Design and Characterisation of a Variable Stiffness Soft Actuator Based on Tendon Twisting

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Abstract.

This short paper presents a preliminary investigation into the implementation of a controllable variable stiffening mechanism, which is achieved through the twisting of tendons around the central axis of a soft actuator. The gradual stiffening effect is realised through the increase in friction between the tendons as those are twisted against each other. This enables an easy to control variable stiffness actuator which is driven through the rotation of a DC motor driving the tendon twisting. The proposed mechanism was integrated within the core of a soft pneumatic actuator based on the STIFF-FLOP design, in order to characterise the increase in stiffness per twist angle for three different tendon materials. The initial experimental results presented here demonstrated that a controllable stiffening effect can be achieved using this technique, which shows dependency on the choice of tendon material. The results also highlighted the impact of braiding the softer tendons to potentially enhance stiffening, although further experimentation is necessary to characterise this behaviour in more detail.

1 Introduction

The field of soft robotics aims to address the challenges faced by traditional rigid robots in less structured and dynamic environments which require more adaptive interactions. Taking inspiration from biological organisms' such as octopus tentacles and elephant trunks, soft robots commonly use elastic materials and novel actuation methods to mimic the continuous deformation of their mostly soft bodies [1]. Flexible Fluid Actuators (FFAs) are one approach to soft robotic actuation that makes use of elastomeric chambers patterned specifically to induce asymmetries when a fluid is forced (or removed) through them [2]. While conventional robotic manipulators, such as those used in the DaVinci surgical robot, offer high precision for minimally invasive surgeries, the capability of soft manipulators to provide a greater degree of flexibility and inherently safe interactions shows great promise that motivates further study. Nevertheless, introducing softness consequently opens new challenges in achieving accurate positional control, stability and sufficient force generation to meet application requirements.

One of the approaches in addressing those challenges can be achieved through varying the stiffness of a soft actuator when more stability or higher force output is required [3] [4]. A common approach is achieved through granular material jamming, which can be simply demonstrated by placing fine granules into a malleable chamber and applying a negative pressure to increase the friction effect between particles causing a “phase change” [5]. The STIFF-FLOP successfully demonstrated the benefits of variable stiffening in the context of minimally invasive surgery by combining material jamming with flexible fluid actuation (FFA) techniques to produce a highly flexible soft arm inspired by the variable stiffness achieved by octopus tentacles[6].

Effective scaling down of soft manipulators utilising granular jamming is often challenging as the granular jamming encounters issues at tighter channel volumes due to material packing, which blocks the vacuum being applied to the rest of the channel. Additionally, as the stiffening channel diameter is reduced, the stiffness effect becomes much weaker due to a reduction in overall surface friction between the fewer particles present. This has motivated the investigation of other jamming techniques such as layer jamming approaches [7] [8], or jamming through interlocking structures [5]. In this paper, the feasibility of a controlled stiffening mechanism based on tendon-twisting is investigated, which draws inspiration from textile applications in which the modelling of structure and mechanical parameters of ropes used in yarns is of interest [9]. Recent work has also demonstrated the potential of twisting individual tendons along their axis to achieve a controlled stiffening effect [10]. The proposed tendon-twisting approach is an alternative stiffening mechanism for soft actuators that can be potentially scaled up or down as needed based on the number and diameter of tendons, material properties, and the arrangements, while offering simple means of controlling a gradual increase in stiffening during operation.

2 Design and Fabrication

The design of the soft fluidic actuator used in this work was based on the STIFF-FLOP surgical manipulator [6]. The actuator retains the three pneumatic chambers of the STIFF-FLOP module, while replacing the granular jamming in the middle core with 4 flexible tendons of equal width (Fig. 1-a), which are secured in place with a plate at the actuator tip (Fig. 1-b) and connected to a Nema 17 stepper motor (rated at 3.7Nm of holding torque) at its base (Fig. 1-c). This motor is responsible for driving the rotation of the tendons at the base end of the actuator causing the tendons to twist against each other, which creates the desired stiffening effect due to friction between the tendons. The stiffening is hence a function of the degree of rotation, so can be changed gradually to achieve desired stiffness, unlike other stiffening methods that switch between stiff or relaxed states.

