Building a complete soft human-like finger

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***Abstract*— Today's traditional prosthetics and manipulators are not safe, robust and compliant enough to work with humans. Having a robot that could work with humans would open new possibilities for prosthetics and other places where robots collaborate with humans. A solution with a soft actuator, cables, and joints results in a robot that is safe, robust and very compliant, as every part is soft. We compared two designs up against each other and see pros and cons with each design.**

I. INTRODUCTION

Robotic manipulators have many uses and can make life easier for us. They can do tedious work with precision and effectivity, be placed to work in toxic or dangerous areas and therefore not putting humans in dangers. They could also enhance humans or give us a second chance at life, with prosthetics. Today's prosthetics are mainly built with your traditional electric drives, batteries and metal/3d printed parts. This could work well, but robots with high gear ratio and low to none compliance is not safe to have with humans. This is where soft robotics come in, a soft robot is a robot that is made with soft materials, making the robot compliant. This could be elastic cables, actuators or the robot itself. Using soft parts we could build a robot that is: (a) safer to have around humans, (b) more robust to abuse, and (c) compliant to external forces, which are all things prosthetics could benefit from. In this paper, we explored the possibility of making a completely soft artificial human-like finger. Using 3d-printer and silicon casting we built and test two different soft fingers, with silicone tendons, ligaments, and actuator.

II. THE SETUP

The complete setup as seen in Figure 1 shows the assembled setup. It consists of a McKibben air muscle, silicone tendons and one of two fingers. The whole structure is mounted on a testing rig, which consists of an aluminum profile with 3d-printed mount points for the muscle and finger. The silicon used in this project is the ELASTOSIL M 4601 two component silicon[1]. A fortus 250MC 3d-printer were used to print the parts.

A. The Muscle

The McKibben is a well known PAM(Pneumatic artificial muscle) which contracts when it is pressurized. My muscle consists of a long silicone tube, that was cast, a surrounding mesh, a 6mm hose connector and 2 hose clamps. The muscle itself is mounted to the railing with a 3d-printed mount. On the other end, a 3d-printed hook was printed for easy fastening of a silicone tendon. The McKibben muscle measured 16cm in between the hose clamps and was created as long as possible so that we could achieve the most contraction in cm from our muscle. The contractions achieved is showed in Table I, as we can see from the table, most of the contraction happens under very low pressure, and increasing pressure has a small improvement up until a cap. Here seen at 1.5 Bar - 2 Bar where the contraction stayed the same. The muscle is elastic and will give after if pulled hard enough, for this setup the muscle was the strongest part and all other silicon part gave after before the muscle. If other parts of the finger were made less compliant, by scaling up, for example, the muscle could have been stretched before inflated, which results in longer contraction.

Fig. 1. Complete setup

TABLE I

CONTRACTED LENGTH FOR MCKIBBEN MUSCLE

Pressure	Muscle Length	Contracted Length
0Bar	16cm	0
0.5Bar	12.5cm	3.5cm
1Bar	12cm	4cm
1.5Bar	11.5cm	4.5cm
2Bar	11.5cm	4.5cm

B. The Tendons

The tendons are cast using silicone in 3d-printed molds, that was printed at a Fortus 250mc. It a long pipe that is placed in a holder after the silicone is injected with a syringe. The 3d-print is totally tight, so a hot air gun was used at the holder, preventing the silicone to spill. Different sizes were tried, needed to scale the diameter up to achieve enough strength in the tendon, 6mm tendons were then chosen as it became difficult printing bigger diameters, without support, when the tendon was laying down. The mold was laying horizontally in the printer so that the layers in the print would

Fig. 2. Contracted muscle at 1 Bar

Fig. 3. Tendon mold and ligament molds

not prevent the tendon from being pulled out. The mold can be seen in Figure 3.

