A Compact Ratchet Clutch Mechanism for Fine Tendon Termination and Adjustment

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***Abstract*— Adaptive, underactuated and compliant robot systems have received an increased interest over the last decade. Possible applications of these systems range from the development of adaptive robot hands to tendon-driven, soft exosuits. Despite the significant progress in the field, some basic design issues such as the tendon termination and adjustment have not yet been addressed properly. In this paper, we focus on tendon-driven, underactuated systems and we propose a compact ratchet clutch mechanism that facilitates a fine tendon termination and adjustment. The proposed mechanism is experimentally compared with six common tendon termination solutions, using two different tests: i) an accuracy test to verify how precisely each mechanism can adjust the tendon length and ii) a tensile test to derive the strength limit of each mechanism. The experiments validate that the ratchet clutch system is a precise and robust mechanism that outperforms all the solutions compared. A cable driven finger was designed and built to accommodate the proposed mechanism and test its efficiency and applicability to devices that require compactness (e.g., adaptive robot hands). The design of the mechanism is disseminated in an open-source manner.**

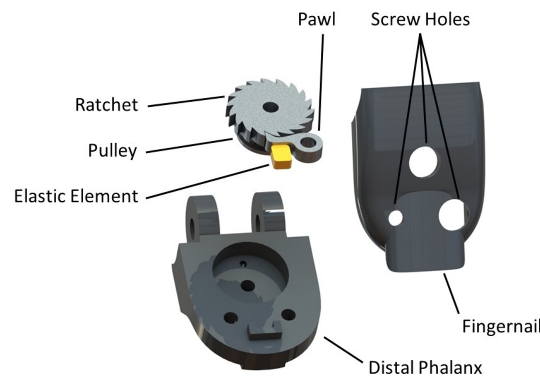

Fig. 1. 3D model of the proposed ratchet clutch mechanism. The mechanism consists of a ratchet - pulley block for tendon wrapping, a pawl that blocks the rotation of the ratchet in one direction and an elastic element that acts as a spring and pushes the pawl against the ratchet teeth, constraining its motion in one direction. In this figure, the ratchet clutch system is attached at the distal phalanx of an adaptive robot finger. A fingernail is used to hide the mechanism.

I. Introduction

Nowadays, the execution of robust grasping and dexterous, in-hand manipulation tasks is often accomplished by fully-actuated robot hands that are equipped with sophisticated sensing elements and that require complicated control laws. Further, the planning of these tasks requires a precise computation of the hand object system Jacobians, accurate contact modeling and accurate descriptions of the object and robot models. Thus, even the slightest uncertainties in the modeling space (e.g., vision based uncertainties due to occlusions or dynamically changing lighting conditions) can render the successful execution of dexterous tasks with the particular category of robot hands, infeasible.

Although multifingered robot hands have been a topic of increased research interest for decades [1]–[3], advances in rapid prototyping and new materials allowed roboticists to design and optimize a new class of adaptive, under-actuated and compliant robot hands of minimal weight, cost and complexity [4]–[6]. The transmission of these hands is based on artificial tendons that mimic the human flexor tendons and which are driven through low-friction tendon routing channels. Finger extension is passive and it is typically implemented using spring loaded pin joints or flexure joints based on elastomer material (e.g., silicone or urethane rubber). Adaptive robot hands have the ability to robustly grasp and manipulate objects even under significant object pose or other environmental uncertainties and they are typically controlled in an open-loop manner offering a simplified and intuitive operation.

The increasing popularity and acceptance of adaptive robot hands are due to the fact that many designs are disseminated in an open source manner [7]–[10]. Adaptive hands can be applied in many different fields and for a variety of applications that range from industrial automation to prosthetics, underwater manipulation and aerial grasping. Different applications impose different design constraints and requirements that are translated to appropriate, task-specific robot hand designs. These designs have optimized motor selection and packaging, transmission systems, finger kinematics, joint characteristics, cost, weight etc. [11].

