Anthropomorphic Twisted String-Actuated Soft Robotic Gripper With Tendon-Based Stiffening

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Abstract—Realizing high-performance soft robotic grippers is challenging because of the inherent limitations of the soft actuators and artificial muscles that drive them, including low force generation, small actuation range, and poor compactness to name a few. Despite advances in this area, realizing compact soft grippers, which exhibit high dexterity and force output, is still challenging. This article explores using twisted string actuators (TSAs) to drive a soft robotic gripper. TSAs have been widely used in numerous robotic applications, but their inclusion in soft robots has been limited. The proposed design of the gripper was inspired by the human hand, with four fingers and a thumb. Tunable stiffness was implemented in the fingers by using antagonistic TSAs. The fingers’ bending angles, actuation speed, blocked force output, and stiffness tuning are experimentally characterized. The gripper achieves a score of 6 on the Kapandji test and recreate 31 of the 33 grasps of the Feix GRASP taxonomy. It exhibits a maximum grasping force of 72 N, which is almost 13 times its own weight. A comparison study reveals that the proposed gripper exhibits equivalent or superior performance compared to other similar soft grippers.

Index Terms—Dexterous manipulation, soft gripper, twisted string actuators (TSAs).

I. INTRODUCTION

Traditional robotic grippers, which utilize rigid components and actuators, offer high grasp strengths, high dexterity, and high accuracy and precision in executing complex manipulation tasks. However, this rigidity is not ideal for grasping delicate, deformable, or soft objects because rigid grippers lack the compliance to conform to different shapes [1], [2]. Furthermore, grippers, which exhibit high dexterity, are usually difficult to control and design with rigid parts [3], [4]. In addition, to grasp delicate objects, traditional robotic grippers require complex force control algorithms [1], [5]. In contrast, soft robotic grippers have been demonstrated to be better suited for dexterous manipulation, manipulation of wide range of objects with different shapes and sizes, and even human–robot interaction without requiring highly complicated force control strategies [1], [2], [4], [6], [7].

Although soft robotic grippers are promising for many applications, it is challenging to realize high-performance soft robotic grippers that are compliant, compact, low-cost, and generate sufficient force. This is mainly because most soft actuators and artificial muscles that drive existing soft robotic grippers exhibit one or more limitations [8], such as fabrication difficulty [1], [9], [10], high power requirement [10], [11], slow actuation [6], [12], [13], or insufficient force generation [14], [15]. A twisted string actuator (TSA) is a mechanism that consists of at least two strings connected to an electric motor at one end and a load at the other end of the strings [16]. As shown in Fig. 1(a), actuation is realized by twisting the strings with a motor to shorten the strings’ length and linearly displace the attached load [16]. TSAs typically generate strains of 30%–40% of their untwisted length, exhibit high energy efficiency of 72%–80%, and possess a power density of 0.5 W/g [8], [16]. TSAs are advantageous over powered tendon motor actuators (SMTAs), as TSAs convert rotational motion to translational motion without the use of any external mechanisms, such as gears [17]. TSAs can also output higher force with less input torque than motors and spools [18], [19]. For these reasons, TSAs are more efficient than the motor and spool configuration. A brief study comparing the torque outputs of TSAs and SMTAs was conducted in [20], which demonstrated that TSAs produce significantly higher force with less input torque than SMTAs with the same motors. This allows for less-powerful and lighter motors to be used in TSAs to generate similar forces. Zhang et al. [8] presented a detailed quantitative comparison of TSAs with popular artificial muscles. As evidenced by these comparisons, TSAs offer an advantageous combination of high force output and high energy efficiency while minimizing mechanical complexity and cost by allowing the use of compact, lightweight, and inexpensive motors.

TSAs have been widely employed in multiple robotic applications, such as tensi-skeletal robots, robotic fingers, robotic hands, and exoskeletons [17], [21], [22], [23], not only as driving mechanisms, but also to achieve variable stiffness [24]. However, they have only been used in one other soft robot so far [25]. This is likely because TSAs require motors, which are difficult to incorporate into soft structures. However, the successful applications of TSAs in exoskeletons and assistive devices [20], [26], [27] demonstrate their strong promise in areas where safe interaction with humans is necessary, supporting their use in soft robots.

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Fig. 1. (a) Schematic of the TSA with the fixed twisting zone and sorter mechanism. (b)–(d) Anthropomorphic soft robotic gripper driven by TSAs. (b) Example of the gripper’s precision grasping. (c) Example of the gripper’s power grasping. (d) Gripper is also capable of tendon-based stiffening via an antagonistic TSA. By actuating both TSAs in the finger, the silicone will compress and stiffen. The bending angle of the finger will be determined by the net relative displacement of tendons #1 and #2.

In addition, although the strings used in traditional TSAs are not largely stretchable, their flexibility could be very useful in soft robots. These advantages of employing TSAs to drive soft robotic structures have been explored in our previous work [25], [28] in which the design and performance of a TSA-driven soft robotic manipulator were presented. Actuating soft robotic grippers with TSAs could present unique advantages due to TSAs’ inherent properties and could result in the realization of large degree of freedom (DOF)-robotic structures while maintaining system compactness.

In this article, we present a soft robotic gripper actuated by TSAs [see Fig. 1(b)–(d)]. First, the design of the proposed robotic gripper is presented. The design is inspired by the human hand, consisting of four fingers and a thumb. The TSAs enable six independently controllable motions, one for each of the four fingers and two for the thumb. Each finger bends due to the contraction of its corresponding TSA, whereas the thumb can both bend and roll using two TSAs. It is widely reported that the thumb is responsible for more than 50% of a human hand’s gripping capabilities [4], [29]. Therefore, the 2-DOF thumb is highly desirable to allow the gripper to replicate more anthropomorphic grasps and perform in-hand manipulation. Each finger, including the thumb, is also equipped with an antagonistic TSA, which can adjust the stiffness of the fingers and the thumb. Second, the angular positions, angular velocities, blocked force output, and the tunable stiffness of the fingers were experimentally characterized. Last, the powerful and dexterous grasping and some in-hand manipulation capabilities of the gripper were demonstrated using various objects.

