An Underactuated, Two-Finger, Biomechatronic Gripper with Joint-Pad Compliance and Differential Actuation

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***Abstract*— In recent years compliant, tendon-driven, underactuated prosthesis has been a primary driver for the biomechatronics field. These devices grant their users many degrees of freedom, without sacrificing key criteria such as form factor or weight. These designs are more accessible and affordable, presenting a promising direction for the field in light of the increasing amputation rates globally. In this paper, we design and validate such a design, using Yale's OpenHand project as inspiration. The gripper detailed in this report is an adaptive, tendon-driven, single-motor system that affords its user 4 degrees of freedom. The gripper was entirely flexure joined, using pins to redirect tendons and a large motor for higher-power applications. To verify its quality, we used our gripper to grasp a variety of objects, including a big bottle of water (full, 1.5L), a credit card (from a table surface), a fork, a washer (from a table surface), a wrench, a drill, a hammer, and a chain (articulated). The designed gripper succeeded in grasping and extrinsically manipulating each of the objects. However, sagging and twists were observed in the flexure joints. This indicates that further improvements could be made to torsionally reinforce the joints - namely the proximal joints.**

I. Introduction

Human dexterity is a mechanism so complex that the prosthesis field of research has barely scratched the surface of its mimicry. The human hand is just one example of the human's dexterous repertoire. The intricacy of the musculoskeletal interactions that dictate the near-enumerable number of poses and grasps a human hand can achieve is impossible to replicate artificially with today's technology. We use our hands' many gestures and grips in everyday tasks - sometimes we are even unaware of when we use them for tasks as simple as gesturing in social scenarios.

Those without these capabilities suffer severe handicaps in performing routine tasks which are often taken for granted. [1] and [2] both cite a rising demand for prosthetic development in light of a marked rise in amputating surgeries across America and Italy & the UK respectively. Presently, market-available prosthetic hands can be priced anywhere between USD$4,000 to USD$75,000 relative to the functionality required [3]. This functionality can range from simplistic, body-powered, transradial control, to complex, externally-powered, transhumeral control. In most cases, the bulk of the cost is due to the (often) many motors comprising the actuation system for a given prosthetic - which often surrender weight and form factor [4], [5].

This presents an opportunity for further research concerning underactuated motors. Achieving the many degrees of freedom (21 DOFs [6]) accompanying a human hand challenges modern-day prosthetics. At present, there is no way to achieve all of the freedom comprising a human hand without sacrificing weight, space and mobility significantly [7]. It stands to reason that in such a case, a cleverly designed underactuated hand could offer a practical concession. The Yale OpenHand project produced a robust and utile hand of this nature - this is the study we will use to springboard our own [8]. However, this is a compromise and does not discount the prevalence of tradeoffs in prosthetic qualities like form factor, weight, and cost [9].

In this design project, we sought to develop a powerful, compliant prosthetic gripper. Though weight was a worthy consideration, we believe power is more vital to the quality of life for a recipient of our prosthesis. Thus, our design houses a larger motor to grant users more power in their grasps, without sacrificing form. We proceeded with an underactuated, tendon-driven, flexure-joined, 3D-printed solution.

The rest of the paper is organised as follows: Section II presents the related works, section III concerns our design choices, section IV describes our observations and results, and Section V concludes the study and discusses its future directions.

II. Related Work

There is an array of market-available prosthetic hands - varying between completely un-actuated, fully-anthropomorphic designs, to fully-actuated, ADL-task-specific designs. One of the first to design a task-focused, grasping hand with some semblance of sensory feedback was [10]. Our study concerns under-actuated (particularly single-motor) prosthetic hands or grippers. The contents of this section will serve to provide an overview of the literature presently available and the current state-of-the-art design for such prosthetics.

