

Design of an Anthropomorphic Robotic Finger System with Biomimetic Artificial Joints

Zhe Xu, Vikash Kumar, Yoky Matsuoka and Emanuel Todorov

Abstract—We describe a new robotic finger that is composed of three biomimetic joints whose biomechanics and dynamic properties are close to their human counterparts. By using five pneumatic cylinders, the finger is actuated through a series of simplified antagonistic tendons whose insertion points and moment arms mimic the anatomy of the human hand. We develop simulation models of the kinematics and air dynamics, and validate them using experimental data. Preliminary results on controlling the finger are also described.

I. INTRODUCTION

The human hand has been used as an irreplaceable model for the development of different robotic hands due to its impressive compliance and dexterity that can accommodate a variety of grasping and manipulation conditions. Towards this end, anthropomorphic robotic hands have been widely investigated because of their inherent similarity to the human hand and can potentially bring many benefits to the fields ranging from hand prosthetics to healthcare robots to space exploration. Current prosthetic hands are often made with few degrees of freedom as an approach to preferably providing human hand appearance with comfortable weight and size. For personal assistance, rather than duplicating a dexterous human hand, industrial style gripper is commonly adopted to focus on executing tasks with precision and robustness. As for space exploration, space walking is still a routine task for astronauts to perform the repair of orbiting or spacecraft. Prosthetic/Robotic hands from each of these categories are often designed with restrictions resulting from not only the technological limitations, but also from our understanding about the human hand. In order to design an anthropomorphic robotic hand with appearance and functionality closely resembling our own, there are many significant challenges need to be overcome, here we focus on investigating the intrinsic biomechanic features required to replicate the compliance and kinematics of a human finger.

The fingers of the human hand possess several biological features that are hard to mimic simultaneously. These include: (1) the unique shape of the bones at the joints, which determines the degrees of freedom at the joint; (2) a joint capsule formed by fine ligaments, which set the range of motion for the joint; and (3) cartilage and synovial fluid, enabling low-friction contact between two articulated surfaces [1]; (4) non-linear interactions between the tendons and bone topology, which

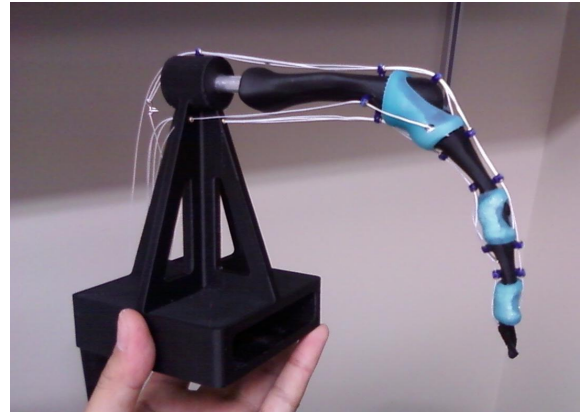


Fig. 1. Anthropomorphic robotic finger with biomimetic finger joints.

dynamically determine the motion of the finger. Typically researchers have not designed anthropomorphic robotic hands to incorporate these biological features or to be anatomically correct.

Over the last decades, many robotic hands have been developed for serving different purposes. Among the most relevant anthropomorphic hands, several important features have been achieved, including high degree of modularity [2], [3], light weight [4]–[6], cable driven [4], [7]–[13], gear transmission with linkage mechanism [14]–[16]. These robotic hands often need complicated joint mechanism such as hinges, gimbals, linkages, or gears and belts in order to achieve the right number of DOFs and mimic kinematic characteristics of the human hand. However, few of them incorporate built-in compliance which is necessary for a human hand to explore uncertainties in the unstructured real world. On the contrary, under-actuated gripper/hand [17]–[19] can comply with different shapes of objects during grasping, but keeps only the basic DOFs. Due to different design constraints, it seems that a compromise has to be made between built-in compliance and high DOFs. Although tremendous progresses have been made, the ability of most of the existing robotic hands to perform human-level manipulation tasks remains limited.

