shown, different routings improve thumb mobility.

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