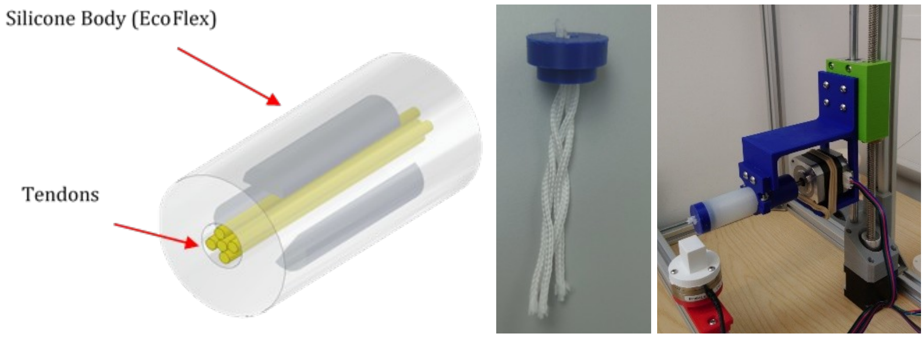

Fig. 1. Actuator construction from left to right: (a) Actuator design showing internal core, (b) braided polypropylene rope with end cap, (c) stepper motor twisting the tendons in the core.

A custom enclosing mould was designed and 3D printed to facilitate moulding the proposed tendon-twisting soft actuator from Ecoflex-50 and following the dimensions on the Soft Robotics Toolkit[1]. Three off-the-shelf tendons of varying degree of flexibility were compared here which are: Ninjaflex, polypropene rope, and steel wire. The choice was made based on the ease of availability and to cover a wide range of material flexibility to assess the feasibility of achieving the desired stiffening effect through twisting. Furthermore, the tendons were tested in two arrangements; straight and braided (Fig. 1-b) - to evaluate the impact of braiding the tendons on the stiffening range.

3 Experimental Characterisation of Stiffening

The experimental setup shown in Fig. 1 was used to assess the range of stiffness achieved when testing the tendon-twisting soft actuator using each of the three tendon materials at both braided and straight cases. An Arduino Uno board controls two stepper motors through a motor driver circuit to control the z-axis displacement of the actuator on the test rig and the twisting angle of the tendons inside the actuator core. For each experiment, the actuator is gradually driven downwards along the z-axis against a 3D printed rectangular object mounted on top of a sensitive force-torque sensor (ATI mini45), then reset to the initial location. This is repeated automatically four times for each test. Tendons are twisted by rotating the torsion control motor clockwise by 2/5 of a full rotation between iterations until the fixed end starts slipping or the actuators becomes too stiff to twist any further. A Matlab Simulink model simultaneously records time-series force data from the force-torque sensor and image feeds from a camera to monitor the actuator deformation during testing.

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[1] More information can be found at www.softroboticstoolkit.com

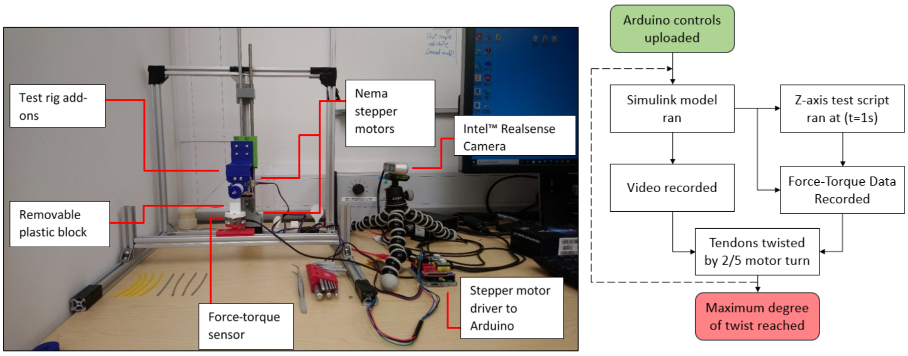

Fig. 1. From left to right: (a) components of the experimental setup, with the z-axis acting vertically, (b) simplified model of experiment procedure.