Despite the promising features of adaptive hands and the good progress of the field, several design aspects still need improvement. One of these aspects is the lack of a compact mechanism that can offer repeatability and accuracy in tendon termination and adjustment. In adaptive hands, tendon tensioning is of paramount importance as it affects the configuration of the fingers and the way they are controlled. For example, if we examine two fingers that have different precision in tendon termination, we will notice that this results to different pretensioning of the finger tendons, different finger configurations and different finger bending profiles. Previous tendon termination solutions do not offer the required precision, repeatability and strength.

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The fine adjustment of the tendon length and force can offer a significant improvement of the grasping capabilities. In [4], [12], researchers do not perform a precise pretensioning of the tendons and choose to control the mechanisms in an open-loop manner, reaching a predefined amount of motor torque. Pretensioning of the finger tendons is also extremely important when differential mechanisms are used. Some robot hand designs incorporate differential mechanisms that connect all the available fingers to: i) facilitate a coordinated control of the robot hand or gripper, ii) guarantee that the fingers will conform to the object geometry even if one of them comes in contact with the object surface earlier than the others and iii) reduce the number of actuators required. Such a design choice reduces also the weight, volume and final cost of the device.

Regarding differential mechanisms, in [13], the authors propose a tendon driven, underactuated robot hand with a differential mechanism that allows the force provided by the single tendon to be distributed to all the fingers using a combination of pulleys. In [5], the authors propose a selectively lockable differential mechanism, which can block the motion of each finger allowing the user to select between 144 grasping postures and gestures that can be executed with a single actuator. In [14], a differential mechanism based on a modified whiffletree is proposed that triggers different grasping postures using the manual relocation of the thumb. An inaccurate pretensioning of the fingers that are terminated on a differential mechanism will result to the mechanism being unbalanced and to not work properly.

Regarding tendon termination, several solutions have been used in the related literature. In [15], a tendon termination mechanism was proposed in which the tendon is wrapped around a pulley and terminated at an anchor point. In [7], a similar approach is used as the tendon is wrapped around a screw (located at the fingernail area) and is terminated using a knot under the screw head. In [4], the authors apply a wire compression sleeve on stainless steel cables in order to anchor the tendon at the distal link. In [16] and [17], the authors tie up the tendon on a washer that acts as a termination anchor. In [18] and [19], the authors use a similar approach by terminating the tendon on a crimp.

All the aforementioned mechanisms do not provide a fine tendon termination and adjustment and they depend on human skill. Possible solutions include cable pretension systems found in other fields (e.g., marine anchors) that could be applied to facilitate tendon termination in cable-driven systems. Many of them are based on the idea of wrapping the cable around ratchets or pulleys. For instance, a widely known item for tensioning wires and straps is the ratchet strainer. This mechanism consists of a double ratchet system with inclined teeth that is installed in a fork type rectangular structure and a pawl that is pushed by a torsion spring on the teeth so as to block the motion of the ratchet in one direction, allowing strap tensioning in the other direction [20], [21], [22]. This mechanism concept can be used in different scales and redesigned to accomplish the task of tendon termination and adjustment in cable-driven systems.

