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An Extensor Mechanism for an Anatomical Robotic Hand

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Abstract -- The human finger possesses a structure called the extensor mechanism, a web-like collection of tendinous material that lies on the dorsal side of each finger and connects the controlling muscles to the bones of the finger. In past robotic hand designs, extensor mechanisms have generally not been employed due in part to their complexity and a lack of understanding of their utility. This paper presents our first design and analysis effort of an artificial extensor mechanism. The goal of our analysis is to provide an understanding of the extensor mechanism's functionality so that we can extract the crucial features that need to be mimicked to construct an anatomical robotic hand. With the inclusion of an extensor mechanism, we believe all possible human finger postures can be achieved using four cable driven actuators. We identified that this extensor mechanism gives independent control of the metacarpo-phalangeal (MCP) joint and acts not only as an extensor but also as a flexor, abductor, adductor, or rotator depending on the finger's posture.

1. INTRODUCTION

We are constructing an anatomical physical model of the human hand as a tool for three research investigations we intend to tackle:

1. As an experimental testbed to investigate the complex neural control of human hand movements,
2. As a working physical model of the human hand for neuro- and plastic-surgeons to test new surgical reconstruction techniques for impaired hands, and
3. As a telemanipulator that mimics both the active and passive dynamics of a human hand for precision teleoperation and prosthetics.

For many years there has been much effort devoted to the designing and building of anthropomorphic robotic hands, but to date it has not been possible to use these robotic hands for any of the above investigations because they have not been anatomical.

For our first prototype we constructed an anatomical robotic hand with materials and structures very similar to those which are found in human hands (Figure 1). We molded cadaver bones and mimicked their joint structures by encapsulating viscous materials with a ligament-like structure. By constructing this hand, we realized that we could not mimic all materials and structures of a human hand because human cells are replaced every day to deal with wear and tear while artificial materials are not.

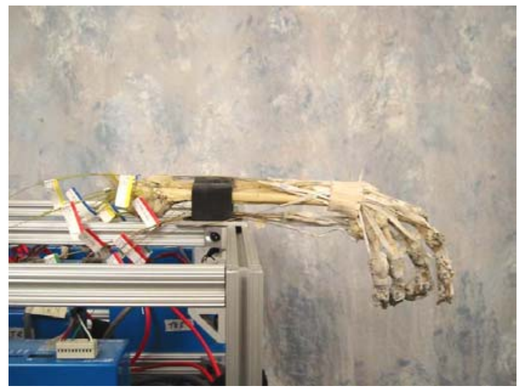

Figure 1. Our first anatomical robotic hand prototype; we molded cadaver bones and mimicked their joint structures by encapsulating viscous materials with a ligament-like structure.

Therefore, until tissue engineering becomes more advanced, we must select and mimic the hand's most important functional features so as to enable us to conduct the three investigations listed above.

The obvious and crucial features to preserve in an anatomical robotic hand are its degrees of freedom, its kinematics, its number of bones and muscles, and its muscle strengths, as well as its musculotendon origin and bone insertion points so that forces are applied by the muscles at the same location and along the same vector as they are on the human hand. In addition, it is important to preserve the hand's musculotendon passive properties, its overall size, and its tendon routing structure. Musculotendon passive properties are known to be spring-like and allow compliance to the fingers. The overall size of the hand must be the same as that of a human hand for surgical and prosthetic applications. Even investigations into the neural control of movement, which often analyze object interactions, require that the testbed be as close as possible to the real size of a human hand. To preserve the tendon routing structure, we must address the structure of the extensor mechanism.

The extensor mechanism is a web-like structure composed of tendons and ligaments that rides on the dorsal side of the finger and connects the controlling muscles of that finger to the three bones. In the past, the extensor mechanism has generally been excluded from any anthropomorphic robotic hand design due in part to its complexity and a lack of understanding of its usefulness. However, there are important finger postures that do not seem possible without the extensor mechanism (see Section

4). This paper presents our first design and analysis effort of an artificial extensor mechanism. The goal of our analysis is to provide an understanding of the extensor mechanism's functionality so that we can extract the crucial features that need to be mimicked for the three investigations listed.

2. BACKGROUND

There have been numerous anthropomorphic robotic hands constructed to allow versatile assembly tasks [2], to investigate human-like manipulation abilities [3,10,16,20], or as a part of a humanoid robot [15,16]. Some of these hands achieved a dexterity that matched that of human hands in specific tasks; however, none of these hands is completely anatomically similar to a human hand due to one of the three following reasons:

1) It was never important to mimic the biology of the hand. As long as the specific tasks the creators wanted to achieve could be accomplished in somewhat human-like ways, then the design was acceptable.