A. Biomechatronic Underactuation

Underactuated biomechatronic hands have been a key driver in the field of research for some time now [7]. Given the drawbacks of multiple actuators (such as motors) in a single design, the necessity for ingenious designs for the minimisation of such actuators has become apparent. In their Karlsruhe humanoid hand project, Fukaya et al. achieved 20 DOFs with a single actuator [11]. However, this design was highly complex and sacrificed robustness to achieve such a high level of freedom. As such, it is worth noting that under actuation inherently surrenders DOFs to achieve low-cost, low-weight solutions. More recently, [12] proposed a truss-mimetic design which was comprised of small linkage structures for underactuation of a finger in two dimensions.

Naturally, developments have been made into furthering bio-mimetic designs using tendon-driven fingers. [13] produced a modular, compliant, tendon-driven finger design. It used two fingers and had both forced-grasp and pinch capabilities. The adaptive SDM hand in [14] also features underactuated tendon-driven fingers. They used protective raceways to direct their tendons. Perhaps most notably, the Yale OpenHand project produced three tendon-driven, underactuated hands using flexible joints and silicon compliance [8]. Ma et al. used low-friction pins to channel their tendons through the finger structure to the termination. Each of these designs sacrifices anthropomorphism in the pursuit of form factor, weight, cost, and power optimisations. This seems a necessary compromise and is deemed so by the field of literature, too.

Furthermore, transmissions in tendon-driven systems are far simpler to implement and facilitate form-factor-conscious design. Some shrewd transmissions can also assume the role of a differential within a given design. These differential mechanisms equip the fingers with adaptability to unknown, variable object shapes. Conforming to object geometry is a fundamental functionality for grippers and biomechatronic prosthetics. In both [13] and [14], a pulley system is used to transmit the force from the chosen actuator to each of the fingers equally. In each case, the pulley system acts as a differential, avoiding over-actuation of fingers (e.g., when attempting to squeeze an object) and subsequent damage to the actuator. Conversely, Kontudis et al. proposed an anthropomorphic design (outside of the scope of this project) which used an array of bar differentials in tandem with locking techniques to operate their hand adaptively [15].

B. Gripper Design

Arguably the most important design challenge presented by the implementation of a thoroughly functional prosthetic hand, is that of the finger. In the pursuit of modularity, applicability, and robustness, the finger holds perhaps the most acclaim [7]. The design of the finger needs to facilitate the hand's actuation method and gripping techniques. Relevant considerations are compliance, joints, materials, and linkage geometry.

1) Compliance: The iHY hand [16], which used the SDM hand as an initial design concept - along with the OpenHand project and Hussain et al., used elastomeric materials to comprise the compliant finger pads. Using HDM moulding (the pouring of silicon, epoxy or otherwise into voidal regions of the finger), they were able to achieve a finger-pad along the surface of the finger. This compliance - in the cases of the iHY and SDM hands - also housed sensor arrays for pressure feedback.

Typically, the materials used for the finger pads are highly compliant, but not very robust - meaning that high amounts of shear stress could result in tearing of the material. However, because most force will be pressing the material against it's line, this is not of concern. The OpenHand compliance differs from the iHY design. To promote cohesion of finger pad and finger link, [8] made use of small T-structures. These T-structures act as anchors, fastening the compliant material to the finger link (Fig. 1).

2) Joints: Strictly speaking, there are two fundamental joint types: pin joint, and flexure joint. Pin joints are simple to implement and highly modular. Auckes et al. produced an entirely pin-joined design which was also tendon-driven, and saw some notable gripping success [17]. For a pin-joined finger to return to its initial position, it requires a return spring to provide it with the necessary spring-back stiffness. However, springs have notably short lifetimes with only a small number of achievable cycles before breaking. This damages the robustness of a model which uses pin joints.

The pin joint's counterpart, the flexure joint, is highly robust and impact resistant, yet has been implemented to varying degrees of success. In the same manner to the finger pads, the flexure joints need to be fastened to the model such that when they bend they do not slip out from between the linkages. The iHY hand used anchoring cavities in the interfaces to do so [14]. The OpenHand project [8] integrated flexure joints into their design using HDM techniques (Fig. 1), but observed that the implementation was highly complex and difficult to scale-up. They also observed a distinct sag and twist in the flexure joints when grasping heavier objects, which at times led to a failed grasp. This points toward the torsional instability of thinner flexure joints.