Although standard design methodology, such as above, can mimic the kinematic behavior of a finger joint it does little to illuminate the salient features that make the human hand irreplaceable for many dexterous tasks. It is therefore necessary to develop artificial finger joints, based on accurate physiology, in order to quantitatively identify these characteristics thus providing insight into anthropomorphic robotic hand design.

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A challenging alternative to conventional robotic hand design is to develop mechanisms which directly utilize the unique articulated shapes of human joints, as well as a tendon hood structure to actuate individual fingers. Following a biologically inspired design may also reduce the total number of individual components, resulting in an elegant design.

The anthropomorphic robotic finger addressed in this paper (as shown in Figure 1) is based on a previously described artificial finger joint [20] whose degrees of freedom, range of motion, and dynamic properties are close to that of a human finger. In this paper, we are interested in designing a close replica of the human index finger along with its pneumatic actuation, and preparing it for high speed actuation through kinematic model based simulation. In the following sections the innovative mechanical design of the anthropomorphic robotic finger is detailed, air dynamic model of the pneumatic system is derived, then the modeling and simulation results are validated through the experimental data.

II. DEVELOPMENT OF AN ANTHROPOMORPHIC ROBOTIC FINGER

Although the anatomy of the human hand provides detailed sources of static models, such as joint structure, tendons routing, and layered skin, how to organically incorporate state-of-the-art engineering advances into a fully functional robotic hand system is what we want to achieve in this paper. This section describes the mechanical design and prototyping process of our robotic finger.

A. Biomimetic design of bones and joints

In the human hand, the bones at the finger joints possess several biological features (As shown in Figure 2), including the unique shape of the bones at the MCP, PIP and DIP joints, which determines the degrees of freedom at the joint; the shapes of the finger bones along the tendon routing path create moment arms for the tendons that vary with joint angle, a behavior critical for accurate hand function [21]. The variable moment arms are necessary for achieving human-like joint-muscle movement relationships [22]. Developing an anatomically correct robotic hand can help researchers to find more critical human hand features that can only be revealed through dynamic interactions with objects.

In order to accurately match the size and shape of the human finger bones. We used the index finger from a Stratasys Corporation's laser-scan model of human left hand bones supplied in STL format, imported the tessellate facets into Pro/Engineer, and created solid models for each bone by fitting new surfaces to the scan geometry. Detailed parameters of the robotic finger are listed in Table I and II.

At each joint of the human finger, joint capsule is formed by fine ligaments that seals the joint space and provides passive stability by limiting movements through its ligaments, therefore sets the range of motion for the joint. As shown in Figure 3, we have developed an artificial joint makes use of three main components: a 3D printed joint with true to life bone topology, crocheted ligaments used to realize the right

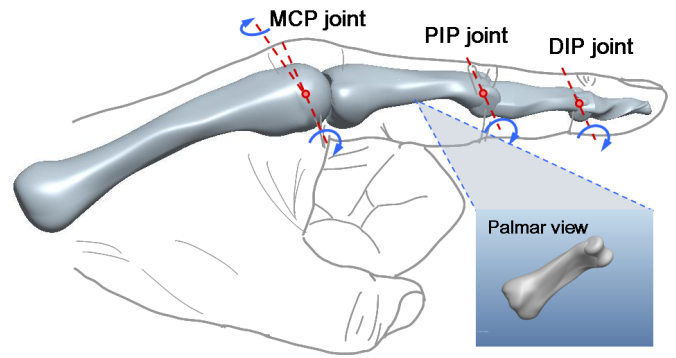


Fig. 2. 3D model of the laser-scanned human index finger.

TABLE I
PHYSICAL PARAMETERS OF THE ROBOTIC FINGER SKELETON

Phalange	Length (mm)	Weight (g)
MCP to PIP	53.4	5.5
PIP to DIP	32.0	2.0
Distal phalange	23.7	1.2

TABLE II
APPROXIMATE JOINT MOTION LIMITS OF THE ROBOTIC FINGER

Joint	Minimum	Maximum
MCP	30° extension 35° abduction	90° flexion 35° adduction
PIP	0° extension	110° flexion
DIP	0° extension	70° flexion