4 Results

The preliminary results of the experiment are summarised in Fig. 1 which compares the three tendon materials used for each of the braided and unbraided cases. Overall, the results in both graphs show a proportional increase in stiffness as the tendon twisting is increased, although the response is not always linear as it is the case for the Ninjaflex tendons. This is likely due to the non-linear material behavior and slippage between tendons particularly when braided. Additionally, the results indicate that when using straight (unbraided) tendons (Fig. 1-a), the stiffer tendons exhibit a higher percentage increase in force, reaching a maximum of around 268% for the steel wire within the tested twisting range. The percentage change in force was calculated along the z-axis direction (Fz) by comparing the first value recorded without tendon twisting (relaxed state) and the final Fz value achieved at maximum possible degree of rotation (stiff state). However, using very soft and flexible tendons, like the polypropylene rope, causes a negligible change in Fz. On the other hand, when tendons are braided (as in Fig. 1-b) the stiffening effect is potentially enhanced for the flexible tendons, with Ninjaflex tendons achieving a maximum overall increase in Fz of nearly 332%. At the same time, the percentage increase in Fz for the steel rod actually reduces upon braiding due to a significant increase in the actuator's initial stiffness, which results in double the initial forces recorded before any twisting (relaxed state), while the final achieved force at maximum twisting remained nearly the same. This has also limited the maximum possible twisting angle as the motor reached its torque limit.

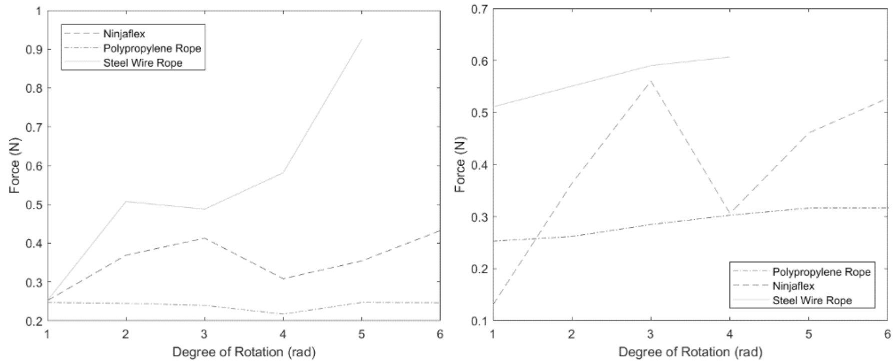

Fig. 1. Z-axis force-torque data plotted until second peak from left to right: (a) unbraided tendon configuration, (b) braided tendon configuration.

5 Conclusions and Future work

The results of this feasibility study highlighted the potential of achieving controlled variable stiffness in a soft cylindrical actuator based on the proposed idea of flexible tendon twisting. The method offers an easy to control stiffening method using stepper motor rotation, which can be scaled up or down based on the number and diameter of the tendons used. The results generally suggest that the choice of materials plays a critical role, although would require further study to characterise and model the impact of specific material properties such as elasticity and surface roughness in more details. Among the tested three materials, there was a correlation between material flexibility and an increase in stiffness upon twisting. If the tendon is too soft and flexible (such as the case of polypropylene rope) it does not generate a noticeable increase in stiffness, while a significant increase in stiffness can be achieved using the stiffer steel wires. Furthermore, preliminary tests showed that braiding the tendons rather than inserting those as straight can potentially enhance the stiffening effect for those flexible filaments, yet decreased the stiffening for stainless-steel wire. This is due to the increase of the initial stiffness of the actuator before any twisting, so the range of generated forces becomes narrower and hence reduces the desired variable stiffening behaviour. Further work will investigate the effect of specific material properties on enhancing the stiffening effect via modelling and further experimental validation to identify the optimum choice of materials properties to maximise the stiffening range. This would be desired in various applications where a soft touch as well as forceful interactions could be simultaneously required, as it is the case with non-invasive surgeries. Furthermore, varying the number of tendons and types of braiding patterns using thinner tendons will be further investigated as a way to enhance the range of force generation while retaining the compactness and desired initial softness of the actuator before stiffening.

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