Analysis of variable-stiffness soft finger joints

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Abstract. This paper addresses the problem of designing an artificial finger with variable stiffness in its joints. Our approach is based on the principle of combining different means of actuation. Two different versions of variable-stiffness joints are presented and used in the design and manufacturing of three prototypes of gripper fingers. Diverse material configurations are used in order to determine which are the distinctive capabilities of each one and how they differ. In order to test the fingers we built a test bench that allows us to measure the movement of the tendon-driven actuation, the pressure of air actuation and the force that is deployed in the tip of the finger. Several tests are made to measure the relation between the actuation input and the force exerted by the fingertips. Our results suggest that the best mechanism to achieve variable stiffness in the joints is a soft-rigid hybrid finger.

Keywords: variable stiffness, soft robotics, grippers

1 Introduction

Traditionally, grippers are meant to perform a single or low number of tasks. However, in the future robots will likely be required to change tasks regularly and this requires the development of multifunctional end effectors [1]. Soft robotics allow to create high-adaptable grippers in order to grasp the maximum possible number of objects. In most cases, these grippers are unable to change their stiffness. Although highly compliant fingers may be desirable for grasping some products, at other times stiffer fingers may be desirable.

Soft robotics is a subject of study that has been booming during the last years, under the assumption that bioinspired systems or robots may have better performance than classical robotics technologies [2], [3]. This also includes soft manipulators and grippers [4]. Natural systems do not consist solely of soft materials, but they also contain rigid materials. For example, in the human body an 11% of the total volume is the skeleton and 42% are the muscles. Thus, there is a combination of hard and soft materials[5]. The combination of soft and rigid materials looks as a promising approach to compliant robotic systems [6]

Recent works [7–11] have developed grippers with the ability to change their own finger or joint stiffness in order to gain the capacity to grasp objects with different mechanical properties or having diverse grasp modes in the same gripper. Different mechanisms are possible [12]. For instance, some of them use materials whose stiffness can change depending on the temperature that is applied on it.

This approach, however, needs some time to set up the desired temperature into the materials in the joints so that the gripper gets the programmed stiffness.

In natural systems, for example the human hand, various muscles with an agonist-antagonist function are used to achieve different finger stiffness while grasping. This kind of systems have been a source of inspiration to develop artificial variable-stiffness grippers [13]. Artificial systems made with an agonist-antagonist design tend to be quite complex [14]; typically using springs, pulleys and various types of elements.

In this article we present the design and evaluation of two types of variable-stiffness fingers. One design is based on the combination of agonistic/antagonistic tendons, and the second, on the combination of a tendon and a pneumatic valve. The aim of the research is to find designs which accomplish two desirable properties for variable-stiffness joints: namely, the joints must be able to change their stiffness almost instantly, and they must be as simple as possible.

To test these designs three different finger prototypes are built. Two of them are actuated with two tendons, but they differ in the type of material uses in the joints. The purpose of this is to test how the material can affect the finger performance without making changes to the design. The third finger prototype uses a combination of tendon and pneumatic valves.

2 Fingers

2.1 Finger design

Finger design is inspired in the human finger, with three phalanxes and soft material in the joints that simulates the ligament between the phalanxes bones. In order to get a variable stiffness joint we also take inspiration of the hand, which uses a system of agonist and antagonist muscles. So, in one finger the agonist work is taken by a tendon and the antagonist work will be done by two elements: the own resilience of the soft material of the joints and the pressure air added into small chambers located in the finger joints. The pressure inside the joint chambers will change the stiffness of the joints, if we increase the pressure inside the chambers the stiffness of the fingers will rise too. In the other finger the agonist-antagonist work is done by two tendons, one that makes the flexion movement of the finger and the other the extension one.

The designs of the fingers are shown in Fig. 1. The parts shown in white were made of a rigid material and the black parts of soft material. The cut in the middle of the The tendons will pass thought the holes in the rigid parts of the fingers, while there can also be seen the air cavities in the soft parts.