This is the first study on TSAs in soft robotic grippers. The main contributions of this article are as follows.

1) Development of a multi-DOF human-hand-inspired soft robotic gripper driven by TSAs. The employment of TSAs resulted in a high-performance, multiple DOFs, and compact soft robotic gripper.

2) Development of a monolithic multi-DOF soft robotic thumb driven by TSAs. The thumb enabled the proposed gripper to efficiently realize different types of grasps.

3) Realization of TSA-based tunable stiffness in the soft fingers of the proposed robotic gripper.

The rest of this article is organized as follows. First, related works are discussed in Section II. Second, the design and fabrication procedures are discussed in Section III. Third, the experimental characterization of the robotic gripper is shown in Section IV. Next, dexterity, grasping, and in-hand manipulation experiments, as well as a comparison of our gripper to other similar grippers, are presented in Section V. Limitations of the current design with potential solutions for future iterations are discussed in Section VI. Finally, Section VII concludes this article.

II. RELATED WORK

TSAs have been used in anthropomorphic robotic grippers in the past literature [30], [31], [32]. Among these notable works is the gripper presented in [33], which utilized underactuated fingers driven by TSAs. This was one of the first works to utilize TSAs in anthropomorphic robotic grippers. Similarly, the DEXMART robotic hand, with 16 controllable DOFs, achieved complex grasps using different hand configurations [30]. The robotic hand presented in [34], while not possessing many DOFs, still achieved the desired biomimetic actuation. However, none of the previously developed robotic grippers were fabricated using completely soft material. Furthermore, most existing TSA-driven anthropomorphic grippers did not possess the high level of dexterity required to perform complex manipulation tasks, such as in-hand manipulation or achieve many of the possible human grasps [33], [34], [35]. These limitations with previous employments of TSAs to drive anthropomorphic traditional robotic grippers motivated further exploration into their application in soft robotic grasping and manipulation.

Since research on soft robotic grippers span over five decades of work, brief discussions on the most relevant studies will be presented in this section. For a detailed review on soft grippers, readers are directed to [5]. The current research on the design and fabrication of soft robotic grippers has mainly focused on the following parts.
1) Developing grippers with multiple DOFs.
2) Developing grippers with varying levels of stiffness [5].

Both of the aforementioned functionalities are highly desirable, but are challenging to realize. This is mainly because most soft actuators and artificial muscles that drive existing soft robotic grippers exhibit significant limitations [8]. For example, SMTAs have been used to drive high-performance soft grippers and realize tunable stiffness [5], [29], [36], [37], [38]. However, due to their low force outputs, SMTAs require high-torque motors or high-reduction gearboxes [20], [25]. High-torque motors and high-reduction gearboxes both add extra mass to the system.

Similarly, dielectric elastomer actuators (DEAs) and hydraulically amplified self-healing electrostatic (HASEL) actuators generate sufficient actuation, but require complicated and expensive fabrication procedures [10], [11]. DEAs and HASEL actuators also require high-voltage power supplies, which may be difficult to include in a compact form factor. Last, thermally actuated shape memory alloys (SMAs) and supercoiled polymers (SCPs) have driven soft robotic grippers and been used for tunable stiffness [6], [12], [39], [40]. However, these thermal actuators have low bandwidth and low force output. Their high temperatures may also be dangerous to the soft robotic devices in which they are embedded.

Pneumatic actuators, by exhibiting appreciable strain and force generation, have been widely adopted to drive soft robotic grippers and enable tunable stiffness [2], [5], [8]. However, pneumatic actuators require bulky pumps or compressors [1], [4]. Furthermore, in pneumatically actuated soft grippers, additional actuators would increase the DOFs of the gripper, but also increase its size and weight [4], [5]. This is because of the numerous compressors or pumps that are necessary for pneumatic actuators. Although some studies have demonstrated the use of pneumatic actuators to drive multi-DOF soft grippers [1], [4], [41], [42], [43], the extra equipment outside the grippers quickly becomes large and heavy, and therefore difficult to incorporate in mobile robotic grippers.

In terms of the design, many previous studies have used three- or four-finger designs [2], [5]. These designs have fingers that are uniformly spaced around a circular base. Grasping is achieved by actuating all fingers simultaneously or separately [1], [44], [45], [46]. Although this design has been effective, it is incapable of realizing many grasp types required to hold different types of objects. Another common strategy to realize soft grippers is to adopt a design inspired by a human hand [5]. The functionalities of anthropomorphic soft grippers are greater in comparison to other designs, especially when they include a multi-DOF thumb [29], [41], [42], [43]. Existing designs of anthropomorphic soft grippers predominantly use pneumatic actuators and SMTAs. Therefore, realizing an anthropomorphic soft gripper with high DOFs is often challenging because the additional actuators considerably increase the volume and weight of the gripper. However, the full potential of an anthropomorphic soft design could be realized when compact and high-force actuators, such as TSAs, are used. In this article, a compact soft gripper capable of dexterous manipulation is presented. The proposed gripper, which is driven by TSAs, demonstrates a high degree of dexterity, as it was able to achieve 31 of the 33 grasps from the Feix GRASP taxonomy [47] and performed basic in-hand manipulation actions.

III. DESIGN AND FABRICATION

A. Design

The gripper consisted of a soft monolithic palm with four fingers, a soft monolithic two-actuator thumb attachment that interfaced with the palm structure, and a rigid base that housed the motors and routed the strings as required to achieve the desired actuation. The joint locations, their range of motion, and the general sizing of the gripper emulated the human hand. The gripper prototype with important parts labeled is shown in Fig. 2.

Each finger of the gripper, including the thumb, was identical beyond its interface with the greater palm structure. This ensured each finger had the same actuation behavior. For the thumb, this meant a design that deviated from the human thumb, featuring an additional joint and a longer overall protrusion. Although anthropomorphism was considered for the design, achieving greater dexterity with minimal controllable DOFs was the higher priority. This thumb was dexterous (as revealed in Section V-A) and also helped the gripper achieve a high number of Feix grasps (as revealed in Section V-B). Therefore, this design was used for this version of the gripper. In future work, modifications can be made to more closely mimic a human hand.