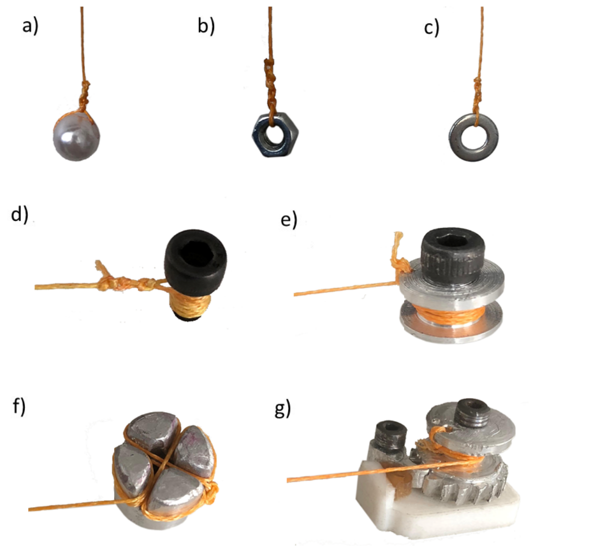

Fig. 2. The seven termination mechanisms that are examined in this paper: a) bead, b) nut, c) washer, d) screw, e) pulley, f) dual channel and g) ratchet clutch. All solutions are tested and compared using two different tests: i) a tendon adjustment test and ii) a tensile strength test.

In this paper, a compact ratchet clutch mechanism is proposed (see Fig. 1) and compared to six other tendon termination mechanisms in terms of accuracy, repeatability and strength. To do that, two different experiments were conducted: i) a precision test that involved manual tendon termination tasks and ii) a tensile test that measured the strength of the examined mechanisms. The proposed ratchet clutch mechanism outperformed all other solutions and its efficiency and applicability in designs that require compactness was experimentally verified by integrating it in the fingertip of an adaptive robot finger. The design of the ratchet clutch mechanism is disseminated in an open-source manner to allow replication by other research groups.

The rest of the paper is organized as follows: Section II presents the design and modelling of the termination mechanisms examined, Section III details the experimental setup used for the tests, Section IV presents the experimental results, while Section V concludes the paper and discusses future directions.

II. Mechanisms

In this section, we present the designs of six commonly used tendon termination solutions and we propose a compact ratchet clutch mechanism that performs not only tendon termination but also a fine adjustment of the tendon length. Fig. 2, shows the mechanisms examined and how the tendons are terminated on them. The mechanisms are divided into two different classes: fixed point tendon termination solutions and wrapped body tendon termination solutions.

The fixed point tendon termination approach uses simple knots on different termination anchors (e.g., a washer, a nut etc.). The wrapped body tendon termination approach requires the tendon to be wrapped around the mechanism's body (e.g., a pulley) before a termination knot is made.

A. Fixed point tendon termination

Three different fixed point tendon termination mechanisms were compared to the ratchet clutch mechanism proposed. These mechanisms involve as an anchor, a plastic bead, a steel nut and a steel washer. The purpose of using a plastic bead was to check if rounded objects behave better than the other anchor solutions. Although nut is a simple and low cost solution, we wanted to assess if the nut's inner threads can damage the tendon when high loads are applied. A third anchor solution is the washer, a small, lightweight and widely used part that suffers from sharp edges that can damage the tendon when high loads are applied.

B. Wrapped body tendon termination

Four different "wrapped body" tendon termination mechanisms were compared: the screw, the dual channel mechanism, the pulley and the ratchet clutch mechanism. The partially threaded steel screw was chosen as a cheap, compact and lightweight solution. The goal was to check if the screw was more accurate than other low cost solutions. The dual channel termination mechanism was fabricated out of steel with two perpendicular channels that allow the tendons to be wrapped around four pillars. Such a rerouting increases the friction in tendon termination due to the Capstan effect [23]. This mechanism was tested in order to assess if wrapping of the tendon around these pillars increases the resistance to load and the tendon length adjustment precision. The pulley tested was also fabricated out of steel for consistency reasons. The pulley has a hole on one side where the tendon is tied up, before being wrapped around the channel. The purpose of testing this termination mechanism was to verify how the rounded surface of the pulley channel and the corresponding friction can affect its performance.

The tendon termination mechanism proposed in this paper, is a ratchet clutch system that consists of a ratchet - pulley block, a pawl and an elastic element that pushes the pawl on the ratchet inclined teeth. The mechanism is once again fabricated out of steel. Although this mechanism has a channel that behaves like a pulley, the motivation for testing it, was to see if the ratchet clutch system offers superior performance in precise tendon length adjustment. The tendon length adjustment accuracy was calculated as follows:

$$\phi = \frac{2\pi r}{N} \tag{1}$$

where ϕ is the accuracy, r is the radius of the channel of the pulley, and N is the number of teeth of the ratchet.