2.2 Prototype manufacturing

The pieces of the fingers are made using fused deposition modelling (FDM), also known as 3D printing. FDM allows making fast prototyping models with materials that can simulate the rigid and soft properties of natural elements.

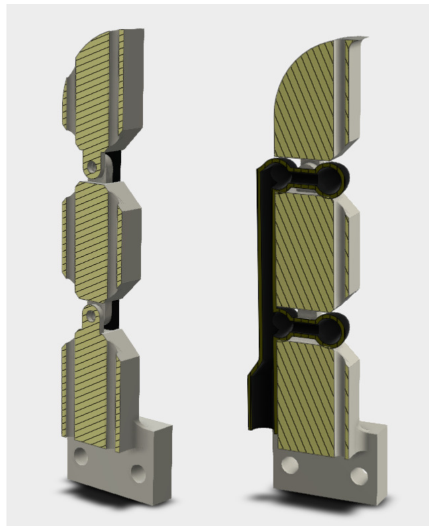

Fig. 1. Finger design

Rigid parts were made of PLA (Polylactic Acid) and soft parts of NinjaFlex (thermoplastic polyurethane). When all the pieces are printed, we assemble all the pieces in both finger models.

For the finger that is activated with tendons two options are manufactured. One is a material hybrid option, with the material distribution that is seen in Fig. 1. The other one is a simple monolithic soft material one. With this two options we can see how the finger performs depending on the material. The two options can be seen in Fig.2.

The hybrid dual tendon will be HTFinger, the monolithic soft dual tendon will be STFinger, and the hybrid finger that is activated with pressure and tendon will be HBFinger.

3 Testing bench

In order to measure the capabilities of the fingers a test bench was designed and manufactured. Its purpose was to measure the linear movement of the tendons, the force at the tip of the fingers and the pressure inside the air cavities. The final bench is shown in Fig. 3 with a finger mounted in it.

3.1 Making the structure

To make the structure of the testing bench an aluminium frame was used, because it grants the main structure of the bench with resistance against the forces applied to it and also because it is easy to mount and unmount in different configurations.

Fig. 2. Tendon-driven fingers

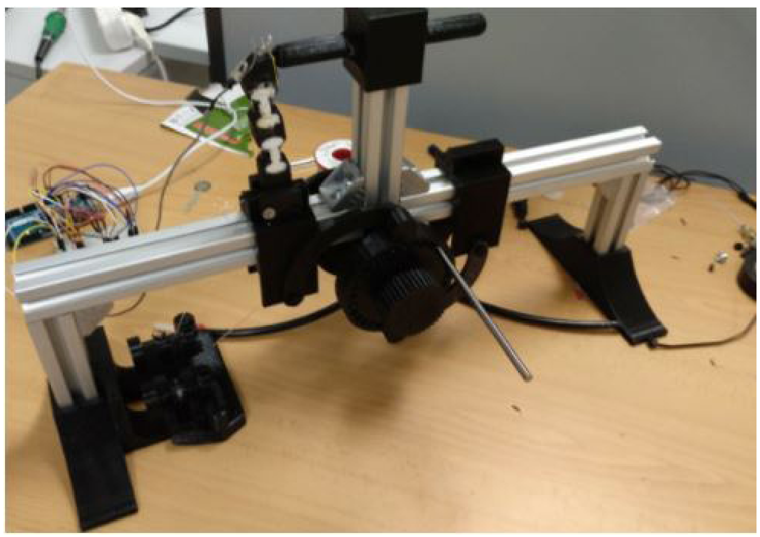

Fig. 3. Bench assembly

The rods are mounted with the help of structural elements as aluminium brackets that are manufactured to work with the frames used to make the core of the test bench. There are also pieces that have been 3D-printed to give more stability to the core.

The structure also provides the fingers with an opening-closing movement, so the grasp of an object can be simulated. This is made manually, thanks to a sort of pieces that transform the rotating movement into a lineal one. To grant this movement a carriage has been designed and 3D-printed, this carriage will be mounted bellow the fingers and and the main rod will pass through its centre thus providing the finger with linear movement. This movement will simulate a parallel finger grasp. That mechanism is shown in Fig.4.