The finger design is shown on top-right figure in Fig. 3. Each finger featured a flat surface along its length planar to the palm, to increase the grasping contact area [48], [49]. Each finger also featured three 90° triangular cuts parallel to the primary axis of bending designed to localize and concentrate the bending at pseudo-joints [48], [49]. This allowed the fingers to mimic the human finger motion, which features one metacarpophalangeal and two interphalangeal joints [31]. The actuation cuts also reduced the finger’s resistance to bending at those locations, therefore decreasing the required actuation force [50]. Each finger also featured two parallel tendon channels along its length.
Fig. 3. Computer-drafted model of gripper with major components of the hand, base, and actuators is shown in detail. The center-top figure depicts the full assembly of the gripper. The top-left, top-right, bottom-left, and bottom-right figures show the detailed depictions of the palm, finger, base with the sorting mechanism, and the thumb, respectively. The center-bottom figure shows the locations (highlighted in red) which housed the 11 motors of the TSAs.

to internally house the TSA strings (top view in top-right figure of Fig. 3). The frontal tendon was used to primarily bend the finger, while the rear tendon was used to counteract the actuation of the frontal tendon and enable adjustable stiffness.

The palm structure of the soft gripper was designed to provide a large, flat surface to aid in grasping. The finger interfaces were angled $10^\circ$ relative to one another (top-left of figure of Fig. 3), allowing the gripper to mimic the resting splayed position of the fingers in the human hand. The finger interfaces of the first and fourth finger positions were also more inset than those of the second and third finger positions (top-left of Fig. 3). The palm also had continuous tendon channels in-line with those in each finger. This allowed the tendons to pass through the palm and into the base where they were connected to the motors (bottom-left figure of Fig. 3). The palm with the primary four fingers was a monolithic structure (top-left figure of Fig. 3). This avoided complex assembly procedures [4], [7], [43], which could require screws and nuts, increase the gripper’s weight [48] and decrease its compliance. The thumb was a separate structure and its design (bottom-right figure of Fig. 3) was inspired by the designs presented in [29] and [42]. It was mounted to an additional jointed section that allowed the thumb to roll across the palm. This roll joint was actuated using an additional TSA. The joint had a theoretical maximum bending angle of $90^\circ$.

The fingers, palm, and thumb structures were cast from Dragon Skin 20 silicone rubber. Reusable molds for the combined palm with four fingers and separate thumb structures were designed and 3-D printed using acrylonitrile butadiene styrene plastic. Once the parts were cast, the two components of the hand were glued together using silicone rubber adhesive (SIL-Poxy, smooth-on). The base for the gripper (bottom-left figure in Fig. 3) consisted of a holder piece that interfaced with the proximal end of the hand to hold it in place, a sorter mechanism that constrained the twisting of the strings, and a collar to hold the TSA motors in place. The sorter mechanism worked by threading the two strings of each TSA string pair through separate channels in the mechanism, creating a constant twisting zone between the motors and sorter mechanism that prevented the strings from twisting within the hand. The separation between the twisted and untwisted regions is shown in Fig. 1(a) [51]. This prevented any twisting of the strings within the silicone hand itself, which could result in friction between the strings and the inner surface of the tendon channels [52], [53]. Steel rods held the collar away from the sorter, creating a twisting region large enough to provide sufficient actuation. The motor collar featured attachment points for the 11 motors used in the TSAs. Overall, the gripper had a footprint of 106 x 106 mm and a total length of 295 mm. The full assembly of the gripper is presented in the top-center figure of Fig. 3. The components of the base were 3-D printed, similarly to the molds used to cast the hand parts. Once the gripper was assembled, to configure the TSA actuators, the string pairs were routed from the motors in the base, through the sorter, hand holder, and the tendon channels in the palm and fingers. The strings were pinned at the fingertips and tied to be slightly taut when unactuated. This helped the gripper maintain a similar neutral position in different base orientations. All the channels in the palm and the fingers were equipped with polytetrafluoroethylene (PTFE) tubes, which both reduced the frictional force experienced between the strings and silicone and reinforced the soft silicone structure. The tendons used in this work were 0.7-mm diameter ultrahigh-molecular-weight polyethylene (UHMWPE) strings [16], [25], [54]. UHMWPE was selected because its frictional coefficient with PTFE is extremely low, previously reported to be 0.04-0.06 [55], [56].
These strings in the TSA act as a rotary-to-linear gear that greatly amplifies the force output compared to the same motor with a spool attached (the increased force output causes a corresponding decrease in speed). As a result, using TSAs allows the use of smaller motors in the base, decreasing the overall footprint of the base, and increasing the compactness of the system. Due to the TSA geometry, the motors are also arranged parallel to the direction of linear actuation, further enhancing the ability of the gripper to be made compact relative to a system using SMTAs, which would require the motors to be arranged perpendicular to the actuation direction. The use of TSAs does necessitate the inclusion of a twisting zone and sorter mechanism, though potentially increasing the required length of the gripper relative to one driven by SMTAs.

**B. Electronics and Control**

To actuate the TSAs, the gripper used 11 brushed dc motors (Micro Metal Gearmotor high-power carbon brush (HPCB) 6 V, Pololu; locations shown in the center-bottom figure of Fig. 3) with 30:1 reduction gearboxes. Each motor weighed 9.5 g. A magnetic Hall effect encoder disc (magnetic encoder, 12CPR, Pololu) was attached to each motor to count the motor rotations for control and data acquisition. This gearbox and encoder combination enabled 360 (30 × 12) counts per rotation, resulting in a $1^\circ \left(2.78 \times 10^{-3}\right)$ rotations sensing resolution in the motor shaft. Each of these motors could output 0.45 kg·cm of torque before stalling. These motors were all mounted on the motor collar of the base.

The remaining electronics used to power and control the gripper were housed outside of the robot and were wired to the motors. Each motor was controlled using a brushed dc motor driver (MAX14870, Pololu). A 32-bit ARM core microcontroller (Due, Arduino) was used for motor control, automated experimental procedures, and data acquisition. Data were automatically logged with a custom-written open-source Python script.\(^1\) Inertial measurement units (IMUs) (9-DOF absolute orientation IMU fusion breakout– BNO055, Adafruit) were mounted to each fingertip and the secondary joint of the thumb structure for characterization purposes, but were removed for later grasping demonstrations.

