Soft biomimetic prosthetic hand: Design, manufacturing and preliminary examination

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Abstract— **The human hand is a complex structure. It is strong but precise. It consists of a very complex mechanical structure that enables the hand to adapt and efficiently handle objects of various shapes, weights and textures. Today's prosthetic devices, struggling to provide similar functions, become overly complex and expensive. They are composed of multiple, precise parts, including miniaturised actuators and sensors as well as complex control, to satisfy the manipulation tasks required. In this paper we propose a soft pneumatic hand that adapts passively to the handled object due to its mechanical compliance. It is pressure driven and enables individual fingers to be controlled independently for dexterity or in groups when a synergistic finger movement is needed. The hand has a truly anatomical shape, is easy to replace and cheap in production. The design can be easily adjusted in terms of shape and size in order to fit each individual user. The paper presents the design, manufacturing technology, current control system and preliminary tests of the hand's capabilities.**

I. INTRODUCTION

Prosthetic hands help amputees to improve their manipulation capabilities. However, today's robotic prosthetic devices can be expensive as they are complex and sophisticated mechanisms. They contain a wide range of precise mechanical and electrical elements and require complex control techniques to satisfy even simple manipulation tasks. They are made of rigid and heavy materials and actuated by the power of electrical motors. Due to the lack of mechanical compliance any flexibility of such devices require additional flexible structures (such as springs) or complex sensing to be embedded into their construction (to achieve software-controlled compliance). Recent years some new prosthetic hands based on 3D printing technology have been proposed. Those projects aim to make the prosthetics affordable and easily manufactured for everyone [1], [2]. They are still, however, rigid.

Soft robotics is an interesting alternative that overcomes above issues. Soft robots are made of flexible materials, hence, they are compliant by design. They adapt easily to the environment without the need for additional sensing or control. The control of soft robot can be simplified as part of it is achieved by the flexible structure itself adapting to the handled object passively. Since soft robots are made of soft and compliant materials such as silicone rubber, they can efficiently operate without expensive sensing; thus, they are cheap and affordable. They are also considered to be safer than traditional robots regarding robot-human interaction because of their inherently soft structure. Over the last years, some examples of hands made of soft and compliant materials had been presented. The Pisa/IIT Soft Hand [3] uses elastic tendons to operate its rigid-component fingers. Exploiting grasp synergies and the flxible tendons, a single motor is sufficient to actuates all the fingers and to achieve a variety of grasps that adapt to the environment. Another compliant hand driven by shape memory alloy is presented in [4]. It can also passively adapt to the environment and offers sensing capabilities. There is no need for any sophisticated control with those hands.

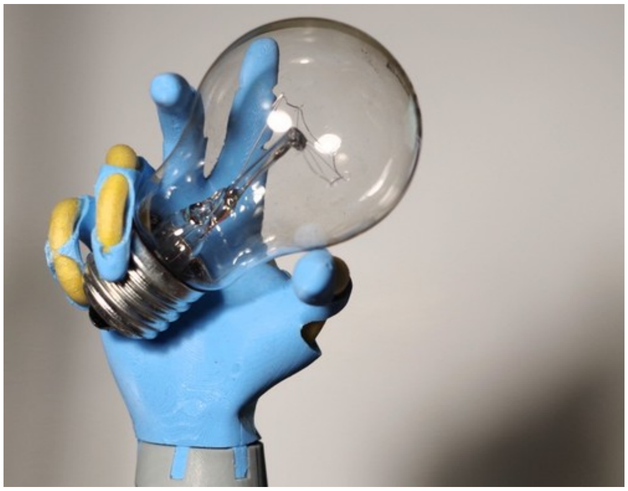

Fig. 1: Soft pneumatic hand

A pneumatic soft hand composed of PneuFlex actuators is proposed in [5]. It contains of one actuator per finger, each individually controlled, one for the thumb and two for the palm. Another hand that propose a similar working principle is presented in [6]. It incorporates sensing capabilities using light-based sensors integrated into its fingers. Desspite the fact that a number of devices that provide a human hand morphology have been proposed [7], [8], very few of them offer a real human-like shape and appearance [9]; this is considered to be a serious issue when the device is to be used as a prosthetic system [10] Here, we present a prosthetics achieving a truly anatomical shape that offers a much more human-like appearance than other soft pneumatic hands, fig. 1. It contains of six degrees-of-freedom actuation that can be operated in groups for simplicity or controlled separately for an enhanced manipulation precision. Each finger has one

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actuator to achieve bending, while the thumb is equipped with two actuators to make it capable of apposition and opposition modes. Since all the fingers can operate within the same actuation group the costs of the final system can be further reduced.