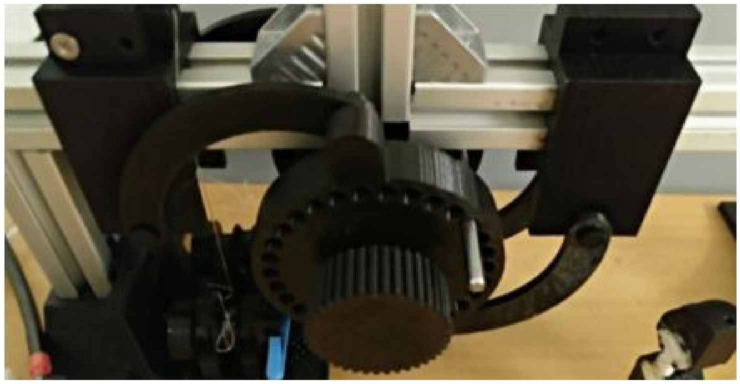

Fig. 4. Open-close mechanism

The legs of the structure provides the testing bench with good stability and allows us to only use two feet instead of tree or more, giving more simplicity to the testing bench. The middle rod is used to mount on it the piece that will interact with a force sensor to provide us with the value of the fingertip force.

3.2 Sensors

In order to measure the performace of the fingers during the test, sensors have to be added in the structure. The data that we need to know is the force applied to a tendon that actuates the finger, along with the air pressure that can be applied inside the soft cavities -which can be used to actuate the finger or change the stiffness inside a cavity- and also the lineal movement of the tendon, as explained before. To embed the sensor in our system we need to design and manufacture some extra pieces. These pieces will be explained next.

Linear movement measure. The first thing that we need to know is how much the finger has moved when we apply the force, or how much force do we have for a known deformation. To be able to have these data we designed and make some parts that will be added to the main structure.

The first part is a pulley that will be the responsible to apply the movement to the finger, and to measure that movement we will measure radians that the pulley turns and transform them to mm.

$$r \times \theta = s \tag{1}$$

Being r the radius of the pulley, θ the angle rotated in radians and s the linear displacement of the tendon. In one side of the pulley we make some indents that have two purposes. The first one is to measure the angular displacement of the finger, as there are 14 indents we can measure displacements of $1/7\pi$ radians, that knowing that the pulley has a radius of 10mm, we can measure displacements in intervals of around 4,5mm. The second function is to hold the little stick that will stop the pulley from moving when a force is applied to it.

Force sensor. We need to know which is the force applied into the tendon that mainly activates the fingers that we are testing. The sensor will be a round Force Sensitive Sensor (FSR). These force sensors are used to measure the force that the finger applies in the tip. The sensor will be placed in the inner part of the distal phalanx of the fingers.

To interact with the sensor we build a piece whose function is to stop the finger movement where the sensor is, so that stopping force can be measured. That piece is shown in Fig.5, this piece can also be moved up and down in the frame, so it can adapt to different fingers.

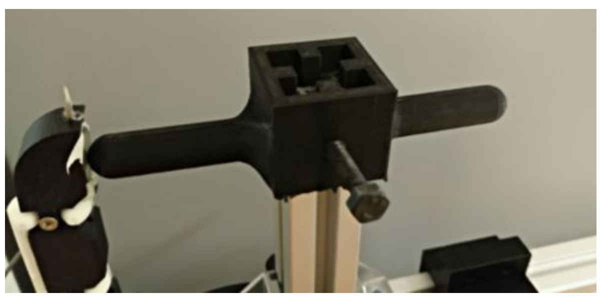

Fig. 5. Force measuring montage

Sensor integration. To integrate all the sensors in the systems an Arduino Board [15] is used, because both electronic sensors work with it. To show the results in real time instead of using a PC we put an LCD screen in the Arduino Board, with that solution the sensor system is portable and it doesnt need any computer to work. Fig. 6 shows how the LCD screen works, showing the analogic values for the Force (Fuerza) and the Pressure (Presión).