The motors were controlled with input voltages that were proportional to the error in the motor shaft angle. Closed-loop control using the bending angle of the finger as measured by an attached IMU was also used for the stiffness experiments, which are described in Section IV. For the grasping demonstrations presented in Section V, push buttons and a custom-written C++ script were used to manually control the actuation of each TSA in the gripper.

**IV. EXPERIMENTAL CHARACTERIZATION**

**A. Position**

The purpose of the characterization of the actuation of the fingers and thumb was twofold.

1) First, these experiments allowed the relationship between the TSA strings’ twists and the bending of the fingers to be mapped.

2) Second, they tested the ability of the gripper to achieve repeated actuation in different gripper orientations (under varying effects of gravity).

1) **Fingers**: The position of the robotic fingers was characterized by measuring the fingertip angles using an IMU (see Fig. 4) and corresponding motor rotation angles of the TSA. The maximum possible fingertip angle (with the particular motors in the gripper) was $230.6^\circ$, as shown in Fig. 5. Four cycles of monotonically increasing and decreasing reference motor angles were used to characterize the finger positions [see Fig. 6(a)]. Each setpoint was held constant for 5 s to obtain the steady-state value. The motor setpoints were increased/decreased in steps of two rotations.

Each finger was experimentally characterized in the following four different orientations.

a) **Vertically Up**: The palm is parallel to the gravitational acceleration direction and the fingers are above the palm.

b) **Vertically Down**: The palm is parallel to the gravitational acceleration direction and the fingers are below the palm.

c) **Horizontally Up**: The palm is perpendicular to the gravitational acceleration direction, and the palm is pointed upwards.

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\(^1\)Online available at https://github.com/EmDash00/ArduinoLogger
Fig. 6. (a) Motor angle input to the fingers that was used during experimental characterization. (b) Typical correlation between motor angle versus bending angle, with the lonely stroke highlighted. (c) Consistency of the correlations for different fingers in the “vertically up” position. (d)–(h) “Moving box-and-whisker plots”: Time-varying medians, 0.25-quartiles, 0.75-quartiles, minimums, and maximums for the fingertip angle of each finger. Univariate statistics are taken from four orientations: Vertically up, vertically down, horizontally up, and horizontally down. Results are shown for the following. (d) Index finger. (e) Middle finger. (f) Ring finger. (g) Little finger. (h) All fingers. (i) Summary statistics that average the minimums, maximums, 0.25-quartiles, and 0.75-quartiles for each finger over each experiment. (j) Four cycles of 20 random step motor angle set points. (k) Fingertip angle corresponding to the motor angle input sequence presented in (j). (l) Correlation between motor angle and fingertip angle when the motor angle setpoint varied randomly.

d) **Horizontally Down**: The palm is perpendicular to the gravitational acceleration direction, and the palm is pointed downwards.

For all experiments with the four fingers, the fingertip angle was computed relative to its initial orientation, which was 0°.

As indicated in Fig. 6(b), the fingertip angle during the first-half cycle followed a different trajectory than during the following cycles. This behavior is known as the “lonely stroke” [57].

As it can be seen from Fig. 6(c), the motor angle–fingertip angle correlation for different fingers showed an acceptable
level of consistency. Due to the compliance and softness of the gripper, inconsistencies in the motor angle–fingertip angle correlation may have arisen when the hand was tested in different orientations. Therefore, a statistical analysis was performed on the experimental data. The motor angle measurements were discretized using a resolution of 0.1 rotations. The encoder recorded measurements with a resolution of $2.78 \times 10^{-3}$ rotations during experiments and the sampling time was approximately 10 ms. This meant that during a single experiment, many motor angle measurements could be grouped into a single “bin” that was 0.1-rotations wide. After the motor angle measurements were grouped into their respective bins, the fingertip angle measurements were grouped into corresponding bins. Then, the summary statistics of the fingertip angle measurements were computed at each discrete motor angle. At each discrete index, the distances between the quartiles and median could be computed for each finger. These values were computed using the following equation:

$$\delta_q = \text{mean}(|\alpha_q - \text{median}(\alpha)|)$$  \hspace{1cm} (1)

where $\delta_q$ quantifies the average distance between the median fingertip angle and the $q$-quartile and $q \in [0, 1]$. The fingertip angle is expressed as $\alpha$. $\alpha_q$ is a vector containing $n$ elements that indicate the $q$-quartile of the fingertip measurements at each discrete index. For each finger, $\delta_0$, $\delta_{0.25}$, $\delta_{0.75}$, and $\delta_1$ were computed.

The summaries of the statistical analysis for each finger are shown in Fig. 6(d)–(h). As expected, there is a much greater spread in the distribution of fingertip angles at each discrete motor angle. The 0.05- and 0.95-quartile are also shown in Fig. 6(h). The shaded regions altogether cover 90% of the experimentally obtained data distribution. Fig. 6(i) shows the values of $\delta$ for all of the four fingers. The measurement error from the IMU and the encoder may have affected the computed variances in actuation. The resolution of the encoder used in our study was 1°. The measurement error uncertainty of the IMU was $\pm 2.5^\circ$.

The data in Fig. 6(a)–(i) were obtained using the same monotonic motor angle input sequence. This systematic procedure enabled fair comparisons between different fingers’ behaviors. However, it was necessary to also characterize the gripper when the motor input sequence was not monotonic. Therefore, four cycles of randomly generated motor reference signals were applied to the gripper’s index finger. The purpose of the random characterization was to qualitatively compare the finger performance against systematic characterizations. For Fig. 6(j) and (k), the top plot shows the entire sequence, whereas the bottom plot shows the sequence for one cycle. Fig. 6(l) shows the correlation between the fingertip angle and motor angle. Despite minor differences, the correlation under random motor angle setpoints resembled that under monotonically increasing/decreasing setpoints. These results suggested that the correlation between motor angle and fingertip angle was mostly independent of the particular input sequence.