2) To make them anatomically similar was complex and difficult to imitate or the space was too limited to fit everything that was needed. As a result, the creators simplified the actual anatomical structure when making their design. A typical example of this is to limit the degrees of freedom within one finger. The Cog hand and Belgrade/USC hand have a single degree of freedom per finger [3,16]. The Robonaut hand has two degrees of freedom per finger [15], and the JPL/Stanford hand has three degrees of freedom per finger [20].

3) The goal of the researchers who created these robotic hands was to construct a hand that mimicked a human hand's degrees of freedom and its joint movements and not to mimic its biological control mechanisms. The Utah/MIT hand has four degrees of freedom per finger as does a human finger [10], but each joint is actuated by two dedicated cables, unlike a human joint, and the lateral degree of freedom at the MCP joints is not anatomically accurate in its kinematics. Lee and Shimoyama [14] built a hand that mimicked the extrinsic muscles of a human hand but did not include the intrinsic muscles due to their complexity. The Shadow Robot hand [6] has four degrees of freedom per finger and fairly accurate ranges of motion for each joint, but because the extension of the second and third joints (PIP and DIP) is achieved with passive springs the performance does not resemble a human's.

To our knowledge, none of the previous mechanical hands built have included an extensor mechanism, with the exception of the partial robotic hand constructed by Barbieri and Bergamasco [1]. They built a conceptual prototype that contains an index finger and thumb with human-like flexor tendon paths and an extensor mechanism. Emphasis was based on creating a generic mathematical model to deal with the kinematics and kinetics of what they called "nets of tendons", not on the specific mechanical, structural, and functional qualities of the extensor mechanism itself.

As a way to understand the human tendon routing structure and to find the optimal robotic cable routing method, the force capabilities of human fingers have been studied and compared to those of two robotic hand systems. Typical robotic hands have symmetric flexion/extension force capabilities, while human fingers have flexion-dominant force production capabilities. It has been shown that for a robotic finger with N=4 degrees of freedom, particular arrangements of either 2N or N+1 number of control cables will yield a finger that achieves the same range of forces as a human finger [19]. Valero-Cuevas [22] has used the principles of robotic manipulation to analyze human digits as serial manipulators and was able to predict muscle activity levels for specific force production.

In the medical field, there have been numerous studies on the anatomy and function of the extensor mechanism, also known as the dorsal aponeurosis, of the human finger [4,7,8,9,11,13,17,21]. Garcia-Elias et al. [7,8] measured seven human extensor mechanism specimens to determine the average stiffness values for different branches of the structure. They also measured the changes in geometry of the web-like structure of the same specimens for different finger postures and determined that, while length changes along individual segments were relatively small, the spatial orientations of the segments varied considerably [7].

3. DESIGN OF AN ANATOMICAL ROBOTIC HAND

3.1. Finger Design

The finger model was designed to closely approximate typical human anatomy shown in Figure 2. Starting from the base of the hand and working along the index finger to the tip, the human finger consists of: 4 bones (1 metacarpal, 3 phalanges) connected by 3 joints (MCP, PIP, DIP) and controlled by 3 intrinsic muscles (2 interossei, 1 lumbrical) and 4 extrinsic muscles via long tendons (EDC, EIP, FDS, FDP). Intrinsic muscles reside solely in the hand, while the extrinsic muscles are located in the forearm. We preserved the human finger's bone weight, joint kinematics, tendon insertion locations, tendon stiffness, and muscle strengths.

The model consisted of four hollowed aluminum links interconnected with three physical joints as shown in Figure 3. The MCP joint is a two-axis universal joint, with the abduction/adduction axis canted by 30^{o} as shown, while the PIP and DIP joints are both single-axis revolute joints. These joint kinematics were taken from one of several anatomical models of the complex interaction of the bones and ligaments that form the human joint and are capable of predicting human joint movements closely [4]. Steel cables coupled with passive springs represent the flexor tendons, while pliable Teflon tubing was chosen for the tendon sheaths due to its favorable friction characteristics and

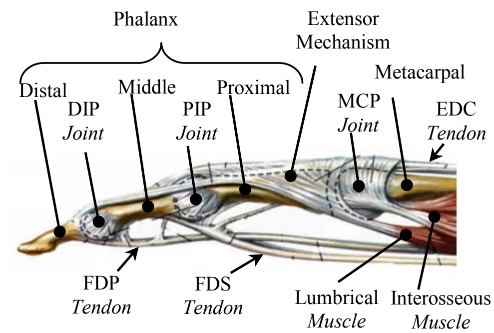

Figure 2. Illustration of partially flexed index finger adapted from [18]. Note the flexor tendons are shown out of sheaths.