4 Experimental testing of the fingers

The next point of this research is to make tests with this bench and the three fingers.

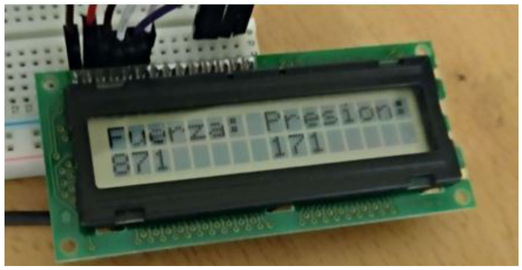

Fig. 6. LCD screen

4.1 Test description

The experiment consists in moving the finger into a known position that is almost touching the sensor with the piece added to the bench. Then we move the tendons to a specific position or inject pressure in the air cavities depending on the finger model. Finally, we measure the data given by the sensors.

The aim of this test is to observe how the force at the tip of the fingers varies when we change the way that the actuators affect the finger.

4.2 Test implementation

First we make tests with the HTFinger. To test all the possibilities of the finger we firstly put the rear tendon in a position when it starts to make a force in the finger, and then we start to move the front tendon to different positions and see how the force value changes. Then we move the rear tendon and repeat the whole process. To the STFinger we follow the same steps as the ones followed with the hybrid fingers. Finally for the HBFinger we follow a process similar to the previous ones, but instead of changing the position of the rear tendon we change the pressure value inside the air chambers.

While doing the tests we move the stick that interacts with the sensor so that the sensor is always actuated in the same point. Due to the deformation of the finger while doing the tests, we need to correct the position of the stick in almost every measurement.

5 Results

5.1 Analogical reading

The results are the analogical readings obtained from the sensors, which are later transformed in order to express the data in SI units. The tendon movements will be expressed as angular displacements; as it was said before, one angular displacement equals to more or less 4.5mm of linear tendon displacement. All the data are the analogic input read in the Arduino screen.

5.2 Calculation of the real values

With the analogical values of the sensor readings we have an approximate idea of the relation between the inputs given the sensor readings. But to know better how these values really depend on each other is better to calculate the real value of each variable.

Force sensors. The analogical force sensor is a sensor that gives a null value when there is no force actuating on it and a value of 1023 when there are 100N force applying over it.

To calculate the force of the finger we have to make an interpolation of the values to get the actual force value in N. The next tables show the real values of the force that the fingers apply to get back to their original position. Also with the linear displacements instead of the angular ones. The linear displacement is in mm and the values of the force are in N.

Table 1. Values of the fingertip force N for HTFinger

Rear position	**Front position**							
Linear displacement (mm)	**0**	**4.5**	**8.9**	**13.5**	**18.0**	**22.4**	**26.9**	**31.4**
0mm	0N	19.5N	27.8N	42.6N	48.3N	50.4N	52.0N	54.2N
4.588mm	0N	0N	14.7N	26.6N	42.0N	46.9N	48.6N	50.3N
8.976mm	0N	0N	10.5N	20.8N	39.7N	44.7N	46.1N	48.9N

Table 2. Values of the fingertip force for STFinger

Rear position	**Front position**							
Linear displacement(mm)	**0**	**4.5**	**8.9**	**13.5**	**18.0**	**22.4**	**26.9**	**31.4**
0mm	0N	17.6N	27.1N	43.9N	54.6N	64.0N	71.2N	74.4N
4.588mm	0N	11.7N	25.1N	42.0N	49.9N	60.7N	66.8N	71.8N
8.976mm	0N	0N	18.6N	35.5N	49.0N	59.9N	63.0N	71.2N

Finger equations The graphs shown in Fig. 7 are the force representations of the fingers depending on the linear position of the main activation tendon. The blue line represents the finger without the activation of the second actuator, the green one is when the secondary actuator is on the first position (4.5mm in the tendon cases and 0.5bar in the pressure one) and the yellow one is when the secondary activation is in the second position (8,9mm in the tendon cases and 1bar in the pressure one).