The prosthetic hand is based on a 3D scan of a real human hand ensuring that the proportions and the shape of the design to be highly anatomical. The shape, configuration and size of the hand can be easily modified to meet the preferences of each individual patient. The manufacturing process is cheap and makes use of 3D printed molds and SmoothOn silicones. Such a property makes it affordable and especially suitable for children amputees that require frequent change of the device due to their body growth. Since it is made of soft materials it is also considered to be safer than traditional prosthetics.

II. DESIGN

The hand contains six independent pressure-driven soft flexible actuators. Each finger exploits one actuator and thus can be controlled independently form the other fingers. The thumb is equipped with two actuators allowing it to bend and to change its pose between opposition and apposition.

The hand is designed to be easily manufactured without any expensive equipment. It is made of two kinds of two-component silicone reinforced with polyester thread. The main part of the device, a rubber exoskeleton, is made of relatively stiff silicone SmootOn SmoothSill 940 (Shore A40) while the actuators are fabricated from the far softer material SmoothOn EcoFlex 0050 (Shore 00 50). Such a combination of materials allows to pre-program the fingers mechanical properties into the hand structure and transform the linear deformation of the actuators into the required curling motion of the fingers. Such a solution is based on previously presented research and proven to be ideal for a wide range of daily grasping tasks [11].

Here, we present a prototype that is 100 mm in length measured from the wrist to the ring finger's tip. Such a size corresponds with the hand of a child that is 2 to 3 years old.

A. Actuator

The actuator is a pneumatic, fiber-reinforced conical tube initially proposed in [12]. It contains two silicone layers and a helical thread reinforcement in between them. The silicone structure of the actuator tends to extend when a pressure is applied inside. The reinforcement constrains radial expansion and does not affect its longitudinal expansion. Thanks to that the used actuators only expand linearly along their longitudinal axis. The circular cross-section for the actuator is preferred as such a geometry remains circular when pressurized. Any other geometry would converge to a circular cross-section, since it strives to attain an energetically more favorable state [13]. The linear expansion of the actuator is converted into a bending motion using the exoskeleton finger structure with its appropriately designed stiffness distribution. Such an approach has already been implemented into industry-type grippers designed for anti-terrorist mobile robots [11] and proved to be an efficient solution for grasping tasks. Similar actuators have already been successfully used not only for grasping but also for manipulation and locomotion [11]–[13].

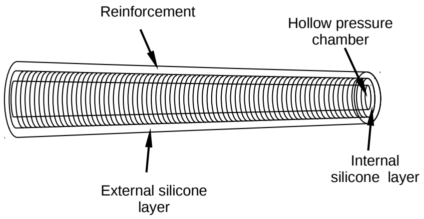


Fig. 2: Structure of the actuator

The structure of the actuator is presented in fig. 2. The small pitch of the reinforcing helix guarantees that its impact on the elongation capabilities is minimized. The internal layer creates an airtight membrane that transfers the pressure onto the reinforcement, the external one prevents the reinforcement from detaching the actuator and keeps it in the desired shape. The bottom and the tip of the actuators are sealed using stiff silicone. A 1.2mm-diameter channel is integrated in the actuator base, acting as a pressure inlet.

B. Hand structure

The hand structure is mainly defined by an exoskeleton structure made of stiff silicone fig. 3. The exoskeleton constrains all the actuators and creates the palm and fingers surface. To be as bio-realistic as possible the exoskeleton is based on the 3D scan of a real human hand. Thanks to that the lengths of the fingers and locations of joints correspond to those of a real human hand. The exoskeleton is designed in a way to constrain the deformation of the actuators in areas that correspond to bones and to transfer longitudinal motion into bending motions in the areas corresponding with the finger joints. This behavior is achieved by carefully choosing the appropriate material hardness for the exoskeleton. The actuators made of soft material elongate when pressurized. They are, however, attached on one side with the exoskeleton that is far less stretchable and extends less than the actuators. As a result, the side of the finger that is attached to the exoskeleton expands less than the loose side, and consequently the finger bends. Since our hand is made without any rigid components, the achieved rotational motion is not limited to discrete joints but distributed along the whole finger.