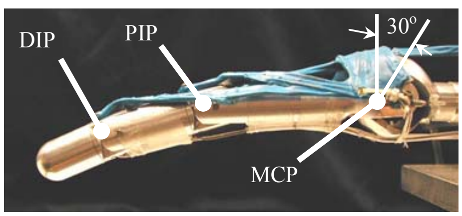

Figure 3. Photograph of finger prototype with the extensor mechanism in place.

flexibility, both important characteristics of human tendon sheaths. The link lengths and tendon insertion locations are based on typical values from [18,19]. Extrinsic muscles are simulated with off-board motors and pulleys, while intrinsic muscles are custom-designed pneumatic cylinders housed in aluminum metacarpal structures (not shown). Studies have shown the lumbrical muscles to be much weaker than the rest of the hand muscles [4] and thus have not yet been included.

3.2. Artificial Extensor Mechanism Design

A typical representation of the human extensor mechanism is shown in Figure 4 (lumbrical insertion is not shown). The terminal slip attaches to the proximal section of the distal phalanx, the central slip attaches to the proximal section of the middle phalanx, and the tendons of the EDC and the interosseous muscles intersect with the proximal end of the mechanism. The lateral bands freely slide along the side of the PIP joint and the hood covers the area from the proximal phalanx to the MCP joint depending on the finger posture. Our artificial extensor mechanism shown in Figure 5 was constructed by building a web of nylon threads in the shape of the human extensor and then coating it with a synthetic rubber coating to add strength and to create a smooth, uniform surface for sliding.

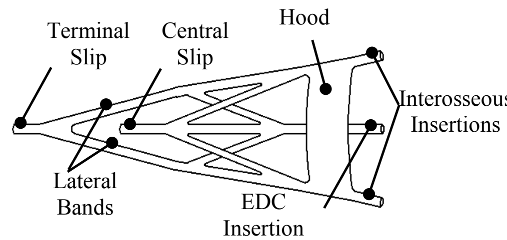

Figure 4. A schematic representation of the extensor mechanism adapted from [8].

Figure 5. Top view the artificial extensor mechanism we created. Functional capabilities, overall geometry and surface smoothness of the human's extensor mechanism were preserved.

In designing the extensor mechanism, we prioritized the desired characteristics as follows:

1. Functional capabilities: The prototype allows the model finger to achieve any posture that a typical human finger can achieve.
2. Fidelity to overall geometry: Its geometry was based on [7] and further refined to allow a full range of motion.
3. Smooth outer surface to facilitate sliding motion: The rubber coating creates a smooth, uniform surface that not only keeps the thread aligned and in place, but also makes it less likely to snag while sliding.
4. Stiffness properties: The nylon thread and rubber form a composite structure that exhibits similar mechanical properties to that of a real tendon.

3.3. Tendon Material Design

The stiffness of the artificial extensor mechanism must match that of the human tendon, which ranges from 1617-4027 N/strain (depending on the segment) according to measurements averaged from seven human specimens [8]. To match the stiffness we pre-selected threads of nylon that are known to have a similar modulus of elasticity as tendon fibers [5]. We also added threads of Kevlar in our study because our preliminary study showed Nylon threads to be too elastic. These materials were wound around two spindles that were 50mm apart for a total of four complete

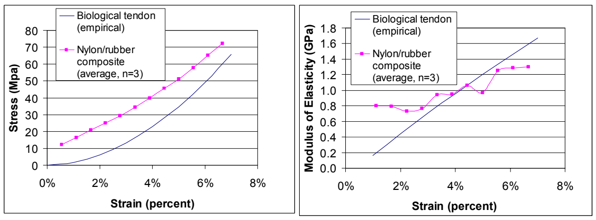

Figure 6. Stress vs. strain (left) and modulus of elasticity vs. strain (right) for biological tendon and our tendon prototype.

turns (2 loops, 2 figure-eights), coated with the synthetic rubber, and then placed in the testing apparatus. The apparatus allows small incremental displacements to be induced in the sample while measuring the resulting force. We found the nylon/rubber composite falls into the human tendon range at a stiffness of 2004 N/strain while the Kevlar/rubber composite yielded 7500 N/strain, too stiff compared to the human specimens. In this study we used the same construction for all parts of the extensor mechanism, but in future designs we plan to vary the number of windings for each segment in order to match the appropriate stiffness for each part.