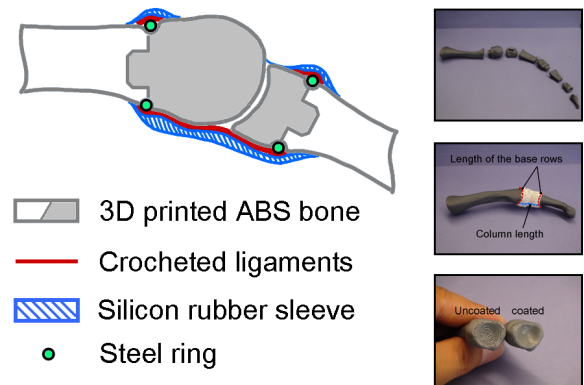


Fig. 3. Biomimetic artificial joint design from [20].

range of motion, and a silicon rubber sleeve providing the passive compliance for the artificial joint. The artificial finger joint designed in this way possesses the similar stiffness and damping properties to those of the human finger [20].

Between the two articulated joint surfaces of the human finger, cartilage and synovial fluid can realize low-friction contact. In our design, thermoplastic coating is adopted to provide low-friction surface at the finger joint. Although, when encountered with the long term tear and wear, commonly

engineered materials cannot regenerate like biological tissues, we believe that through low-cost, rapid prototyping technology the modular design can make maintenance of our proposed robotic finger/hand economically regenerable.

B. Tendon hood design and its simplification for the extensor system

Underneath the skin of the human finger over the dorsal side of the finger bone, extension motion of the finger is realized via a complex web structure as shown in the leftmost picture of Figure 4(a). On the palmar side of the finger, antagonistic tendons called flexors are connected from the bone insertion points to the extrinsic muscles located in the forearm to enable the flexion motion.

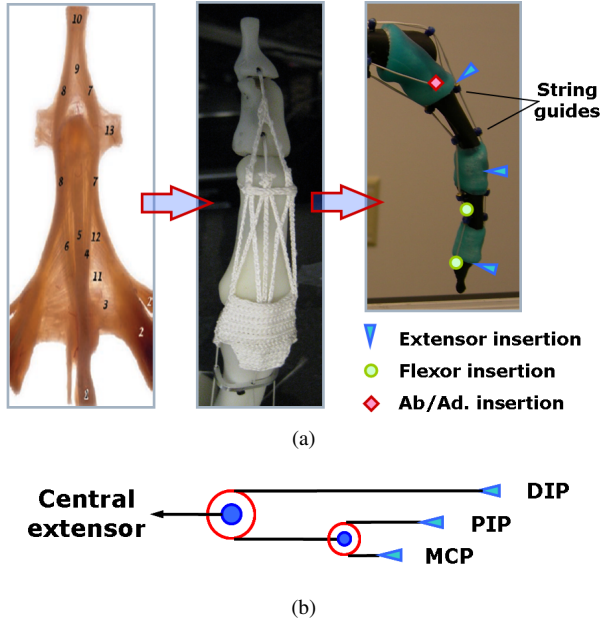
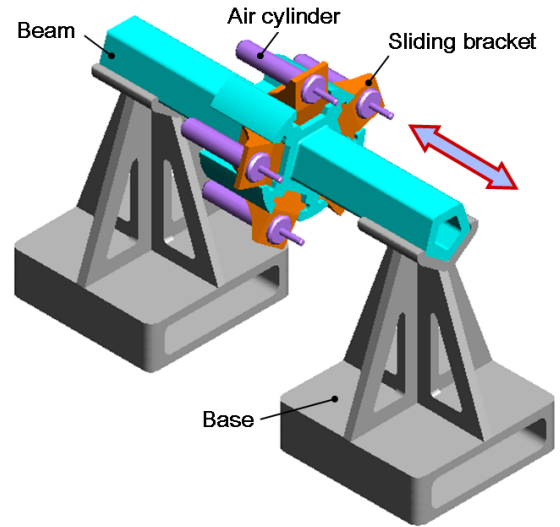


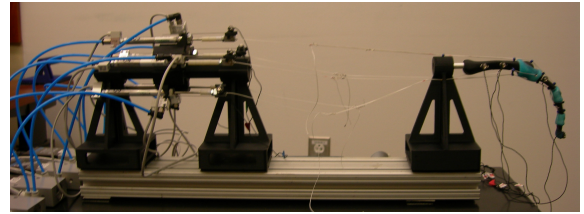
Fig. 4. Comparison of the extensor mechanism between the human hand [23], the ACT Hand and the robotic finger (a) Design evolution of the tendon hood. (b) Schematic drawing of the pulley system used for the robotic finger.