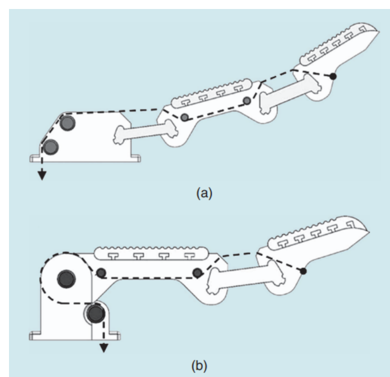

Fig. 1: OpenHand finger design. Both flexure (a) and pin (b) joined metacarpal linkages. Note the use of pins to reroute the tendon in both designs. Retrieved from [8].

3) Materials: The elastomeric materials required to produce flexure joints and finger pads should ultimately differ in robustness and end-compliance. In [18], Leddy proposes a hybrid composition of two Smooth-On elastomeric formulations. He proposes either Dragon-Skin or VytaFlex for the compliance and PMC for the flexure joints. Dragon-Skin being the the most soft and compliant of the three, and PMC being the stiffest and most robust (VytaFlex's properties fall somewhere in the middle of these two). Smooth-on is also used in the OpenHand project, in which its success is cited in the finger pads and successful moulding of the flexure joints [8].

4) Linkage Geometry: From a higher-level perspective, most fingers are comprised of three linkages, for the purposes of this report, we will denote them as: the metacarpal (base of the finger), the proximal (central linkage), and the distal (end of the finger). Most tendon-driven mechanisms allow for the tendon to channel through the center of the finger before terminating in the rear (to maximise pinching force). To achieve this, many state-of-the-art gripper designs [8], [14], [16], [19] push their (flexure) joints to the rear of the finger linkages, allowing for tendon routing without joint interference. To accommodate the HDM of elastomeric materials, some designs have made use of pre-buit moulds and even in-built moulds [8]. For designs using fewer fingers, it is common to widen the fingers significantly - like in the OpenHand project's Model T42.

III. Designs

A. Gripper Fingers

For our design, we proceeded with two fingers. This allowed simplicity of implementation which in turn provided robustness and ease of use. Furthermore, reducing the complexity of the overall design meant we could dedicate more resources toward iterating upon certain design failures cited in section II.

As discussed in prior sections, the design of the finger can be divided into four primary sections: compliance, joints, materials, and linkage geometry. As such, we will also discuss our own design through these four paradigms. It is important to note that we elected to actuate our fingers using tendons. This decision was made because of the modularity and simplicity of the tendons. Should a tendon break, it is far easier to replace than if a linkage or otherwise were to break. To channel these tendons we opted for pins - to avoid the significant friction and potential cutting associated with raceways.

1) Compliance: For our compliance, we opted to use elastomeric materials (as opposed to rubber pads). We fastened our compliance pads to the linkages using deep cavities within the linkages. These cavities anchored compliance material to the linkage sufficiently such that it would not shift or slip out of position while the hand grasped objects. Each linkage had two unique cavities on either side for the HDM. This was to allow space for the tendon routing (discussed in subsequent sections). We designed three escapes into the cavity on both sides of the finger, for each linkage (equating to six escapes per finger).

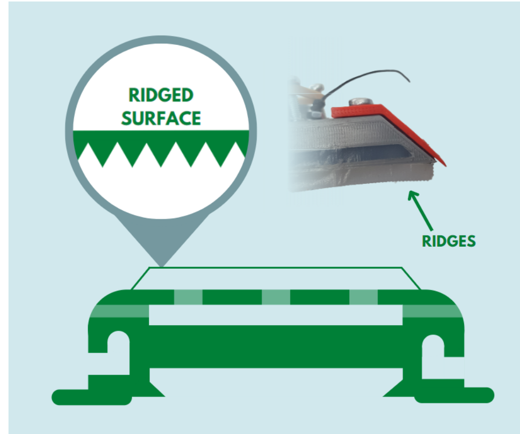

Fig. 3: Graphic representation of the small ridges printed onto the interior surface of the mould face. This produced rough compliance.