Furthermore, it is known that tendon material has non-linear stiffness characteristics. It tends to get stiffer as it is stretched and has been shown to behave according to the following stress (σ)/strain (ε) model:

$$\sigma = E\varepsilon^n \qquad (1)$$

where E is the empirically determined modulus of elasticity and n is a constant based on a number of human and animal studies obtained from [12]. Figure 6 shows the relationship between this empirical data and an average of the three nylon/rubber test specimens. The modulus of elasticity of the specimens increases with strain. Between a range of 0-7% strain, the average modulus of elasticity is 0.94 GPa for the biological data and 0.99 GPa for the nylon/rubber composite.

4. FUNCTIONAL ASSESSMENT OF AN ARTIFICIAL EXTENSOR MECHANISM

4.1. Lateral Bands and Hood Functions

Two distinctive features of the extensor mechanism are the lateral bands and the hood structure. Without them, the extensor mechanism would be simply a straightforward structure with the extensor muscle (EDC) allowing extension of the entire finger and the interosseous muscles allowing lateral movements at the MCP joint. Through our analysis, we have found that both the lateral bands and the hood structure have crucial and multiple purposes.

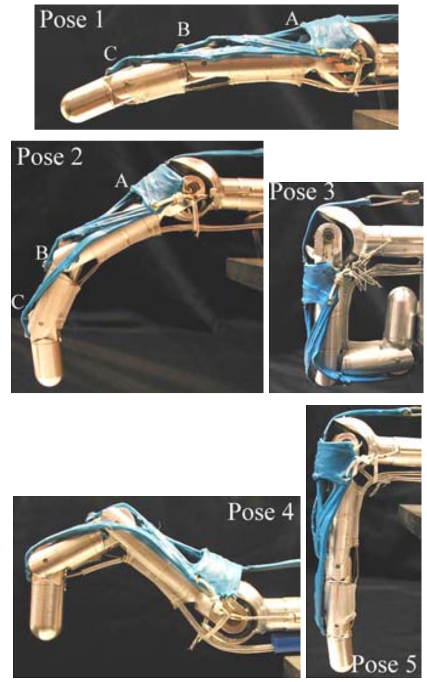

Figure 7. A variety of finger postures that can be achieved with our finger with the extensor hood. These poses represent the full set of postures that humans can achieve (excluding the lateral movements).

The lateral bands have three functions that are worth noting. The first function is to assist with lateral movements via the interosseous muscles when these muscles are activated as antagonists. The second function is to allow the extension of the distal phalanx and a finger as a whole when the interosseous muscles are activated as agonists in concert with the EDC muscle. The third and most difficult function to mimic is to coordinate the two distal joints (DIP and PIP) in flexion and extension. As the two distal joints flex, the extensor mechanism is pulled distally as shown in Figure 7, from Pose 1 to Pose 2. Then the lateral bands slip down around the sides of the finger (Pose 2) to find the shortest path between the origin of the bands (point *A*) and their insertion point (point *C*). In a tendon system without an extensor mechanism, segment *AB* would be slack in all cases except in the case of full extension, because the path length change for segment AC is greater as it must pass over the DIP joint. When testing human hand specimens, the same functional results of the lateral bands have been seen [9]. This function is difficult to mimic because the length of the lateral bands must be calibrated precisely so that the ratio of the segments AB and AC is correct.

The hood structure enables two additional sets of movements at the MCP joint. First is the flexion of the MCP joint independent of other joints. Without the hood structure, the MCP joint cannot flex independently of other joints because the proximal phalanx does not have any flexor muscles attached to it. Instead, the extensor mechanism at full extension is positioned so that the interosseous tendons pass slightly dorsal of the MCP joint axis (Figure 7, Pose 1). As the flexor tendons pull the finger into flexion, the hood portion of the extensor mechanism slides distally and the interosseous tendons slide to the palmar side of the MCP joint axis (Figure 7, Pose 2). When the interosseous tendons cross over the center of the MCP joint axis, the interosseous muscles turn from extensors to flexors, and the hood structure hugs the proximal phalanx closely to achieve full flexion of the MCP joint (Figure 7, Pose 3). The second set of movements the hood allows for is rotation at the MCP joint. When the MCP joint is fully flexed, the interosseous muscles act as antagonists that rotate the finger rather than laterally moving it.