In terms of cost, the mechanisms a), b), c) and d) are the cheapest solutions and can be purchased for < 1 USD per unit. The ratchet g), is a complex mechanism that has to be accurately manufactured and for this reason, is considered to be the most expensive solution used, while e) and f) can be manufactured more easily and they are more affordable. Table I shows the dimensions and weight of each one of the mechanisms examined. Special attention has been given in minimizing the size of the tendon termination mechanisms so as to be easily applicable in designs that require compactness.

TABLE I
MAXIMUM DIAMETER AND WEIGHT OF THE SEVEN MECHANISMS TESTED. THE MECHANISMS WERE DIMENSIONED TO FIT ON A ROBOTIC HAND WITH THE SIZE OF AN ADULT HUMAN HAND.

Mechanism	Maximum diameter (mm)	Weight (g)
Washer	8	<1
Bead	8	<1
Nut	6	<1
Pulley	12	4
Dual Channel	10	7
Ratchet	12	5
Screw	5	1

III. EXPERIMENTS

Two different experiments were executed. The first test focused on comparing their tendon termination accuracy, while the second experiment focused on a tensile test that compared the maximum load that could be withstood.

A. Tendon Length Adjustment Test

For the tendon length adjustment test we used the experimental platform presented in Fig. 3-a). The platform consists of an aluminum slotted extrusion base, a spring, a high performance UHMWPE (Ultra-High Molecular Weight Polyethylene) braided fiber line of 0.34 mm diameter (that acts as a tendon and holds up to 36.2 kg), two plastic supports where the finger terminations were attached, one yellow sticker on the base and one black sticker on the tendon as references for the accuracy measurement. The horizontal support was used to attach the pulley, the ratchet, the screw and the dual channel part while the vertical plastic support has a small hole where the line goes through and where the washer, the nut and the bead were used as anchors.

During the experiment the participants were asked to terminate the tendon on each one of the examined mechanisms simulating a real situation of tendon length adjustment. They were instructed to align the sticker on the tendon with the sticker on the base as accurately as possible. This procedure assures that all termination mechanisms required the same amount of tension, since the same spring-based restoring force was used. Each attempt of the participants was timed so as to compare the ease of use of each mechanism. A total of five participants were asked to do the accuracy test three times on each mechanism. On the termination mechanisms d), e), f) and g) the participants were required to wrap the tendon around the object for at least five times and make a knot. To prevent the sharp threads of the screw from cutting the tendon, we wrapped it around the shoulder of the screw. For termination mechanisms a), b) and c) it was necessary to make two knots in order to guarantee that the tendon wouldn't get loose. After finishing each tendon termination attempt the distance between the two stickers was measured.

B. Tensile Strength Test

The second experiment executed was the tensile strength test. The main goal of this experiment was to derive the maximum load that each termination mechanism was able