In earlier work, we investigated a finite soft rotational joint; this joint type had been considered as an actuator for the design presented here, [13], as finite joints lead to a more human-like hand motion. However, we found that such a solution would require a separate actuator for each joint, making the overall design and fabrication process too complex. For that reason we found it not suitable for the presented prosthetic hand.

As mentioned, each finger can be controlled independently, but they can also operate in groups in an efficient and synergistic way as they are flexible and compliant. Thanks to that the control complexity of dexterous manipulation is reduced as the hand structure and its compliance simplifies the interaction with objects.

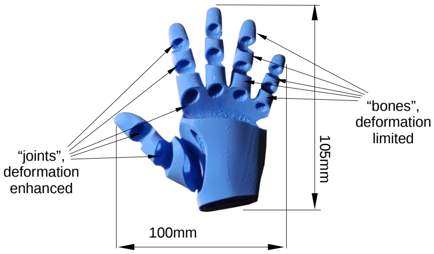


Fig. 3: Exoskeleton. Defines the hands' shape and generates bending motion.

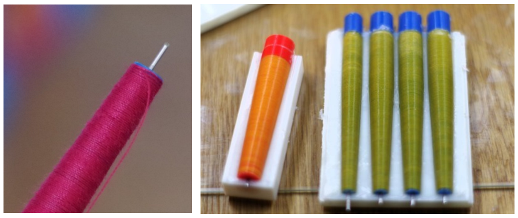
The exoskeleton fuses the fingers together in a way that they affect each other - very similar to the way the real fingers of a human hand do. For example, the actuation of the index finger causes the middle finger to bend slightly, the actuation of the middle finger makes the index and the ring finger to move too, and so one. For that reason, the synchronous actuation of all the fingers results in more bending and in higher grasping forces than actuation of separate fingers, just like in a real human hand. An additional actuated joint is embedded into the thumb's base to change the thumb operating mode between opposition and apposition.

III. MANUFACTURING

The manufacturing process used here is an extended version of the approach presented in [11]–[13]. It consists of several molding steps and involves a set of 3D printed molds. To create the molds, a Zortrax M200 printer was used.

A. Actuators

First, the actuators are manufactured. Starting with winding the reinforcement onto conical 3D printed cores that are to be inserted into a dedicated mold. The mold is then filled with silicone creating a thin layer on the outer side of the reinforcing helix. When the silicone is cured, the cores are removed. The actuators are then filled with new silicone material and another set of cores is inserted inside to create a thin layer of silicone inside the reinforcement, see fig. 4.



(a) (b)

Fig. 4: Actuator manufacturing. a) thread winding for reinforcement, b) actuators in mold, external silicone layer cured.

The following manufacturing steps focus on sealing both ends of the actuator. The base of the actuator contains the pressure inlet. The inlet is created by inserting a 1.2-mm diameter rod into the sealing mold. Pressure to the actuator is provided with 2-mm diameter tubes that combined with the 1.2-mm diameter hole in the actuator base creates a reliable and tight connection that does not even require gluing. The tubes are glued anyway in order to prevent them from being pulled out, fig. 5. It is noted that the proposed manufacturing approach is more reliable and requires less manual work than the manufacturing of similar pneumatic actuators [5], [14]. This is because the most crucial and work-consuming operation that is winding the actuator with thread reinforcement is quickly done using an electrical drill. The manufacturing steps order has also been improved so that the reinforcement is created on a rigid rod and does not cause stresses in the silicone material, as is the case for other actuator manufacturing approaches [5], [14]. Such an approach is also a step towards an industrial manufacturing as most of the process can be easily automated. A fully automated process will require the molds to be redesigned to manufacture many parts at once and to be easily operated with industrial robots and machines.

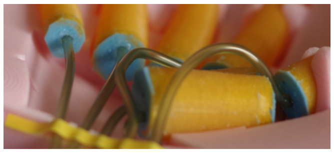


Fig. 5: Fingers bases with pressure pipes connected. The actuator pressure inlets are 1.2mm in diameter, the pipe diameters are 2mm.

B. The Hand

The prefabricated actuators are arranged inside a main mold that creates the exoskeleton. There are specially designed sockets that keep the actuators in position and ensures that the joint areas will not be covered with stiff silicone material. This is a crucial aspect of the process, as the areas covered with non-stretchable silicone do not expand. Due to that the shape and arrangement of sockets define the joints positions and "program" the finger motion. The main mold is shown in fig. 6.