4.2. Finger Postures and Muscle Activation Patterns

Due to the extensor mechanism allowing the interosseous muscles to be versatile (acting as agonists to achieve flexion or extension, depending on joint position, and acting as antagonists to achieve abduction/adduction or rotation), the MCP joint can be controlled independently of other joints. Figure 7 shows the postures that are possible with the finger we constructed excluding the lateral movements. All combinations of finger postures are possible except for those which require the DIP and PIP joints to be controlled separately. Besides the fully extended (Pose 1) and fully flexed (Pose 3) positions, there are two other full postures that are possible under active control (Poses 4 and 5). One of these postures has the DIP and PIP joints fully flexed and the MCP joint fully extended (Pose 4). This posture is achieved with the same muscles used for full flexion but with different activation timing. To fully flex all the joints, the flexor muscles contract first until the interosseous tendons cross toward the palmar side of the MCP joint axis, at which time the interosseous muscles are activated. Conversely, if the interosseous muscles are activated from the beginning then they keep the MCP joint extended the entire time. Pose 5 is achieved with the extensor muscle acting against the interosseous muscles in order to flex the MCP joint independently of other joints.

Because the DIP and PIP joints do not have independent active control, human fingers, in practice, have only three degrees of freedom in the absence of external forces. If we assume that force production is irrelevant, all natural human finger movement can be achieved with four muscles: one extensor (EDC) and one flexor muscle (FDP) attached at the distal phalanx and two interosseous muscles attached to the extensor mechanism. The EDC and FDP muscles control the DIP and PIP joints to flex and extend, the interosseous muscles acting as antagonists provide abduction/adduction, and the interosseous muscles acting as agonists along with help from the EDC and FDP muscles give the MCP joint flexion and extension independent from other joints.

We quantified the total tendon excursions required to make postures in Figure 7 and found that maximum contraction (excursion of the cable) for the FDS tendon occurs at Pose 3 at 46mm while maximum contraction for the interosseous tendons occur at Pose 4 at 11mm. Because the interosseous muscles have pennate structures (i.e. they do not originate from a single point but rather from the long sides of two neighboring metacarpal bones), they are capable of producing the same amount of force as the flexor muscles with only a quarter of the excursion length [4].

5. DISCUSSION

This study has led to a better understanding of the extensor mechanism, a mechanism that is crucial for achieving all human postures with human-like muscles. The extensor mechanism allows control of the MCP joint independent from the rest of the finger as well as a variety of other functions including flexion, extension, abduction, adduction, and even rotation. By constructing the finger with the extensor mechanism, we identified many crucial features of the extensor mechanism that need to be mimicked to construct an anatomical robotic hand. First, the length and the stiffness of the lateral bands and the hood structures are critical in precise control of all finger joints. If these structures give too much slack during dynamic movements, joint movement would not be coordinated. Second, the friction of the tendon surface is important. The extensor mechanism slides on the dorsal side of the finger back and forth for almost an inch between fully flexed and fully extended positions, and smooth sliding is important between these points. Meanwhile, the hood structure must hug the proximal phalanx and flex the MCP joint, so there must be enough friction to allow this action.

We realized that we did not incorporate in our prototype one of the most crucial pieces to create an anatomical hand: the bumps on the bones that allow specific tendon routings. We excluded them from the first version for simplicity, but have since learned that they help tendons to stay in specific areas as well as to change the tendon routing in ways that affect the force production significantly. We also need to investigate the tendon material further as we observed some initial creep in the nylon composite.

There are six muscles attached directly to the extensor mechanism for all fingers (excluding the index finger which has another extensor muscle to give it an independent degree of freedom). Even though all postures can be achieved with four muscles, we believe that the extra flexor muscle (FDS) gives the asymmetric strength toward the flexion side which is important in object manipulation [19]. We excluded the lumbrical muscle from our prototype because all extrinsic muscles and interosseous muscles produce significantly more force than the lumbrical muscle (from 4 to 15 times greater in most cases), and we could not construct a sufficiently realistic model with the point of origin on the extensor tendon. Without the lumbrical muscle, we were able to achieve all possible postures. We plan to incorporate the lumbrical muscle in the next iteration to investigate the importance of its function.

6. ACKNOWLEDGMENTS

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