Previously, we designed a tendon hood for the ACT Hand to mimic the extensor web of the human finger(as shown in the middle picture of 4(a)). The artificial extensor is fabricated by crocheting nylon composite to emulate the geometry and functionality of the human counterpart as closely as possible. Instead of adopting the same extensor design, in this paper we apply what we learn from the ACT Hand and keep only the tendons essential for the index finger flexion/extension and abduction/adduction in order to concentrate on investigating the performance of our robotic finger.

As shown in the rightmost picture of Figure 4(a), the locations of insertions points and string guides of the robotic finger are all inherited from the ACT Hand. The tendons are made of 0.46 mm Spectra[®] fiber (AlliedSignal, Morristown, NJ). The fiber was chosen because of its strength (200N breaking strength), high stiffness, flexibility, and its ability to slide smoothly through the string guides. In the case of the human hand, tendons from the three extensor insertion



(a) 3D model of the actuation system



(b) Experimental setup

Fig. 5. The actuation system of the anthropomorphic robotic finger.

points are all merged with the extensor hood at the MCP joint, therefore a pulley system is used to make sure each individual tendon is constantly in tension (see Figure 4(b)).

III. ACTUATION SYSTEM

Our robotic finger system is actuated using a "Pulling-only pneumatic actuation system" (see Figure 5a). Because of its robustness, smooth dynamics and inherent damping properties, pneumatic actuation seems promising for modeling muscle behaviors. The robotic finger system consists of five double-acting cylinders (Airlpel-anti stiction cylinders, model M9D37.5NT2) evenly mounted along the perimeter of a cylindrical beam through five sliding brackets. Cylinders being used are modules specially designed for low friction-anti stiction operations. Stiction and friction values are so small that the piston falls under its own weight if cylinder is not horizontal. The sliding brackets are designed to eliminate any potential slack between the tendons and actuators. The pistons of the five cylinders are connected to the central extensor, abduction and adduction tendons, DIP and PIP flexors, respectively.

The front chamber of each cylinder is connected to a proportional 5/3 pressure valve (Festo, model MPYE-5-M5-010-B). When pressurized the front chamber resembles the muscle contraction and the back chamber is left open to the atmospheric pressure as tendons cannot push the finger (Pulling-only actuation). The valve receives a command volt-

age from a National Instruments D/A board. This voltage (0-10V) specifies the position of a linear actuator inside the valve, which in turn sets the aperture connecting the front chamber to the compressor (90 PSI above atmospheric pressure). The control command (in Volts) 5 - 10 pressurizes the systems and 5 - 0 exhausts. The pressure inside the front chamber is measured with a solid-state pressure sensor (SMC, model PSE540-IM5H). The sensor data are sampled at 50 KHz, and averaged in batches of 500 to yield a very clean signal at 100 Hz. The difference between the pressures in the two chambers of each cylinder (denoted D) is proportional to the linear force exerted on the piston. For protection of the finger, each cylinder's piston contraction is limited by excursion of the tendon it acts upon.

IV. MODEL OF AIR DYNAMICS

Ideally we would be able to control the piston force with minimal delay. This is difficult to achieve in pneumatic systems because the air dynamics have non-negligible time constants that depend on multiple factors such as compressor pressure, valve throughput and response time, length of the air tubes between the valve and the cylinder, volume of the chamber, and air temperature. These effects are hard to model accurately, yet for control purposes it is important to have a model that enables the controller to anticipate the resulting delays and compensate for them. We did rigorous system identification to find the model for air dynamics.

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We performed rigorous system identification to find the model for air dynamics, evaluating all models up to fourth order in pressure (P), flowrate (dP/dt), valve voltage (V), valve voltage rate (dV/dt), chamber volume (v) and chamber volume velocity (dv/dt). Models were evaluated in parallel over 24 cores of 3.33 GHz Intel Xeon with 24 Gb RAM running *Matlab2010b* for about 25 hours.