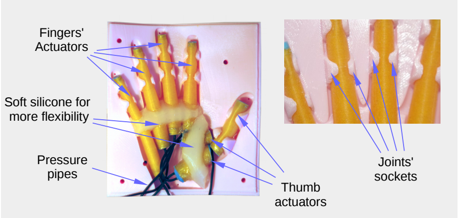


Fig. 6: Alignment of pneumatic actuators in the main mould.

Since some areas of the hand require enhanced flexibility (i.e. *metacarpophalangeal joint* - the base joint of all the fingers and *carpometacarpal joint* - the base thumb joint) there are auxiliary structures made of soft silicone deployed into the main mold together with the actuators. Before filling the mold with the silicone all parts are glued to the mold using soft silicone. This operation reduces the risk of stiff silicone penetrating into undesired areas during the injection operation. The mold is filled with stiff silicone using a big syringe via a small hole on the top part of the mold. The filled mold and the hand out of the mold are shown in fig. 7.

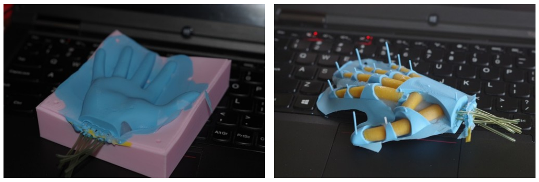


Fig. 7: Main mould open and demoulded hand with degassing channels visible.

IV. KINEMATICS

The hand has six actuators, one per finger and two for the thumb, fig. 8. Each finger can be controlled separately, however, since the whole hand structure is compliant and adapts to the handled object, they can be actuated in groups, i.e., synergistically, reducing control requirements.

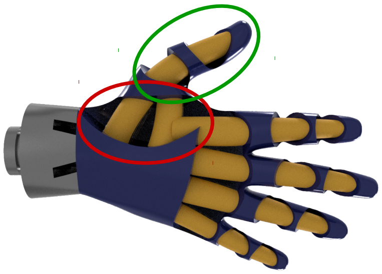


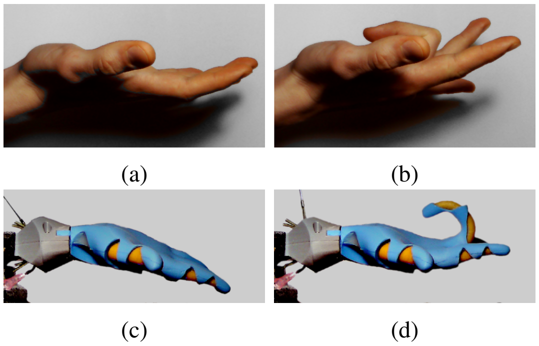
Fig. 8: The degrees of actuation. One actuator per finger and two for the thumb: thumb actuation in green, thumb mode control (apposition/opposition) in red.

The hand is designed to mimic the human hand as much as possible: the exoskeleton is designed to fuse the fingers at their bases, leading to an interference between finger movements as is the case for human hands, fig. 9. In the figure, only the middle finger is actuated for both the real and prosthetic hands, but a movement of adjacent fingers can also be observed.

To further increase the biomimetic aspect of the hand, a second actuator was added to the thumb allowing it to work in apposition or opposition mode. In the current prototype this functionality require relatively high pressure, and is a subject of future refinements. Both modes are shown in fig. 10.

V. CONTROL

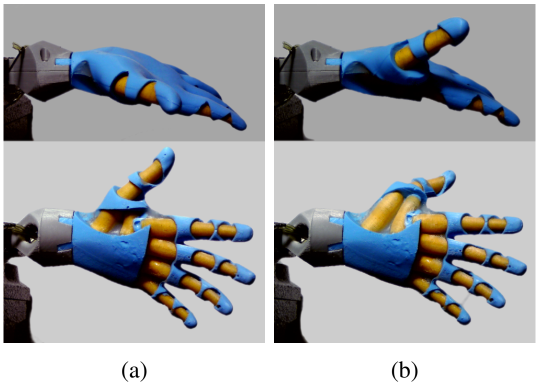
The hand is driven by pneumatic pressure. For the current prototype a control unit composed of a Raspberry PI computer and 6 proportional solenoid valves has been developed fig. 11a. Each valve is controlled independently with PWM (Pulse Width Modulation) signals and provides pressures in the range form 0 to 2 MPa. The controller can be commanded by a joystick or mimic the operator's hand using LeapMotion controller fig. 11b. Such an interface allows for smooth and natural control that is very useful for development purposes, but does not make much sense in the target system since it requires a healthy hand as a command input. Thus we are working on an EMG interface to control the hand directly from the activities of remaining muscles of the amputee. Our developed software allows to create a sequence of different pressure values that then can be applied in the requested order. All code used in this project is written in Python and is planed to be released as open-source software in the nearest future. Desired grasp motions can be saved and loaded form a file, fig. 11.