Table 3. Values of the fingertip force for HBFinger

Rear pressure	Front position							
Linear displacement(mm)	**0**	**4.5**	**8.9**	**13.5**	**18.0**	**22.4**	**26.9**	**31.4**
0 bar	0N	12.7N	17.8N	36.4N	42.5N	47.9N	50.6N	56.6N
0.5bar	0N	0N	12.7N	22.5N	30.2N	42.8N	47.9N	52.3N
1bar	0N	0N	11.4N	18.1N	24.1N	35.8N	40.1N	48.4N

For every one of the results we make a regression and see which kind of function fits better the data given in the results. While doing the statistics tests we will get an r^2 value, which shows the probability that the data is following the equation calculated by the software, the value of r^2 is between 0 and 1. We will only take the equations that surpass the value of 0.9 for r^2. In these equations the variable x is the linear displacement of the front tendon in mm.

The first finger (HTFinger) has the equations for the tree tests that are shown below. Equation 2 is the one that the fingers have when there is no rear activation, Equation 3 is when the rear tendon has made a movement of 4,5mm and Equation 4 is when the rear tendon has made a movement of 8,9mm. All the equations have an r^2 higher than 0.9.

$$F = 11.630x \tag{2}$$

$$F = 8.616x - 0.204 \tag{3}$$

$$F = 8.991x - 0.676 \tag{4}$$

The second finger (STFinger) has the equations for the tree tests that are shown below. Equation 5 is the one that the fingers have when there is no rear activation, Equation 6 is when the rear tendon has made a movement of 4,5mm and Equation 7 is when the rear tendon has made a movement of 8,9mm. All the equations have an r^2 higher than 0.9.

$$F = 13.546x + 1.842 \tag{5}$$

$$F = 14.872x + 1.269 \tag{6}$$

$$F = 12.810x - 0.757 \tag{7}$$

The last finger (HBFinger) has the equations for the tree tests that are shown below. Equation 8 is the one that the fingers have when there is no pressure in the air cavities, Equation 9 is when there is a pressure of 0.5bar in the cavities and Equation 10 is when there is a pressure of 1bar in the cavities. All the equations have an r^2 higher than 0.9.