Unlike models used in [24], [25] which are for big cylinders with significant chamber volume (the length of the cylinder is of 50 cm), our system consists of compact cylinders (3.75 cm) fed using high flow valves. Benefits from accounting for the chamber volume for our cylinders were so low that we choose to ignore it for a simpler model.

$$dP/dt = a_0 + a_1V^2 + a_2V^3 + a_3P + a_4PV + a_5PV^2 + a_6PV^3$$

Above model was validated with five cylinders. Model parameters a_i were independently determined for individual cylinders using linear regression. For all the cylinders, our model outperformed other models with $R^2 > 0.9$ over wide

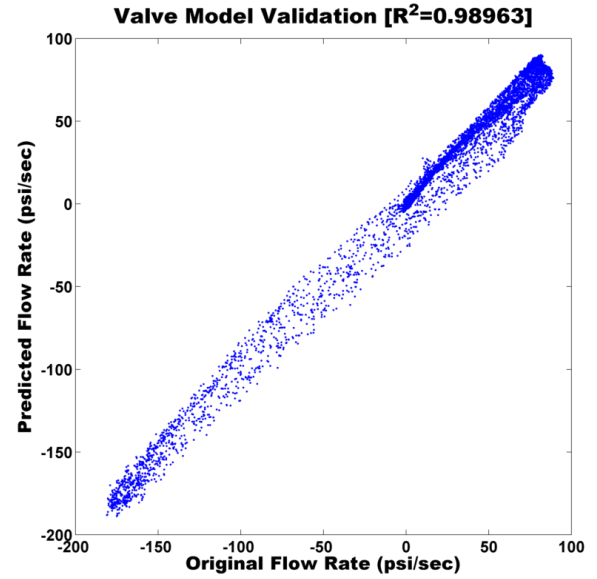


Fig. 6. Original flow rate vs model predicted flow rate comparison

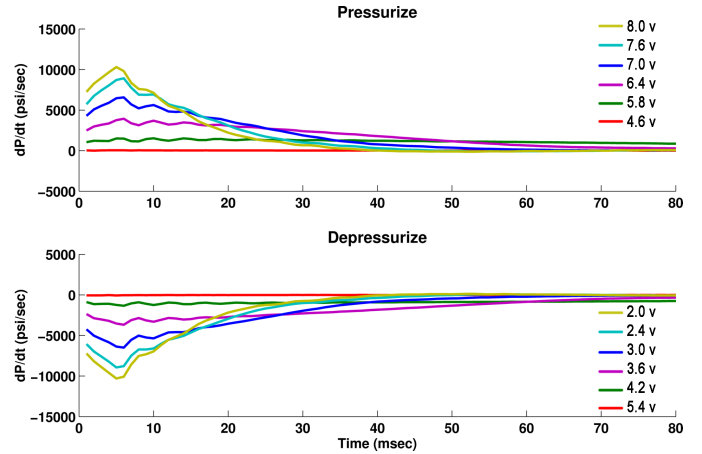


Fig. 7. Pressurization/Depressurization flow rate for different voltage step change starting from extreme pressure values

range of unseen datasets collected at different frequencies. Figure 6 shows model predictions for one randomly selected cylinder.

Pneumatic systems incur non zero-latency due to response time of the valves and tube length connecting valve with cylinder. To investigate the latency of the air dynamics incurred by our system, we performed a sequence of instantaneous pressurization and depressurization experiments. During a pressurization/ depressurization experiment, we started with a depressurized ($V = 2$ volts)/ pressurized ($V = 8$ volts) chamber. At the beginning of each experiment, valve's command voltage was instantaneously changed to an intermediate voltage. Figure 7 shows flow rate response due to instantaneous voltage change during pressurization and depressurization experiments. We observe that air dynamics incurs a latency of about 6 ms, irrespective of the intermediate voltage level, before it reaches its maximum effect.