C. The Ligaments

Both fingers used the same sized ligaments, the function of the ligaments is to hold the finger together and return it to a resting position when the tendon is relaxed. The ligament slides down in a 6mm circle hole, and are 2mm thick. Different lengths of the ligaments were cast, and the shortest possible ligament was attached to a finger to eliminate looseness between joints. Finger 1 had cross-ligaments, this stopped the joints to glide over each other and rather pivot in a fixed position. The molds can be seen in Figure 3.

D. Finger1

Finger1 got inspiration from flexy hand[6], we took the ligaments connecting the finger on the inside and design a new finger around it. The Finger would return to a resting position when no external forces were given to it and be compliant. The ligaments also allowed for an external force to be applied in other directions, other than the curl movement the finger was designed to do, since the silicone can be stretched in any direction, meaning it was quite robust. The ligaments were first constructed without the cross, this caused the joints to glide over each other before bending and therefore require more force to get the revolute joint like a finger. Therefore the cross was created to stop the joints from gliding over each other and rather have a more fixed revolute point. The first finger design with cross ligaments can be seen in figure 4. The first version would have 3mm tendons running down from each joint, connecting to McKibben muscle. With version 2 we removed this need of multiple muscles by running one thicker 6mm tendon through all joints. The tendon is attached to the fingertip with a screw and then runs down tunnels before it connects to the McKibben muscle. This way we could achieve the curling motion of a finger with just one tendon, simplifying the manipulator. Version 2 can be seen in Figure 5 with tendons running down the finger on each side. The second tendon would be used to help the ligaments stretch out the finger again when the muscle relaxes.

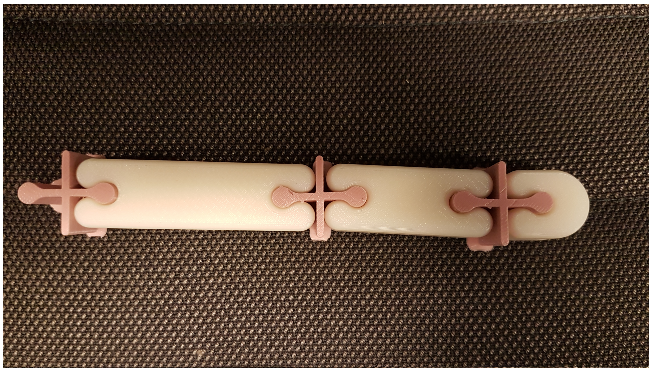

Fig. 4. Finger 1 version 1 with cross ligaments

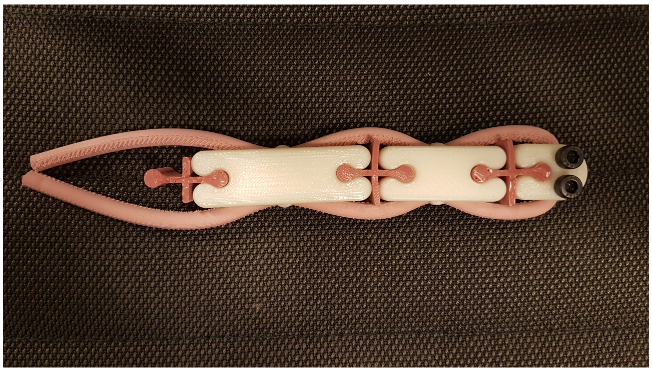

Fig. 5. Finger 1 version 2 with cross ligaments and tendons

E. Finger2

Finger 2 version 2 was putting the ligaments on the outside of the finger, constraining movement and returning the finger to a position when the tendons are relaxed. It was also based