2) Thumb: Similar to the four fingers, the thumb motion was characterized in four different gripper orientations. Fig. 7(a) shows the motor input sequence to characterize the bending of the thumb, whereas Fig. 7(b) shows the motor input sequence
to characterize the roll of the thumb. “Bending” indicates that motor #1 is ON and motor #2 is OFF. “Roll” indicates that motor #1 is OFF and motor #2 is ON. The thumb’s design meant that it did not rotate about only one axis. Therefore, it was important to study its changes in orientation about the $x$, $y$, and $z$ axes, whose locations relative to the thumb are shown in Fig. 4.

As an example, Fig. 7(c) shows the change in orientation of the thumb when only motor #1 was ON when the gripper was in the “vertically up” orientation. Under the aforementioned operating conditions, the orientation change about $x$-axis was most significant, with negligible creep. Similar results were obtained in the other gripper orientations. As an example, Fig. 7(d) shows the orientation of the thumb when only motor #2 was ON when the gripper was in the “vertically up” orientation. Under the aforementioned operating conditions, the orientation change about $y$-axis was significant. In addition, the orientation changes about $x$ and $z$ axes were also non-negligible. Similar results were obtained in the other gripper orientations. This shows that the motion about the different axes ($x$–$y$–$z$) was coupled with each other while actuating the roll of the thumb. We believe that since the orientation change about the $x$-axis can be individually controlled through the bending of the thumb, the orientation change about $x$-axis can be controlled independently within a range of angles. In contrast, due to the design of the thumb, the orientation changes about $y$ and $z$ axes are coupled, which consequently enables the thumb to achieve the desired degree of dexterity.

Fig. 7(e) and (f) show the statistical analyses for the thumb bending and thumb roll, respectively. These values were determined by computing the absolute changes in orientation by utilizing the measured Euler angles for each case. Fig. 7(e) and (f) show that while variations in the gripper orientations did not affect the bending actuation, they affected the roll actuation significantly. This can be inferred by the high variance in the roll actuation profiles. This aspect will be further examined in future work, and the design of the thumb will be modified to minimize the effect of gravity on the roll actuation.

B. Force Output

Two experiments were conducted to evaluate the force outputs of the gripper. Since all the fingers shared the same design, the force output of only one finger was characterized.

1) Blocked Force Output: The blocked force output of the index fingertip was experimentally obtained using the setup in Fig. 8(a). A load cell (LSP-2, transducer techniques) was first fixed to a machine vise and the gripper was placed in the vertically down position. Then, the motor was first rotated to 13 rotations, and then to 26 rotations. The motor stalled just before reaching its setpoint of 26 rotations. At its stall, the finger exerted its maximum blocked force on the load cell, which was 6.8 N [see Fig. 8(b)].

2) Constant Deflection and Varying Motor Angle: For the second experiment, the motor angle of the primary TSA was adjusted to keep $\alpha_2$, the $z$-axis Euler angle, approximately constant under varying loads. Analogous to the human hand anatomy, the IMU was mounted on the index finger’s proximal phalange, as shown in Fig. 8(c). The following procedure was used for this experiment.

a) Let $\alpha_{0z}$ denote the initial angle. Record $\alpha_{0z}$ when the motor angle $\theta = 0$ and the hanging mass $m = 0$. In this study, $\alpha_{0z} = 4.00^\circ$.

b) Apply increasing hanging masses $m$ to the finger. In this study, $m = \{0, 100, 200, 300, 400, 500\}$ g.

c) At each mass, adjust $\theta$ such that $\alpha_2 = \alpha_{0z} \pm \epsilon$. In this study, push buttons were used to manually twist the motors. The tolerance $\epsilon = 1^\circ$.

The purpose of the abovementioned experiment was to show that despite the gripper’s softness, its finger could maintain constant bending angles under increasing loads. Results [see Fig. 8(d)] show that the index finger supported a hanging mass of 500 g while maintaining its initial deflection angle (within the tolerance of $\epsilon$). This maximum mass was limited by the stall torque of the motors; stronger motors would have allowed the gripper to support a greater mass. However, they could also reduce the speed or increase the mass of the gripper.

C. Velocity

To study the peak velocity of the gripper’s fingertip, the input sequence in Fig. 8(e) was used. The velocity was obtained by numerically differentiating the position measurements. A Savitsky–Golay filter was applied during data postprocessing to both the fingertip angle measurements and motor angle measurements to eliminate noise. In Fig. 8(f), the peak angular velocities were 31.3712 rev/s and 235.2922°/s for the motor angle and fingertip angle, respectively. The motor shaft velocity and the fingertip velocity were mostly positively correlated [left-hand side $y$-axis in Fig. 8(g)], but there was a large amount of hysteresis, and “lonely stroke” in the right-hand side quadrant. The correlation between the motor shaft velocity and motor shaft angle, shown on the right-hand side $y$-axis, was a product of the proportional control scheme and the voltage–motor angle transfer function. The Jacobian—the ratio of the fingertip angular velocity to the motor shaft angular velocity—provided in Fig. 8(h) is defined as

$$\mathcal{J} = \frac{d\alpha}{d\theta} = \frac{d\theta}{dt}$$

where $\mathcal{J}$ is the Jacobian, $d\alpha/d\theta$ is the angular velocity of the fingertip, and $d\theta/dt$ is the angular velocity of the motor shaft. The Jacobian (also known as the reduction ratio) typically increased as the motor angle increased. It is well-documented that the Jacobian of the TSA also increases as the motor shaft rotations increases [16]. At the extreme ends of the $x$-axis, $\mathcal{J}$ sharply increased in magnitude, because of the jerk caused due to the sudden acceleration when the motor changed direction.

D. Tendon-Based Stiffening

In the experiment conducted to evaluate the adjustable stiffness property of the gripper, both the primary TSA and the antagonistic TSA were actuated. The setup shown in Fig. 8(c) was used for this experiment as well. The following procedure was used.
1) With both TSAs fully untwisted, record $\alpha_z$. Let $\alpha_{z0}$ denote the initial angle.