Once the HDM was complete, we removed the outer shell (shown as a thin green line in Fig. 2), exposing the moulded material beneath. We had initially designed a designated mould, but found that incorporating the mould made for faster iteration and decoupled our new designs from the old moulds.

Our compliance moulds were also furnished with rough, ridged interior surfaces and spanned the entire width of the finger (Fig. 3). This made for broad gripping surfaces with maximised surface area and contact points. Furthermore, it was made certain that the fingernail only protruded half the size of the smallest object we could conceive of picking up. This way, we ensured that any object could foreseeably be jostled up and secured into the compliant material, and thus gripped tighter. It is worth noting that the compliance at the fingertip was designed to be rounded off, but was still ridged.

2) Joints: We elected to proceed with flexure joints for our fingers. This was because of the short lifetime of springs, which we could not justify given the purpose of the project. We used elastomeric material for both joints, and the same moulding strategy as above - removing the casings once the pour was complete. We attempted to remove the torsional component by widening the joint itself.

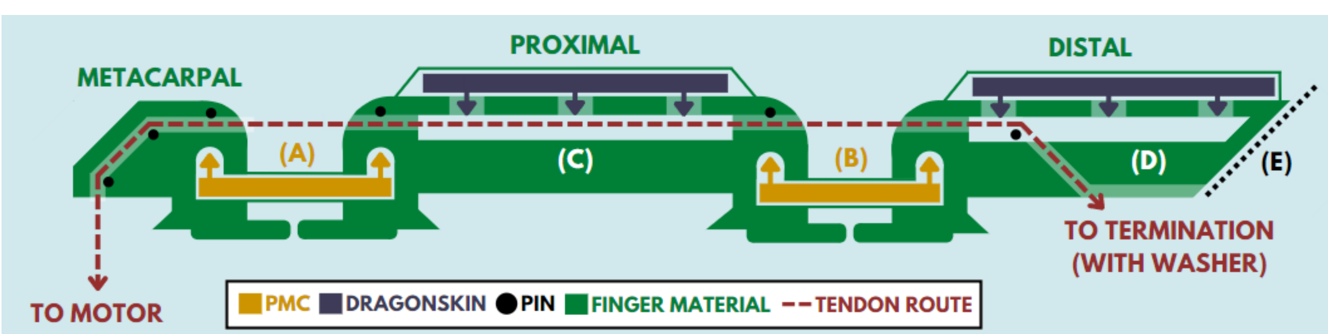

Fig. 2: Graphic representation of our finger design. Note the thin-walled in-built mould for HDM. Proximal (A) and Distal (B) joints filled with Smooth-On PMC, and Proximal (C) and Distal (D) linkage cavities filled with Smooth-On Dragon Skin. Note also the mounting for the fingernail (E).

To that effect, we also extend the anchoring cavity across the span of the width of the finger. The anchoring cavity itself was biased against the direction of rotation for the joint. This removed any possibility of the joint coming free of the anchoring point and made for a robust, monolithic design.

3) Materials: For the joints and compliance, we used Smooth-On PMC and Dragon Skin respectively. This was primarily due to their applicable properties. PMC is far less compliant but stiffer and more robust. This made it a suitable choice for the joints, as they are to undergo many cycles and thus need to be reliable and resistant to deterioration over long durations of time. Dragon Skin is weak and insipid, but also soft and compliant. Given the majority of the force was pushing the Dragon Skin *into* the linkage, tearing was not an issue.