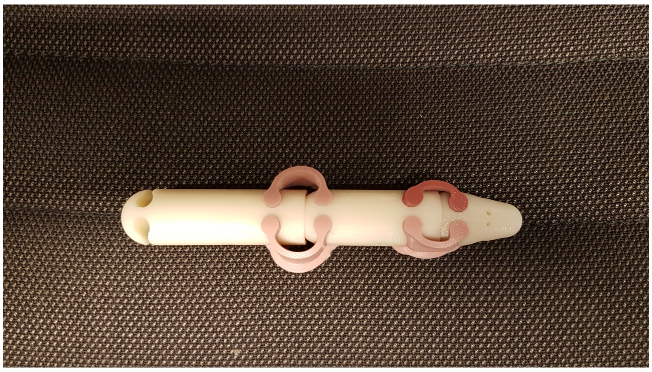

Fig. 6. Finger 2 version 1

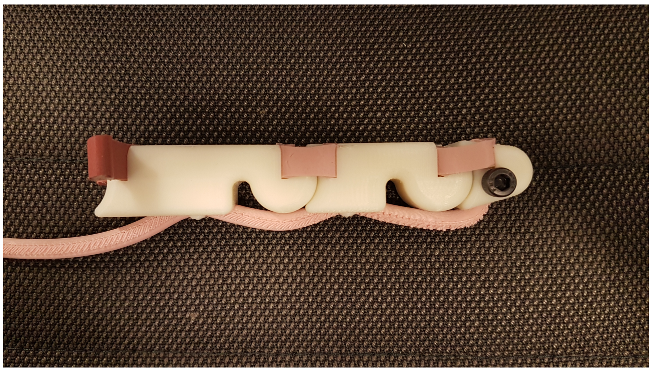

Fig. 7. Finger 2 version 2

on bones sliding over each other like human finger bones. As we can see in Figure 6 the finger had circular ends fitting into the next joint, creating the possibility of movement. A few problems became quickly obvious when the finger was assembled. The ligaments running on the outside of the finger restricted movement more in the direction that we want it than it restricted movement sideways. Also, the joints were not able to bend far enough before stopping either in the next joint itself or the ligament. So version 2 was designed with these 2 problems in mind. Figure 7 show finger 2 and the new design. The shape of the finger is no longer circular, allowing only the finger to bend in the direction we want. The ligament is moved to the side, half in size and mounted only on the top. This was due to space issues, as with the first finger, finger2 also got the simplification with one tendon running through tunnels. Now with the tunnel and the new shape on the finger, that allowed for a far greater inwards curl, the ligaments needed to take less space. So they were moved up, and are now pulling the finger back to original position when the tendon is relaxed. The tendon is attached to the fingertip with a bolt, same as finger1.

III. EXPERIMENTAL RESULTS

Version 2 of Finger 1 and Finger 2 were both mounted to the experiment rig and pulled on with the McKibben muscle.

A. *Finger 1*

Mounting the finger to the muscle it showed that the extra force that the muscle has in the silicone easily stretches out the tendon. So for mounting the tendon running to the muscle had to be mounted under stress and would also allow the muscle to pull more on the finger, creating more motion. Pressurising the muscle made the finger bend significantly in the first joint, compared to the other joints. The rest of the joints bend less, but there was motion all the way to the fingertip. Releasing the pressure brought the first joint back to the original position, mainly due to gravity. The other joints were harder to bend back and especially the fingertip were left at an angle. This is due to friction between the tendon and the tunnel in the 3d-print. The tendons were 6mm and the tunnels 7mm, so it was somewhat a tight fit, creating too much friction. The ligaments in the finger had no problems straightening the finger without the friction of the tendon, so it's clear that more force is needed and/or less friction from the tendon. The finger gave after for external forces, since the tendon stretched and the ligaments moved with. We could push and pull on the finger and once released would bounce back to its position. The tendon was also pulled manually to see if it could overcome the friction and make the finger curl as is were designed to do. Every joint except the fingertip bend at a great angle, the first joint was almost 90, second at far greater than 90.