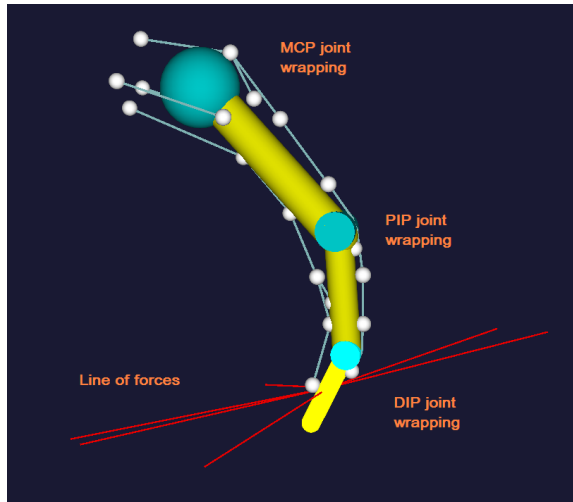


Fig. 8. 3D Visualization of the kinematic model of the robotic finger in OpenGL.

Third order air dynamics and latencies from pneumatic actuation on top of the non-linearities from the tendon routings and wrapping along bone segments make our control problem quite challenging. At the same time, pneumatic actuation is desirable from the perspective of bio-robotics as they have many essential properties (detailed in [25]) of biological muscles at mechanism level; which we believe are very different from trying to recreate them using properties of feedback controller.

V. KINEMATIC MODEL OF THE SKELETON AND TENDONS

We constructed a kinematic model of the finger skeleton and the tendon paths. This was done by taking the numeric data from the CAD file used to 3D-print the finger, and importing it in an XML file that is then read by our modeling software. Our software – called MuJoCo which stands for Multi-Joint dynamics with Contact – is a full-featured new physics engine, with a number of unique capabilities including simulation of tendon actuation. In this paper we only use the kinematic modeling features of the engine, as well as the built-in OpenGL visualization.

The skeletal modeling approach is standard: the system configuration is expressed in joint space, and forward kinematics are used at each time step to compute the global positions and orientations of the body segments along with any objects attached to them. Tendon modeling is less common and so we describe our approach in more detail. The path of the tendon is determined by a sequence of routing points (or sites) as well as geometric wrapping objects which can be spheres or cylinders. The software computes the shortest path that passes through all sites defined for a given, and does not penetrate any of the wrapping objects (i.e. the path wraps smoothly over the curved surfaces). The latter computation is based on the Obstacle Set method previously developed in biomechanics.

Let \mathbf{q} denote the vector of joint angles, and $\mathbf{s}_1(\mathbf{q}), \dots, \mathbf{s}_N(\mathbf{q})$ denote the 3D positions (in global coordinates) of the routing points for a given tendon. These

positions are computed using forward kinematics at each time step. Then the tendon length is

$$L(\mathbf{q}) = \sum_{n=1}^{N-1} \left((\mathbf{s}_{n+1}(\mathbf{q}) - \mathbf{s}_n(\mathbf{q}))^T (\mathbf{s}_{n+1}(\mathbf{q}) - \mathbf{s}_n(\mathbf{q})) \right)^{1/2}$$

The terms being summed are just the Euclidean vector norms $\|\mathbf{s}_{n+1} - \mathbf{s}_n\|$, however we have written them explicitly to clarify the derivation of moment arms below. When the tendon path encounters a wrapping object, additional sites are dynamically created at points where the tendon path is tangent to the wrapping surface. These sites are also taken into account in the computation of lengths and moment arms.

Moment arms are often defined using geometric intuitions – which work in simple cases but are difficult to implement in general-purpose software that must handle arbitrary spatial arrangements. Instead we use the more general mathematical definition of moment arm, which is the gradient of the tendon length with respect to the joint angles. Using the chain rule, the vector of moment arms for our tendon is

$$\frac{\partial L(\mathbf{q})}{\partial \mathbf{q}} = \sum_{n=1}^{N-1} \left(\frac{\partial \mathbf{s}_{n+1}(\mathbf{q})}{\partial \mathbf{q}} - \frac{\partial \mathbf{s}_n(\mathbf{q})}{\partial \mathbf{q}} \right)^T \frac{\mathbf{s}_{n+1}(\mathbf{q}) - \mathbf{s}_n(\mathbf{q})}{\|\mathbf{s}_{n+1}(\mathbf{q}) - \mathbf{s}_n(\mathbf{q})\|}$$

This expression can be evaluated once the site Jacobians $\partial \mathbf{s} / \partial \mathbf{q}$ are known. Our software automatically computes all Jacobians, and so the computation of moment arms involves very little overhead.