In the case of the main body of the finger and all other larger parts in our design, we opted for 3D printing. To address robustness and structural integrity whilst also optimising weight where possible, we selected varying infill percentages from part to part. In the case of the finger, cutting of the tendon through the main body presented a problem. Furthermore, given the monolithic design of our finger, it was sensible to preserve the durability of the parts over all else. Should a linkage fail - so too would the entire finger. Thus, combined with pins (discussed subsequently), we used 80% infill, 3D-printed parts to comprise the linkages.

Finally, for the tendon, we chose one of 1.6mm diameter (making the channel profile approximately 2mm wide to accommodate the tendon). We did so to avoid any potential breakages through fraying of the tendon during operation - a thicker tendon is more durable.

4) Linkage Geometry: To redirect the tendon through to the front (in the metacarpal linkage) and then to the rear (in the distal linkage), we used smooth-surfaced pins. These pins were slotted and fastened into each linkage. The tendon is to run through the front of the main body of the finger to maximise grasping power. It is to terminate in the rear of the finger to maximise pinching power. The pin positioning along this path was designed such that no single redirection exceeded 45°. We did so to keep losses due to friction as low as possible.

Furthermore, we drove the positioning of our joints to the rear of the finger. This was done to make way for the tendon (thereby reducing friction by minimising the number of redirections - pins - required) and eliminate joint-tendon interference. Moreover, the joint positions made it easier to implement hyper-extension blocks for both the proximal and distal joints (Fig. 2). We also designed our fingers wide (40mm, significantly wider than any other design), to test for torsional strengthening of the flexure joints. Our joints were of different thicknesses to promote movement in the distal joint before the proximal (i.e., the distal joint was slightly thinner than the proximal).

Additionally, we ran a 45° cut out of the rear of the fingertip not only to flatly mount the fingernail but also to allow our finger to meet flush with the supporting surface before picking up an object. To produce the fingernail, we printed a thin plate with the same width as the finger. This was filed to a sharp edge, then mounted onto the fingertip.

Finally, we made use of clasps to the rear of each linkage joint cavity to be able to tune the stiffness of each joint using rubber bands. This meant that - should any of the joints produced cause an imbalance in the finger, we could freely make changes to tune this back to a satisfactory state.

B. Gripper Base

1) Spacing: To maintain form factor but also regulate the amount of space required for our pulley-differential system, we used printed spacers. Along with these, we also used our motor itself to space the base parts. We wanted to maintain a solid base design and using the motor as a spacer was pivotal to that. However, we found that this did not leave enough room for the fingers to completely tense (i.e., the differential did not have enough room to move down before interfering with the pulley). To counteract this, we left our fingers in a permanent state of tension - the maximum opening of the hand was less due to the differential's limits within the base (Fig. 4), but this allowed our hand to reach fairly high grip strength. That said, improvements could be made to improve the spacing and allow for more tensile grips - one way of doing this is by extending the spacers connecting the base plats and the motor.

2) Motor Housing: The motor housing was built into the base design and was (strictly speaking) four supports to which we bolted the motor. We found that this secured the motor substantially, and worked well as an anchor to act against the high tension in the tendons when gripping. Because the motor acted as a spacer, the entire base acted as a solid housing for the motor too.

3) Motor, Pulley & Differential: To drive the tendons, we attached a simple pulley to the motor horn and winched the tendon with the motor's rotor. The motor we selected was the larger of the two Dynamixel motors available - the MX64AR. Though slightly heavier, this motor was more powerful than its counterpart, and we felt that the true necessity of our design was power. Given that the main object of our implementation was force (as opposed to speed), the pulley diameter was designed to be fairly small. Our pulley had

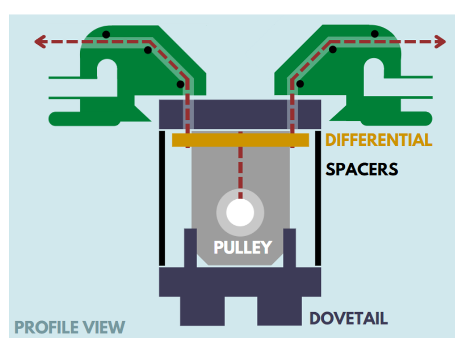

Fig. 4: Graphic representation of the base design from a profile viewpoint. N.B: The base compliance components have been committed for ease of viewing. See Fig. 5 for further detail.