B. *Finger 2*

Before the finger was mounted to the muscle, its joints were sanded down to remove the lines from 3d-printing. The lines created too much friction in between the joint to let the ligaments straigthen the finger out again. After sanding down the ends, this was not an issue anymore.The finger was also mounted with its tendon strected out a bit, as with finger 1. Using the muscle as the actuator the finger did not curl up, there were only motion in the first joint, and the rest of the finger were straight. This due to the hight friction between the tendon and the tunnels in the finger. Since there was only movemnet in the first joint, the finger was able to return to its original position once the pressure was released. The finger were compliant and could easily be moved out of the way even though the muscle were pressured at 2 bar, the tendon stretched. The muscle did not give after since this requries a much bigger force. Grabbing and curling the finger when under pressure would cause the finger to stay in that position, since we helped it over the friction between the tendon and tunnel. Releasing the pressure when this were done, the finger would not be able to straigthen out again, as the friction the tendon created were too big for the ligaments. The tendon was also pulled manually in this case and the finger curled up as designed.

IV. RELATED WORK

Similar work has been done before and applied in different ways. The shadow Dexterous hand[3] can be delivered using air muscles to move the fingers, the finger is still metal, the tendons non-elastic strings and joint are ball bearings. Even though this gives the hand compliance as the air muscle could be stretched. The hand is a finished product and could also be used in different applications than prosthetics.

Frank Daerden and Dirk Lefeber[2] wrote a survey paper on using PAMS for actuators in robotics, mentioning the McKibben muscle. Pams have low weight and a compliant behavior as they state in the introduction. Pams work like a compliant spring even at a static pressure. The pams are also small so they can be fitted into small spaces, offering big strength and no need of gear reduction, meaning they could be direct drive. This removes backlash and extra inertia as stated in their paper[2]. Also, they state that the use of PAMs is well suited for safe man-machine interaction.

Chung Lik Lau[4] showed how the McKibben muscle was well suited for a low-cost PAM for actuating a robotic hand. The hand was not soft only the muscle, but she found that PAM actuated hand was safe to work with humans due to the natural compliance in the McKibben muscle. The muscle also delivered sufficient force for a hand to grasp objects. As for controlling the finger with precision, Oliver Salazar[5] characterized individual PAMs for controlling a mechatronic finger. The control was based on experiments that lead to the characterization of the pams. The finger was able to move as wanted and even when weighed down the muscle could overcome the extra weight.

V. FURTHER WORK

The silicon tendons do not need to be circular, therefore removing the need for using pipes to cast silicon in. They could be square and that would simplify the casting process. The tendons could be cast laying flat and more complex designs could be made, such as a tendon that splits into two parts and then joins together at a later point. Also scaling the tendons up, making them bigger, would also not be an issue. The McKibben muscle could pull a great amount of weight and does not contract really far. As we saw when the tendon was pulled manually, the finger had greater movement and achieved to curl up in one of two designs. Creating a different muscle that could pull further or utilize the strength of the McKibben for more movement, would result in greater result. For the finger designs, both of the fingers need bigger tunnels, or a different design to remove a lot of the friction. A suitable lubricant could also be a solution, but a better design is better for a solution that requires less maintenance, making it more robust. Finger 2 could also benefit from an extra ligament going on top of the knuckle, as in version 1, this would make the finger harder to curl, but easier to return to its original position. The ligaments could also be thicker, make them less compliant, which could be an improvement in both finger 1 and 2.

VI. CONCLUSION

In this project we looked at building a complete soft human-like finger, that is robust, compliant and could bend in an XY-plane. We looked at two different design and tested them with a McKibben muscle. The muscle may not be optimal for this purpose, it has a lot of unnecessary strength and lacking motion. Finger 1 is robust and very compliant, making it safe among humans. The finger does not bend too well in an XY-plane mainly due to high friction between the tendons and the 3d-print. Finger 2 has the same results as finger 1, however with improvements to the ligaments and the friction problem, the design offers a better way to bend the finger like a human finger, which would be much more efficient in a prosthetic use. A finger with this many soft parts offers a much more robust finger, that allows far greater external forces to be applied to it, without breaking. As it would be compliant and mainly go with the force, the compliance would also offer a softer grip for grasping objects, should the design be taken on to a full gripper.

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