$$F = 10.518x + 1.432 \tag{8}$$

$$F = 16.358x - 1.524 \tag{9}$$

$$F = 18.864x - 2.161 \tag{10}$$

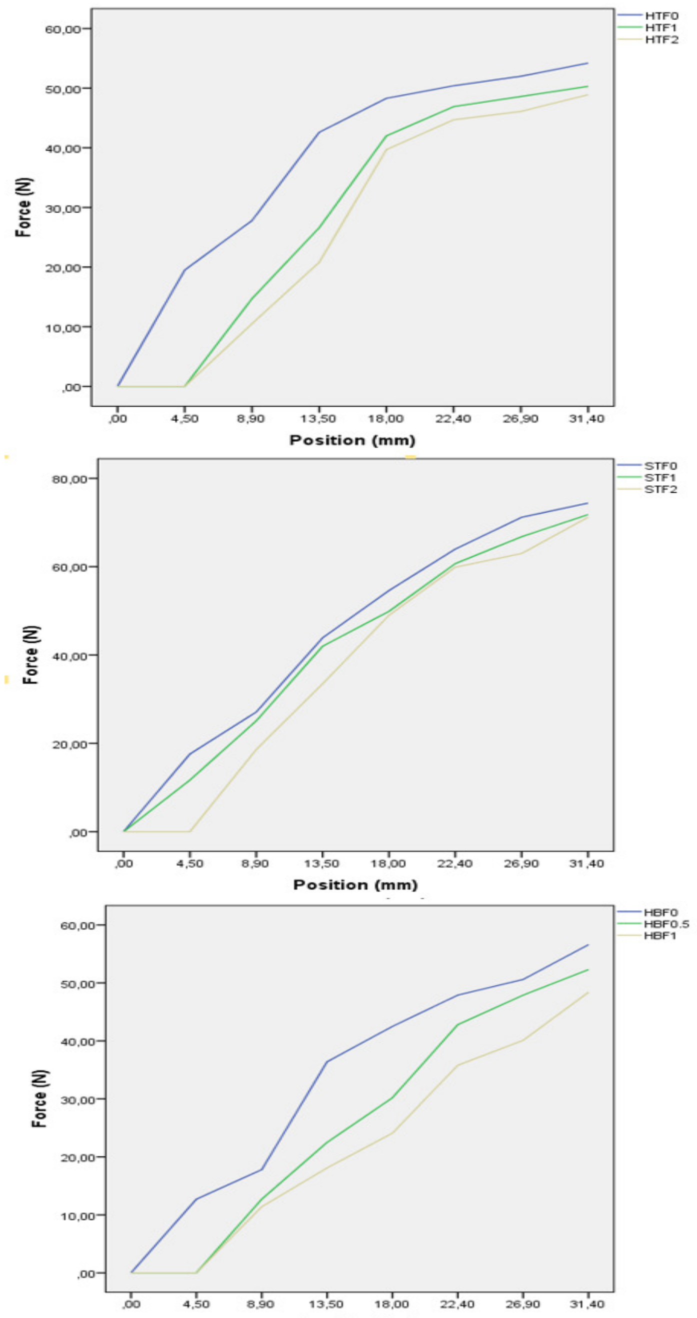

Fig. 7. Finger graphs

5.3 Discussion

From the results in the previous section we can see that when the secondary actuation is set into motion, an additional movement from the principal actuation is needed in order to get the same fingertip force in the sensor. So, when the secondary activation is called up the finger joints became stiffer and the principal actuation has to make further linear movement in order to get the same fingertip force.

The equations show us how the stiffness of the fingers augments when the secondary actuation is activated. The intercept in the equations becomes more negative as we keep actuating the secondary drive. That means that as the finger gets stiffer more force of the principal activation is needed to surpass the stiffness of the finger and start moving it.

The slope of the equations show us how the quantity of force that the fingers deploy with a millimetre of displacement of the principal actuation, being $\sim 9mm/N$ for HTFinger, $\sim 13mm/N$ for STFinger and $\sim 15mm/N$ for HBFinger. With these results we can see that the finger that in a medium term deploys more force is HBFinger.

6 Conclusions and future work

In this paper we have developed two different approaches to variable-stiffness actuation, that allow us to build three variable-stiffness fingers and test them in diverse forms of actuation usage using a self-made test bench. Out of these fingers, two were made with a hybrid soft-rigid use of materials and the other one as a soft monolithic object. In addition, two of the fingers have a dual tendon-driven actuation and the other a combined tendon-pressure actuation in order to get variable stiffness in the joints.

More developed versions of these fingers can be used to create variable-stiffness grippers that have the same capablities of traditional grippers such as the Barret Hand [16].

Both methods of making a variable-stiffness joint succeed in overcoming the problems that had previously arisen for variable-stiffness joints. These problems were the lack of immediacy when changing different stiffness parameters, and the complexity of the systems used for changing the properties of the joints. Indeed, both our methods can change the value of the finger stiffness almost instantly, because of both secondary actuation methods can change their intensity almost instantly, and also both systems have a quite simple design.

For the two fingers that were developed with the same design but distinct material structure (HBFinger and STFinger), we can see from the results above that the soft solution can deploy more force per millimetre actuated than the hybrid one, but the slopes in the equations are more similar in the hybrid one if we do not count the inactivated one. Then, we can conclude that the soft material gives us more strength, but it turns out to be less reliable.

In future research we will implement the joints into a full gripper to test object grasping. The aim will be to be able to grasp the maximum number of objects with just one gripper by changing the stiffness of the joints in order to reproduce different kinds of grasps, such as power or precision grasps. We will mainly focus on the air cavities solution, mostly because of its design, that allows us to control different joints with a design and control structure that are simpler than in the case of the tendon-driven solution.

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