2) Twist the primary TSA by a given amount, $\theta_p = \{0, 8, 10, 15\}$ rotations. This pretwist will cause $\alpha_z > \alpha_{z0}$.

3) Twist the antagonistic TSA until $\alpha_z = \alpha_{z0}$. This was realized using closed-loop control of the antagonistic TSA where the voltage input to the motor was proportional to the error in $\alpha_z$. Let $\theta_a$ denote the amount of twists from the antagonistic TSA that makes $\alpha_z = \alpha_{z0}$. Note
that $\theta_p \neq \theta_a$ because the primary and antagonistic TSAs may have slightly different amounts of initial tension and string lengths.

4) Systemically apply monotonically increasing and decreasing hanging masses of $m = \{0, 60, 100, 120, 140, 160, 200\}$ g to the finger. The masses were hung from the string shown in Fig. 8(c). Each mass was held constant for 30 s. To distinguish between the “lonely stroke” and the subsequent cycles’ behavior, two loading cycles were applied.

5) At each loading condition, record $\alpha_z$ and compute $\alpha_{z0} - \alpha_z$.

6) Compute a first-degree polynomial that correlates the load (in N) to $\alpha_{z0} - \alpha_z$ as

$$mg = K_{\alpha}(\alpha_{z0} - \alpha_z) + K_0$$

where $m$ is the mass of each hanging load, $g$ is the gravitational acceleration, and $K_{\alpha}$ and $K_0$ are the coefficients to be computed. Because $\alpha_{z0}$ is defined as $\alpha_z$ when $m = 0$, $K_0 = 0$. $K_{\alpha}$ is then the stiffness of the finger, in terms of its angular deflection.

As shown in Fig. 8(i), the stiffness increased as the pretwist increased. However, there was an insignificant change in stiffness $K_{\alpha}$ between pretwists of 0 and 8 rotations. This was likely due to the following two reasons.

1) At low motor angles, the TSA had low linear contraction per twist.

2) The strings may have been slightly loose initially such that the first twists of the TSAs caused zero linear contraction of the strings.

Note that the maximum amount of pretwist was limited by the torque output of the motor. As the pretwist increased, the primary motor needed to exert more torque to overcome the opposing force from the silicone material and the antagonistic motor. These results are similar to those presented in [24] in which both empirical and simulated results showed a decrease in the effectiveness of an antagonistic TSA to increase stiffness at the extreme ends of a joint’s actuation.

Although the fingers were designed to bend primarily in one direction, a defining characteristic of soft materials is that they do not rigidly constrain motion in other directions. Thus, the lateral bending stiffness was experimentally characterized. The following two types of experiments were conducted.

1) First, the effect of bending actuation on lateral bending was investigated. For this purpose, the antagonistic TSA was maintained at zero pretwists. The finger was subjected to a load in the lateral direction, and the corresponding TSA was actuated to induce bending of the finger. Fig. 8(j) shows the motor angle input sequence versus time. Five different hanging loads were applied, with one unique load per cycle. Loads of $\{0, 0.1, 0.2, 0.5, 1.0\}$ N were applied. For each load, the average inclination is computed. The results [see Fig. 8(k)] show that the fingers were susceptible to significant deflection as a result of the lateral loading.
In these tests, the bending actuation mildly affected the lateral bending of the fingers, with the fingers deflected slightly more as they were contracted further.

2) Second, the effect of stiffness tuning on the lateral stiffness of the finger was examined. The three different amounts of pretwist in the antagonistic TSA were studied: a) 0 twist; b) 3 twists; and c) 9 twists. At each pretwist, loads of \( \{0, 0.1, 0.2, 0.5, 1.0\} \) N were applied in a monotonically increasing manner. Fig. 8(1) shows the antagonistic pretwist versus the stiffness, which are positively

Fig. 10. Achievable grasps from the Feix GRASP taxonomy; grasps are numbered and labeled as described in [47]. 1: Failed grasp: Thumb is not capable of fully realized parallel extension. 2: Failed grasp: Adduction grip is maintained passively with the actuators not actively applying the force.
correlated, adding antagonistic pretwists increased the lateral stiffness of the fingers. While the two variables were indeed correlated, the amount of stiffness tuning induced was less compared to the stiffness tuning induced in the bending direction.

V. GRASPING PERFORMANCE

A. Thumb Dexterity

The dexterity of the thumb was quantified using the Kapandji test [59]. With increasing research activity in the field of dexterous manipulation, researchers have employed the Kapandji test to quantify thumb opposability [4], [42], [43]. As shown in Fig. 9(a), in the Kapandji test, the tip of the thumb has to touch ten different locations on the hand, which include the tips of the other fingers. A score is then assigned based on the number of locations the thumb can touch. A score of zero would indicate no thumb opposability, while a score of ten indicates fully anthropomorphic opposability. The soft thumb presented in this study achieved a score of 6. While the thumb was able to touch all the locations on the index finger and the tips of the other fingers, it failed to touch the remaining locations on the little finger and distal end of the palm, as shown in Fig. 9(b)–(h). This is because the mobility of the thumb decreased at the extreme end of its roll actuation. This also meant that, although achieved, the contact between the thumb and the tip of the little finger was less substantial as compared to the contacts with the other fingers. Increasing the range of motion of the roll joint of the thumb could help improve the Kapandji score of the thumb.