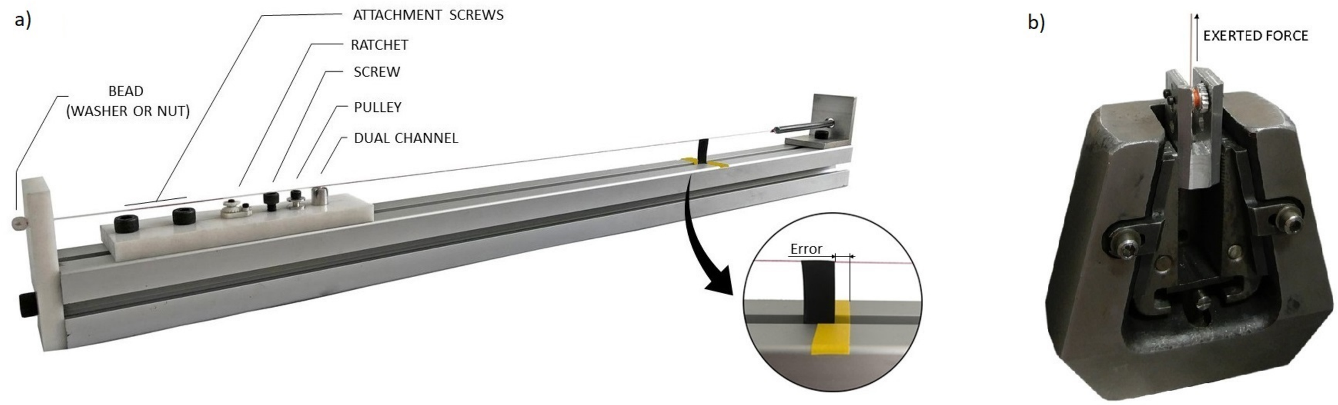

Fig. 3. Subfigure a), depicts the experimental setup that was used in order to measure the tendon length adjustment accuracy for each termination mechanism. It consists of an aluminum bar where the termination mechanisms are attached, a spring that is fixed in one end of the bar (to resist the tendon displacement during the execution of the accuracy test), and the tendon that is tied up to the spring in one end. In order to remain fixed, the screw, the ratchet, the pulley and the dual channel mechanisms are connected to a plastic base that is attached to the aluminum bar. The bead, the washer and the nut are hold against a bulkhead that contains a hole where the tendon goes through. In order to measure the accuracy of each mechanism, the participants were instructed to tie up the tendon to the mechanisms, aligning two stickers, one on the bar (yellow) and the other on the tendon (black). The distance between the two stickers was measured as the mechanism's accuracy. Subfigure b), depicts the end-effector of the Instron 5567 machine, while clamping the ratchet clutch mechanism. An aluminum adapter was used to facilitate clamping.

TABLE II

MEAN AND STANDARD DEVIATION VALUES OF ERROR, TIME AND MAXIMUM STRENGTH THAT WERE OBTAINED DURING THE TENDON LENGTH ADJUSTMENT ACCURACY TEST AND THE TENSILE STRENGTH TEST.

Mechanisms	Error (mm)		Time (s)		Max strength (N)	
	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
Pulley	1.27	0.92	54.33	14.27	794.86	63.71
Dual Channel	1.08	0.51	60.58	22.44	485.81	34.17
Ratchet Clutch	0.87*	0.00*	42.57	11.37	877.56	69.62
Screw	1.20	1.36	33.47	10.78	508.72	44.19
Nut	4.07	1.67	49.20	12.72	480.47	54.24
Washer	2.93	1.44	50.93	14.73	474.55	43.39
Bead	3.20	2.11	63.07	26.89	112.43	12.16

*For the ratchet clutch mechanism we report the nominal values. The actual accuracy is always better than the nominal values.

to withstand and compare it to the ratchet clutch mechanism performance. An Instron 5567 tensile tester was employed to perform the experiments and a clamp was designed to fix all seven tendon termination mechanisms on the Instron machine, as shown in Fig. 3-b). For the tensile strength test we used a high performance UHMWPE braided fiber line of 1.00 mm diameter (that holds up to 136 kg), as the tendon used on the previous test could not withstand high loads.

The tensile test was executed until either the tendon or the mechanism was broken. A total of five tensile trials were performed for each mechanism and in all of them six half hitch knots [24] were used for tendon termination. Different types of knots such as the Clinch knot, the Lindeman knot and the Grinner knot [25], [26] were tested during the experiments, but at high loads (above 300 N) and during constant application of force for long time the knots started slipping and couldn't be used. The machine crosshead speed was set to 10 mm/min.