The extensor tendon of our finger uses a pulley mechanism, which is modeled as follows. The overall tendon length L is equal to the sum of the individual branches, weighted by coefficients which in this case are 1/2 for the long path and 1/4 for the two short paths. Once L is defined, the moment arm vector is computed as above via differentiation.

TABLE III
MOMENT ARMS THAT THE SIMULATOR COMPUTED IN THE DEFAULT POSTURE (IN MM)

Finger joint	Central extensor	DIP flexor	PIP flexor	Abduction tendon	Adduction tendon
MCP (ab/ad.)	0.00	-0.00	0.00	-8.44	8.86
MCP (fl/ex.)	10.93	-13.47	-13.47	-6.17	-6.06
PIP (fl/ex.)	1.81	-7.99	-7.99	0.00	0.00
DIP (fl/ex.)	1.13	-6.14	0.00	0.00	0.00

Numerical values for the moment arms computed by the model in the resting finger configuration are shown in Table III. These values change with finger configuration in a complex way, and are automatically recomputed at each time step. Moment arms are useful for computing the tendon velocities given the joint velocities:

$$\dot{L} = \frac{\partial L(\mathbf{q})}{\partial \mathbf{q}} \dot{\mathbf{q}}$$

and also for computing the vector of joint torques τ caused by scalar tension f applied to the tendon by the corresponding linear actuator:

$$\tau = \left(\frac{\partial L(\mathbf{q})}{\partial \mathbf{q}} \right)^T f$$

Note that these are the same mappings as the familiar mappings between joint space and end-effector space, except that the Jacobian $\partial L/\partial \mathbf{q}$ here is computed differently. Another difference of course is that tendons can only pull, so $f \leq 0$.

Following our initial control experiments, we realized that the tendons cannot move the finger in all directions for all postures. To analyze this phenomenon, we extended our software to compute the 3D acceleration of the fingertip resulting from the activation of each tendon. The results are shown in Figure 8 with red lines. Note that these lines lie close to a 2D plane, meaning that moving the finger outside that plane is very difficult – it requires strong co-activation of actuators that are near-antagonists. This prompted us to add another actuator (a second extensor) and rearrange the tendon attachment points, aiming to decorrelate the tendon lines of action to the extent possible. The model in Figure 8 is after the rearrangement; the problem is alleviated to some extent but still remains. The underlying difficulty is that the flexors and extensors acting on the distal joints also have large moment arms on the proximal joint. The only way to avoid this would be to route the tendons for the distal flexors/extensors closer to the center of the proximal joint – which we will investigate in future work.

VI. EXPERIMENTAL VALIDATION OF THE KINEMATIC MODEL

To validate our model (before the addition of the 6th actuator), we performed the following experiment. Infrared markers (PhaseSpace, 120 Hz sampling rate) were glued to the fingertip, proximal finger segment, and the moving part of each cylinder. Another 3 markers were glued to the immobile base so as to align the reference frames of the motion capture system and the model. All markers were glued at (approximately) known positions which we entered into our kinematic model as sites, similar to the sites used to route tendons. The cylinders were pressurized slightly above the stiction point (using empirically determined pressure values), so that they always pulled on the tendons and prevented tendon slack. We moved the finger manually to different poses in its workspace, attempting to span the entire workspace. After each repositioning we waited for a couple of seconds, so as to let everything "settle" and obtain clean position data.