(a) (b)

(c) (d)

Fig. 9: Influence of the middle finger actuation on other fingers. (a) and (c) hand passive, (b) and (d) only middle finger active but index and ring fingers affected.



(a) (b)

Fig. 10: The thumb in different modes. (a) apposition and (b) opposition mode.

VI. EXPERIMENTS

A. Bending and force assessment

The hand has been tested in terms of forces and bending angles generated by the fingers as a function of pressure. During the tests the hand was fixed with a vise and observed with an USB PS3-eye camera. For each finger the rotation of the hand was adjusted so that the bending plane of the examined finger was always parallel to the camera imaging

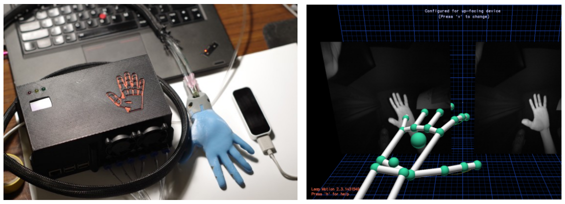

(a) (b)

Fig. 11: (a) The control unit and the LeapMotion controller. (b) LeapMotion-based hand tracking.

plane. Using an image processing algorithm, a colour marker attached to the finger tip was tracked during the actuation process. The pressure was tracked with the same camera using the same techniques, fig. 12. The actuation process was repeated for 6 times and recorded at 60 frames per second. Each frame of the recorded video has been processed and the value of the actuation pressure and the corresponding bending angle was determined. For bending and force evaluation, two scenarios were tested: an individual actuation of each finger separately and simultaneous actuation of all fingers.

The force assessment utilized the same experimental setup and a custom 3d-printed force sensor as in [15]–[17]. The generated forces have been measured using the force sensor for each finger separately for individual finger actuation and for the whole hand actuation scenario. The results of all the performed tests are presented in fig. 13, fig. 14 and fig. 15. Graphs present the average of all trials for each configuration.

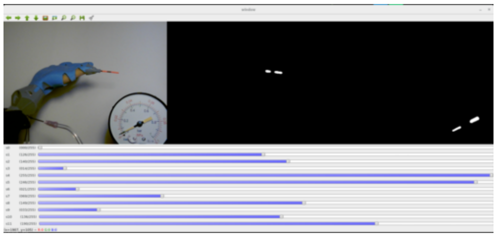


Fig. 12: Bending characterization. Imaging techniques are used on images from USB PS3-eye camera to extract the bending angle and pressure value for each recorded frame.

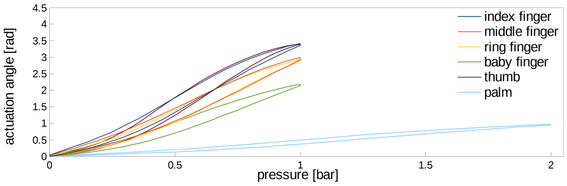


Fig. 13: Actuation angle vs actuation pressure, whole actuation cycles.

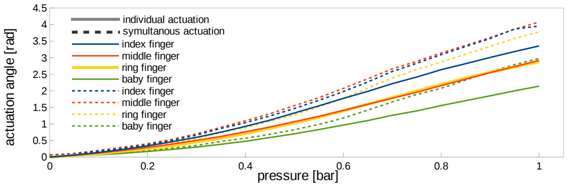


Fig. 14: Actuation angle vs actuation pressure, single finger actuation compared to the simultaneous actuation (all the fingers together). Only pressurization shown.

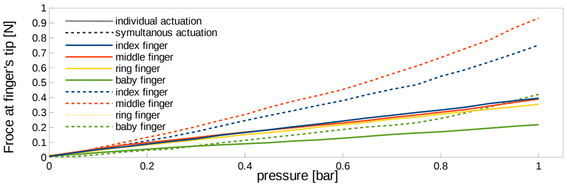


Fig. 15: Experimental results. Force measured at the fingertip vs actuation pressure, comparing actuation of individual fingers and whole hand. Note that during the simultaneous actuation the ring finger force sensor failed - no data gathered.