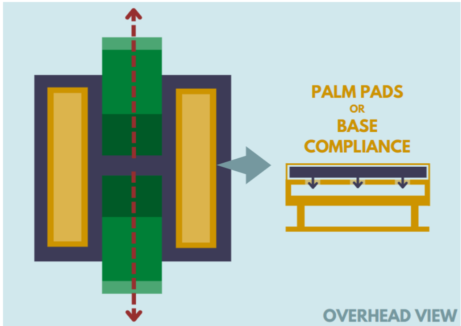

Fig. 5: Graphic representation of the base design from an overhead viewpoint.

OBJECT (RESULT)	OBSERVATIONS
BOTTLE OF WATER, WRENCH, HAMMER (PASS)	The gripper succeeded in picking up each of these objects. However, twist and sag (torsional instability) was observed during the extrinsic manipulation of these objects. This torsion was observed
CREDIT CARD, FORK, WASHER, DRILL, CHAIN (PASS)	Each of these items was picked up without a hitch

TABLE I: Photograph of the real model with all parts printed, cut, or moulded. Note the ridged compliant material on the fingerpad near the fingertip.

a high relative torque output, which made grasping heavier objects less challenging.

Regarding the differential, we opted for a simple bar. Given we designed a hand that used only two fingers, there was no need for over-complexity in using a whiffle tree or pulley-system differential.

Given that these two parts came under the most stress in our design we laser-cut both our pulley and differential to avoid any breakage during operation.

4) Base Compliance: To achieve a quality palm pad akin to the finger pads discussed in prior sections, we used the same mould shell methodology. We used Smooth-On Dragon Skin to attain a soft, highly-compliant palm. Just as in the finger pads, the palm pad material was poured into the void and had three escapes into a deep cavity within - securing the Dragon Skin to the part. The base compliance was designed such that the palm pad itself was elevated slightly above the height of the metacarpal joint sitting on the base plate. Any object subject to a power grasp had many compliant points of contact, and our fingers could drive an object into the palm for a secure grip.

C. General Modifications

To further improve the integrity and functionality of the gripper, we made some post-modeling modifications to the design. Firstly, we chamfered all sharp edges where possible to improve the structural integrity of each part. We also filleted all entries and pathways of the tendon - this was to reduce friction or the likelihood of a snag in the tendon during operation. Additionally, we added minor tolerances (approximately 0.1mm across the board) to all screw or pin holes. This meant that the screws fit snugly into their allotted holes, but we also had enough take on the holes to thread them if necessary.

IV. Experiments and Results

To test the design's reliability and robustness in real-world gripping scenarios, we experimented with a variety of objects with different geometries, including a big bottle of water (full, 1.5L), a credit card (from a table surface), a fork, a washer (from a table surface), a wrench, a drill, a hammer, and a chain (articulated).

The results recorded, as well as any noteworthy observations concerning the grasp, are indicated in TABLE I. Our results were very encouraging and indicate that this design is certainly substantial for many objects. However, we can determine that there is an obvious object type which leads to problems in our gripper's grasp. It seems as though objects with mass distributed across a greater length are a challenge for the design's mechanism. During the water bottle test, a clear twist and sag in the flexure joints could be observed (just as in [8]). We speculate that this may be due to using only two fingers, combined with potentially weak flexure joints. This could be amended by using stiffer joints (discussed in subsequent sections), or swapping the proximal flexure joint for a pin joint. Most of the torsion occurred in the proximal joint. A pin joint will constraint the rotation to one direction - as such it would be a good alternative to the fully flexure hand.