IV. RESULTS DISCUSSION

Table II, shows the results for the accuracy test. The distance between the two stickers is the precision of the tendon length adjustment and is called "Error". The term "Time" is used to denote the time required to terminate the tendon. From the data gathered during this experiment it is clear that the termination mechanisms that presented a higher mean accuracy are the ones that belong to the "wrapped body" class. This is due to the fact that when the line is wrapped around the mechanism's body the imposed friction does not let the tendon slip and as a consequence the tension can be more easily adjusted. It is also evident that the ratchet clutch mechanism offered the best performance, as it was the easiest to use and the most precise. The participants faced difficulties while adjusting the tendon length using the washer, the bead and the nut because the restoring / resisting force of the spring was significant. When the tendon is wrapped around the mechanism's body, the friction prevents slipping and less force and effort is required to handle the tendon, resulting to faster and more precise termination (e.g., for pulleys). The accuracy results for the fixed point termination mechanisms show high deviation values that are also due to the aforementioned difficulties. Comparing the mean time required by the participants to do the experiments, we can notice that the termination mechanism with the lower mean time is the screw. This is due to the fact that wrapping the tendon around the screw is a fast and simple process.

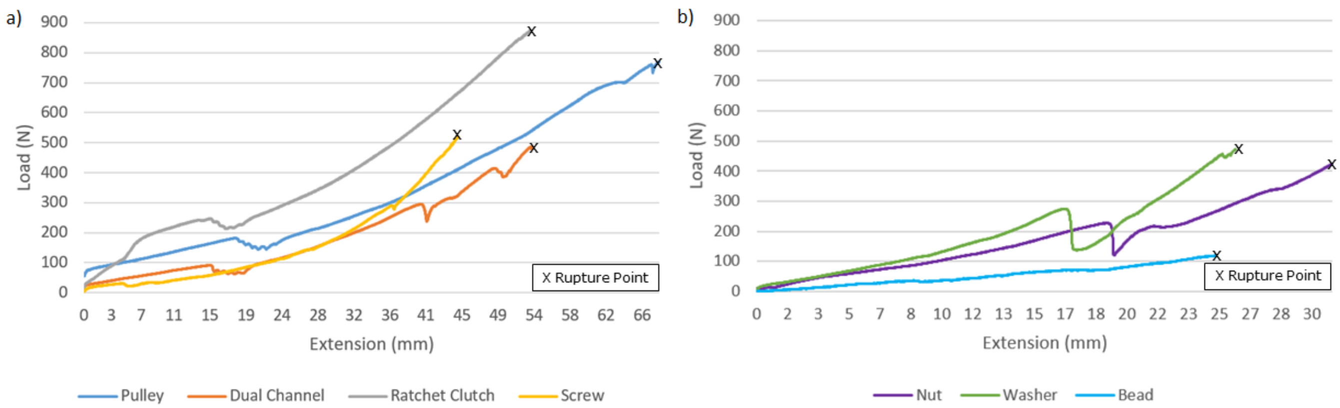

Fig. 4. Load values obtained during the tensile test of the mechanisms show a sudden drop on the tension. These drops on tension are interpreted as knot accommodation during the tensile test. It can be observed that for the fixed point based terminations (bead, washer and nut) that are depicted in subfigure 4-b), there is more knot accommodation because the knots are directly exposed. The pulley and the ratchet clutch solution are not affected as much.

Table II, reports also the results for the tensile strength test. The "Max Strength" refers to the maximum force withstood by each mechanism (mean and sd). During the tensile strength tests, six out of the seven termination mechanisms resisted the loads applied and the tendon broke before the mechanism. The bead was the only item that did not resist the load and broke before the tendon at around 112 N. For this reason this mechanism is not suitable as an anchor for tendon termination. The nut and the washer showed a similar performance but managed to resist the tensile test. The pulley and the ratchet clutch mechanism provided the best results in terms of maximum withstood force. An important result was that the rupture point of the tendon for these two mechanisms was not near the knot (which is typically the weakest part). This means that the friction imposed guarantees that less force reaches the knot. The Eytelwein's formula [23] for the ratchet clutch mechanism and the pulley is:

$$\frac{F_{machine}}{F_{knot}} = e^{\mu\beta} = 4.81, \qquad (2)$$

where $F_{machine}$ is the force exerted by the machine, F_{knot} is the force at the knot, μ is the friction coefficient (we use a friction coefficient of 0.05 according to [27]), and β is the number of tendon revolutions / wrappings in radians. In our case, the maximum force applied to the knot during the experiment was 4.81 times lower than the maximum force applied to the tendon (breaking point).

During the tests, the mechanisms that involved as anchors, the nut, the washer and the screw behaved similarly. As the knots on these three mechanisms were exposed, the tendon broke at these stress concentration points. It was also observed that the force withstood by the tendon was about 500 N. This value can vary according to the type of knot used. The dual channel termination mechanism withstood a mean strength load of 485 N. The rupture point was not in the knot area but close to the edges of the channels, indicating that they were probably too sharp due to manufacturing issues. Fig. 4-a) and 4-b) show the relationship between the applied tendon force and tendon extension for all the mechanisms examined. From these graphs it is evident that there are sudden tendon force level drops while the tendon extension is increasing. This happens because when the force is increasing, the knots get tighter or the tendon moves quickly to a more stable position contributing to the tendon extension and reducing instantaneously the tendon force. It is also evident that this phenomenon is stronger on the fixed point termination mechanisms as well as on the pulley and the screw. The ratchet clutch mechanism exhibits a good performance having an almost linear relationship between the tendon extension and the tendon load after 250 N.

It must also be noted that when we are applying a significant amount of force on the tendons they elongate, as some UHMWPE fibers elongate up to 6% of the cable / tendon length [28]. For this reason after long periods of operation with very high forces, the tendon must be retensioned in order to guarantee a fine control of the system. The only tendon termination mechanism that allows a quick retensioning is the ratchet clutch solution.

In order to experimentally validate the efficiency of the proposed ratchet clutch mechanism and its applicability in designs that require robustness, we integrated it at the fingertip of an adaptive robot finger. The designed ratchet clutch system has a pulley channel with a diameter of 5mm and 18 teeth, offering a precision of adjustment of 0.87mm, according to Eq. (1). A small elastic structure made out of urethane rubber (Smooth On PMC780) was used to act as a spring that pushes the pawl against the ratchet teeth constraining its motion in one direction. The ratchet system designed for the robot finger can be seen on Fig. 5. During the tensile tests, the maximum force obtained for the ratchet clutch mechanism was 950 N before the cable / tendon rupture, indicating that the maximum force that the mechanism can withstand is even bigger.

All the designs (e.g., CAD files) required for the replication of the proposed ratchet clutch mechanism are disseminated in an open-source manner at the following URL:

www.github.com/newdexterity

Fig. 5. An adaptive robot finger that was developed to accommodate the proposed ratchet clutch mechanism. It can be easily noticed that the mechanism is compact enough to be integrated in the robot fingernail area. A yellow, small, elastic structure acts as a spring that pushes the pawl against the ratchet teeth, constraining its motion in one direction. A plastic fingernail is used to hide the tendon termination and adjustment solution.

V. Conclusions

In this paper, we present a compact ratchet clutch mechanism that facilitates a fine tendon termination and adjustment. The mechanism was compared to six different alternatives that are being used in related studies. Two different tests were performed in order to validate the efficiency of the examined mechanisms as well as to compare them. The experimental results demonstrate that the ratchet clutch mechanism outperforms all other solutions providing excellent accuracy and robustness. In order to experimentally verify the efficiency of the mechanism and its applicability to devices that require compactness, we integrated it in the design of a tendon-driven finger.

Regarding future directions, we plan to use the proposed ratchet clutch system for terminating and adjusting tendons in new adaptive hands and soft exo-suits.

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