B. Grasping Performance

The performance of the gripper was analyzed by replicating a variety of anthropomorphic grasps according to the Feix GRASP taxonomy presented in [47]. This taxonomy has been widely used to demonstrate the dexterity of grippers in previous studies [4], [7]. The proposed gripper was able to achieve 31 of the 33 grasps (see Fig. 10) presented in [47]. The gripper failed to achieve the parallel extension grasp (grasp #22); the best effort is shown in Fig. 10. To achieve this grasp, the fingers and thumb needed to actuate from their bases to clamp an object while remaining extended. However, due to the pseudo joints in the proposed finger design, the bending was uniformly distributed across the length of the finger. This can be addressed by adding a second DOF in each finger to allow decoupled proximal bending. Furthermore, for the adduction grip (grasp #23), the gripper was only able to hold on to the object through passive force and not using a controllable DOF. Enabling this actuation can be addressed in the next iteration of the gripper by adding a controllable DOF in the palm of the gripper. In addition, other commonly used grasp strategies by the human hand, such as the top grasp, flip grasp, and the edge grasp strategies [7], [58], were also demonstrated. For this purpose, the gripper was controlled in an open-loop fashion to grasp a ping-pong ball, a roll of tape, and a circuit board off a table with a flat surface to demonstrate the top grasp, flip grasp, and edge grasp strategies, respectively. For the top grasp, the tips of the fingers touch the flat surface, which then guides their actuation until a precision grasp is achieved [see Fig. 11(a)]. For the flip grasp, the fingers used the opposing force from the thumb to flip the object before achieving a precision grasp to firmly hold the object [see Fig. 11(b)]. During the edge grasp employed to grasp flat objects, the hand makes use of the table’s flat surface to slide the object toward the edge, until the object’s bottom side is accessible. This is followed by the gripper performing a precision grasp to firmly hold the object [see Fig. 11(c)]. In addition, the robotic gripper’s suitability for human interaction is shown in Fig. 12(a) and (b) through a handshake and a fist bump, respectively.

C. Grasp Strength

As a preliminary evaluation of the grasp strength, the gripper was made to lift a 2-kg dumbbell in different orientations, as shown in Fig. 13. The total mass of the gripper, including the actuators, was 565 g, which meant it supported nearly six times its own weight. The gripper’s grasp strength was further evaluated by investigating its ability to hold on to an object when an external force was applied to pull out the object. Note that the object’s gravitational force was not considered to be an external force. The gripper was made to hold cylindrical objects made with different materials in a power grasp, and forces were applied by suspending known masses from the object. The direction of the load [see Fig. 14(a)] was changed by adjusting the orientation of the base.

The objects grasped included a 21-mm diameter polyvinyl chloride (PVC) pipe, a 41-mm hard plastic cylinder, a 49-mm
metal pipe, a 66-mm hard aluminum can, a 75-mm soft plastic container, and 43-, 56-, and 76-mm paper towel rolls. The hard pipes and cylinders were rigid objects with smooth surface finishes. The soft plastic container was compliant and had a smooth surface finish. The paper towel rolls were compliant and had high surface friction. Finally, sandpaper was adhered to the 21-mm PVC and 49-mm metal pipe to see the effect of the added friction on the grasping performance. These results are presented with the label “wSP” in Fig. 14(b). Friction and object compliance significantly increase the grasping potential for the side and vertically up orientations where the actuation of the TSAs does not directly oppose the loading. Medium-sized objects also performed the best in these orientations, as it was difficult to achieve a tight grasp around smaller and larger objects. In the vertically down and palm down orientations where the tension in the TSAs could directly oppose the loading, the gripper was found to be much stronger. In these orientations, the compliance of the grasped objects improved the performance. However, size and friction were more deterministic factors, as smaller objects with higher friction provided the highest grasping potential.

D. In-Hand Manipulation

Simple tests were conducted to assess the gripper’s in-hand manipulation ability in its current configuration, through human-controlled actuation of the TSAs. Three types of manipulation patterns were demonstrated [7], rotation of the object about the: 1) proximal–distal axis; 2) radial–ulnar axis; and 3) palmar–dorsal axis [see Fig. 15(a)]. The objects that demonstrated the aforementioned manipulation patterns were a marker, a screwdriver, and a ping-pong ball, respectively.

First, rotation about the proximal–distal axis was achieved by using the thumb and the middle finger for maintaining the grip on the object and the index finger for the manipulation [see Fig. 15(b)]. Second, rotation about the radial–ulnar axis was achieved by using the thumb for maintaining the grip on the object as well as manipulation [see Fig. 15(c)]. Last, rotation about the dorsal–palmar axis was achieved by using the thumb for maintaining the grip on the object and the ring and index fingers for both maintaining the grip as well as manipulation [see Fig. 15(d)]. This manipulation was enabled by combining the high frictional coefficient of the silicone rubber of the gripper and its dexterity. Early results indicated that a future version of a gripper produced with similar materials and design could be capable of more robust in-hand manipulation.

E. Comparison With Other Anthropomorphic Grippers

Although the reported metrics of gripper performance vary greatly in the existing literature, the metrics that could be collected indicated that our gripper had comparable or superior performance relative to similar grippers that used alternative actuation methods (see Table I). The combination of high force output and low cost, along with reasonable thumb dexterity, high-performance grasping, and simple in-hand manipulation achieved by our gripper, showed that TSAs can be highly effective actuators for dexterous soft robotic grippers.

For their combination of controllability and high force output, pneumatic actuators have been used in many grippers aiming to be both anthropomorphic and dexterous [4], [7], [42], [43], [60], [61]. Applications of nonpneumatic actuation methods, such as SMAs [62], SMTAs [48], or combined actuation methods [63], have been less developed with grippers using these actuators being limited in force output and dexterity. Our gripper’s grasp force was higher than all the grippers, confirming that TSAs can provide high actuation forces in soft robotic grippers. A fair comparison of gripper masses was difficult because most grippers reported their mass, excluding the actuators’ weight [60], [61]. Among the papers that reported complete mass, our gripper was the lightest with the exception of [48], which does not claim the high degree of dexterity we achieved. Similarly, the low overall cost of our gripper, which was made possible by using inexpensive motors, indicates that this was also an advantage of using TSAs.

Comparing dexterity was also difficult, as performance metrics varied in the literature. We chose to use the Kapandji test [59] and the Feix GRASP taxonomy [47] to quantify the dexterity and grasping capabilities of our gripper. Kapandji test’s metrics varied between papers, with a minimum of eight locations in [4]...
Fig. 14. (a) Various directions in which external force was resisted by the gripper. Load was suspended from a cylinder held in a power grasp for various base orientations. The arrows indicate the direction of this load. (b) Maximum resisted grasp force exhibited by the gripper while holding various cylindrical objects in different loading directions.

and a maximum of 11 locations in [43], [60]. We tested ten points of which six were achieved. This was the lowest score of these grippers. However, our 6 DOFs were also the lowest among these grippers, which explained the lack of thumb dexterity. Although our gripper only had 6 DOFs, it achieved 31 of the 33 Feix grasps, which was comparable to other soft grippers. We also demonstrated basic in-hand manipulation abilities with our gripper, which was not quantified in the existing literature making the comparison between grippers difficult. Although our manipulation abilities were likely limited compared to other works [7], [43], the basic demonstrations prove that the precise control and dexterity required for in-hand manipulation can be achieved using TSAs.