The heavy object which required mainly power - the water bottle - was picked up with minimal issue. We observed slight torsion but nothing close to that of the other heavy objects. Our gripper picked up lighter, pinch objects with ease. The credit card, washer and pen (indicated in the video submission) were each fairly simple pinch grasps.

Overall, we believe that the design was validated via our experiments, but we would like to iterate further to see how far its robustness can be pushed. Its durability and power are its greatest virtues, so we would like to test their limits.

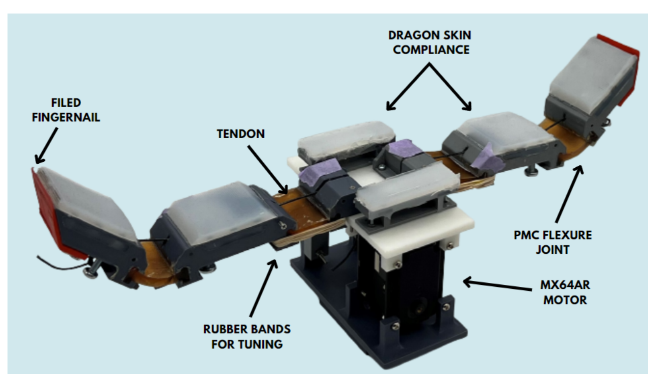

Fig. 6: Photograph of the real model with all parts printed, cut, or moulded. See the ridged compliant material on the finger pad near the fingertip. Note that at rest the gripper is partially in tension.

V. Conclusions and Future Directions

In this study, we proposed a two-finger, tendon-driven, underactuated prosthetic gripper. We sought to investigate its applicability through the testing of a variety of grasps and grips. Though our design was only somewhat validated in our experimental trials, the takeaways and their application or both clear and encouraging. Through the gripping tests, we concluded that the design works very well for gripping lighter objects - like the credit card, washer or chain. Yet struggles significantly with heavier, less-uniformly distributed objects - like the hammer, water bottle or drill. We attributed this to the torsion and sag observed in the flexure joints (just as observed in [8]). This is a curious result as we actively widened our finger design to mitigate this - which clearly did not have the expected effect.

That said, there is still hope for flexure joints. There are yet emerging options for reinforcing flexure joints torsionally. Gerez et al. proposed a laminar jamming technique in which laminates are layered within a flexure joint and the stiffness can be changed by varying pressure within the joint [20] (Fig. 7). Godaba et al. showed that a similar effect can be achieved using morphing flexible flaps in combination with pneumatic drivers [21].

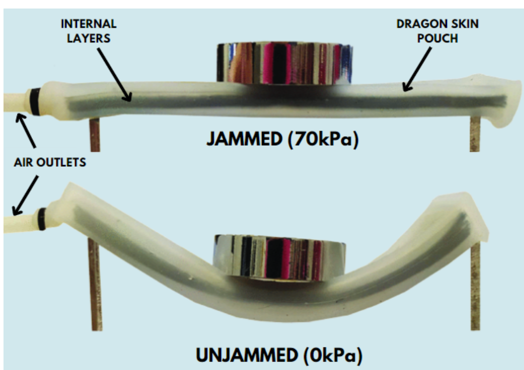

Fig. 7: Example of the laminate jamming with and without pressure within the flexure joint. Retrieved from [20].

Further iterating on our own design, we could firstly reduce the elastic tuning clasp length to extend just half the width of the finger. This would ensure that the rubber bands act to extend the finger rather than compress it in certain scenarios. We would also replace the proximal flexure joints with pin joints as a short-term solution to the torsional instability.

Concerning future study, investigation into the torsional strengthening of flexure joints is certainly a worthwhile pursuit. Flexure joints such as those discussed in this report are becoming more accessible and popular in the field of study, and further research into making these more applicable than they already are is a good first step. Furthermore, another interesting point of investigation is the application of non-anthropological grippers. If we can determine whether there is a place for non-anthropological grippers in the world of prosthesis, we can refine our research and direct our resources toward the most viable option.

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