B. *Grasping tests*

Preliminary grasping tests were performed. During these experiments we were trying to perform different types of grasps on different objects. The grasp postures have been chosen from the postures described in the literature [5], [18], [19]. In [18], 33 different types of grasps are distinguished. To investigate the hand's capabilities we have tried a number of those. The results are presented in fig. 16.

VII. DISCUSSION

The tests show that our design is promising. The hand is capable of a suitable range of motion. The bending tests prove that fingers influence adjacent fingers when pressurized, providing a natural finger motion. This is especially notable in case of activation scenarios when not all the fingers are directly activated. Simultaneous actuation results in significantly higher force exerted by each finger - this is helpful when trying to lift heavy objects. Some actuation hysteresis has been observed. Grasping tests show that the hand is capable of efficient grasping of various objects. A passive adaptation capability was observed during those tests. It is noted that the hand was able to grasp the test objects despite its small size. We anticipate that an adult-size hand will provide similar dexterity whilst being able to exert higher grasping forces; this is to be quantified through future experimental studies.

During the tests we have encountered a number of issues. The valves are controlled by providing voltage signals in a range from 0 to 10 V. In our case the voltage signal is emulated by a PWM signal generated by a Raspberry PI running a Python script. Since Raspbian Linux is not a real time system, the PWM signal is not very stable and we were experiencing oscillations of the actuation pressure. In the natural control mode we discovered that the LeapMotion controller does not work properly in some configurations. Its performance highly depends on the lighting conditions and the gesture. Some of the gestures are not possible to achieve

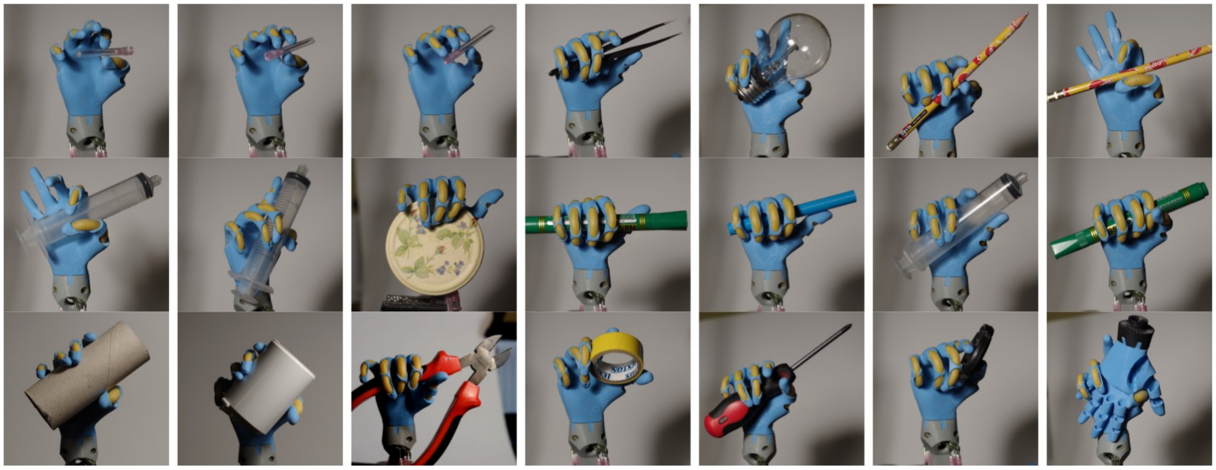


Fig. 16: Various grasping postures.

using the LeapMotion, however we still find this approach useful for some test scenarios. The Leap Motion interface is very simple to use even for inexperienced users.

VIII. CONCLUSIONS

In this paper we presented the design, manufacturing strategy, control system and prototype of a soft pneumatic prosthetic hand. The hand we propose is closely modeled after the anatomical shape of a human hand - far more human-like than other similar devices currently researched. The manufacturing process is simpler and requires less manual effort than other manufacturing approaches. The proposed hand is easy to manufacture and low cost. It can be easily reshaped and resized. It is made of soft materials and, thus, safe. We believe that the proposed hand is especially suitable for child amputees. Our tests show that the hand provides sufficient grasping capabilities to perform a range of manipulation tasks. In the future, we plan to manufacture and test prototypes of different sizes and further optimize our designs. Finite element based simulations are also considered to be used in this context. We will also develop an EMG interface and a mobile pressure source to enable amputees to use our soft prosthetic hand for daily tasks.

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