VI. LIMITATIONS

A. Usage of Soft Material

As described in Section I, the use of soft materials to fabricate dexterous anthropomorphic grippers has multiple advantages. However, the inherent limitations of using soft materials, namely slightly unpredictable deformation of the material, increased nonlinearity of the components, and low force outputs in comparison to rigid grippers, naturally appear in the proposed gripper.

First, although the fingers had a maximum theoretical bending angle of 270°, the experimental characterization revealed that the maximum bending angle was approximately 230° (see Fig. 5). This discrepancy could be a result of the compliance of the soft fingers. The theoretical maximum bending angle was calculated under the assumption that the finger would only deform due to bending while actuated. In reality, it appeared that there was some axial deformation that reduced the internal angles of the triangular actuation cuts, which reduced the true maximum bending angle.

Second, the motor angle–fingertip angle correlations of the fingers and the thumb were nonlinear (see Figs. 6 and 7). The nonlinearities consisted of hysteresis with lonely stroke behavior and some creep. These nonlinearities could be due to the inherent material properties of the silicone [25] and the frictional force between the strings and the PTFE tubes [52], [53]. Readers are encouraged to read [53] where the force outputs of a TSA are modeled while sliding on a surface with friction. Although all the fingers exhibited acceptable consistency in their respective motor angle–fingertip angle correlations under different orientations, the presence of the aforementioned nonlinearities could complicate the physics-based modeling process. In future work, data-driven approaches similar to the ones presented in [57] and [68] could be used. The design of the fingers could also be modified to reduce the nonlinearities’ effects.

Third, the force outputs of the fingers could be increased by using higher torque motors. However, this could result in decreased actuation speed of the fingers if the torque was increased with a gearbox. Since the actuation speed of the TSAs depends on the radius of the strings used, optimization techniques could be employed to select a motor-string combination that permits the required force output yet maximizes the actuation speed. Last, the adjustable stiffness capabilities of the proposed gripper can be further explored by using softer material to fabricate the gripper. However, as discussed in Section III, using a softer material would also make the gripper less structured, potentially decreasing the lifespan of the silicone and the weight that can be supported by the gripper, as well as exacerbating the axial deformation issue noticed with the actuation cuts. The silicone in this work caused mild variation of the fingers’ stiffness.
B. Grasping Capabilities and Thumb Dexterity

The proposed gripper managed to achieve almost all the grasps presented in [47]. However, it failed to realize the parallel extension grip (grasp #22) and the adduction grip (grasp #23). Furthermore, the thumb design presented in this work only achieved a score of 6 out of 10 on the Kapandji test. Although these results were deemed to be acceptable, further improvements could be incorporated in the next iteration of the gripper to address these grasping-related limitations.

1) First, by removing the pseudo joints from the finger design and adopting a continuous design similar to the design presented in [4], [42], [43], the grasping performance would improve. This may also help the gripper achieve the extension grasp. With a continuous design, the compliance of the fingers increases, thereby allowing them to achieve the grasps in a more efficient manner.

2) Second, including an additional controllable DOF in each finger could enable the gripper to achieve better grasping performance, as demonstrated in previous studies [7], [69], [70].

3) Last, including a controllable DOF in the palm of the gripper could lead to a higher score on the Kapandji test and also achieve the adduction grip.

Previous studies have shown that a controllable DOF in the palm aids the thumb to touch the locations on the little finger in the Kapandji test [4], which could help our gripper to achieve the missed little finger and distal palmar crease contacts.

However, increasing the DOFs of the hand would also increase structural and manufacturing complexity, weight, and size. Accordingly, any additional DOFs must significantly improve the grasping performance, dexterity, or manipulation capabilities of the hand beyond the benchmark of the current iteration to justify their inclusion.

C. Exclusion of Sensors

Despite limitations due to the usage of soft material and limited controllable DOFs, the proposed gripper performed satisfactorily in achieving different Feix GRASP taxonomy grasps, resistance to external force, and preliminary in-hand manipulation. However, all the aforementioned tasks were performed in
open-loop. This is because the data from the encoders are not directly used to control the posture of a particular finger [28]. Furthermore, sensors to measure the force outputs from the fingers and palm will also be required to perform effective grasping [60]. The inclusion of sensors in the gripper design will be explored as a part of future work. To maintain the compactness of the gripper, self-sensing TSAs, which use conductive SCP strings, can be used to measure the pose of a finger [68], [71]. In addition, tactile sensors [60] could be embedded into the design of the gripper for force sensing.

VII. CONCLUSION AND FUTURE WORK

In this article, the use of TSAs to drive a soft robotic gripper was explored. First, the design and fabrication of the gripper were discussed. The design included a soft thumb with two controllable DOFs. It additionally included an adjustable stiffness mechanism. Second, the fingers were experimentally characterized in terms of their bending angles, force outputs, actuation speeds, and adjustable stiffness capabilities, and these experimental data were statistically analyzed. Finally, the grasping capabilities of the gripper were demonstrated. The experimental results and comparison confirmed the high performance of the TSA-driven soft robotic gripper.

Despite the satisfactory capabilities of the proposed robotic gripper, further improvements can be made.

1) First, the design of the fingers and thumb could be modified to minimize the nonlinear effects in their actuation profiles and to improve the grasping capabilities and the dexterity of the gripper. Additional controllable DOFs could also be included to improve the grasping performance and manipulation abilities of the gripper.

2) Second, mathematical models could be developed to accurately predict the behavior of the gripper.

3) Third, the in-hand manipulation capabilities of the proposed robotic gripper could be further studied. For this purpose, advanced motion planning and grasping algorithms that utilize machine learning techniques [72], [73] could be developed.

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