The data analysis began with frame alignment, by subtracting the translational bias between the centers of mass of the modeled and measured base marker positions, and then performing orthogonal procrustes analysis to compute the optimal rotation between the motion capture and model frames. The data for the moving markers were then transformed into the model coordinate frame, and were further processed as follows. We implemented a MATLAB script that automatically identified non-overlapping time intervals in

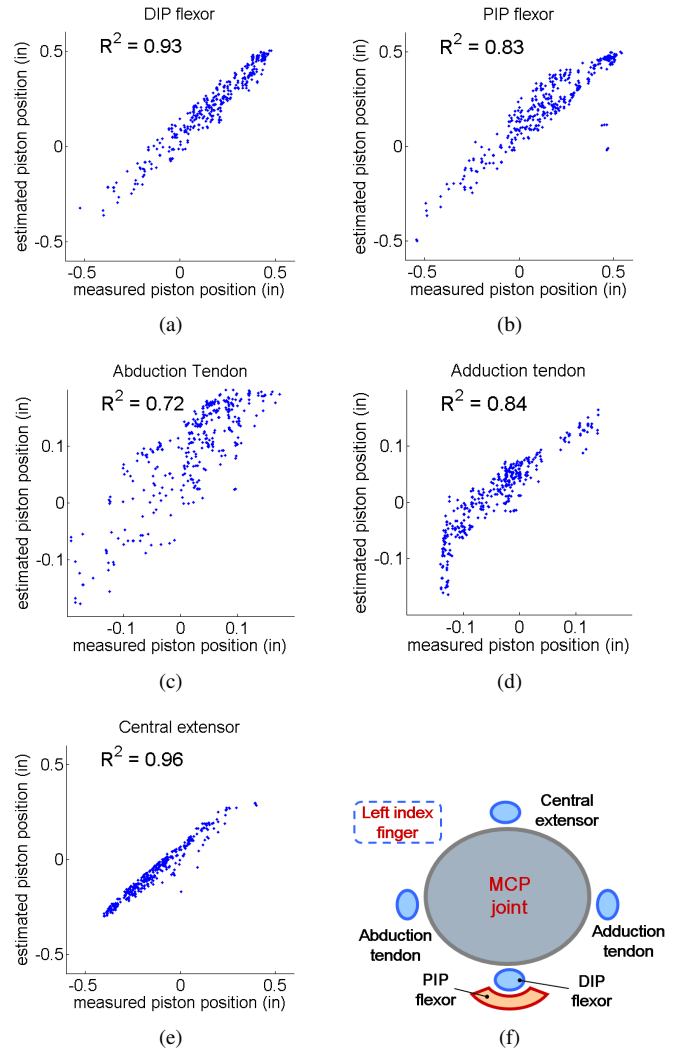


Fig. 9. Comparison of measured and estimated tendon excursion data (a)-(e) and illustration of tendon structures at the MCP joint of our proposed robotic finger (f).

which every marker position remained within a ball of radius 2 mm (i.e. all markers were stationary), and averaged the position data for each marker within each time interval. This yielded 460 data points, each consisting of the 3D positions of the seven module markers (five on the cylinders, two on the finger).

The next step was to infer the joint angles of the finger given the positions of the two finger markers. This was done by an automated procedure (which is part of the MuJoCo engine), whereby the residual difference between the observed and predicted marker positions is minimized with respect to the set of joint angles (note that the predicted positions are functions of the joint angles). The minimization is done using a Gauss-Newton method with cubic line-search. Even at the optimal joint angles, there was some residual in the marker positions (around 5 mm on average) which we believe is mostly due to the fact that the finger is somewhat flexible and has additional degrees of freedom (even though their range of motion is very

limited). Data points where the residual was larger than 7 mm were excluded from further analysis, leaving us with 400 data points.

Once the joint angles in each pose were inferred, we applied our tendon model to compute the predicted tendon lengths, and compared them to the measured positions of the cylinder markers. The comparison is shown in Figure 9 for all five tendons. Overall the fit is very good, especially for the flexors and extensor that have larger excursions. The adduction tendon shows saturation, which we realized is caused by the position limiter on the cylinder (we attempted to place those limiters just outside the finger motion range, but this one ended up inside the range) causing the tendon to go slack in some extreme poses. The abduction tendon is the most noisy, which we believe is due to the fact that it presses on the joint capsule and curves over it. This can be corrected by adjusting the routing points.

VII. SUMMARY AND FUTURE WORK

We have described the design of an anthropomorphic robotic finger system that has the potential to become a close replica of the human finger. The system has three main components: a modular design of three highly biomimetic finger joints, a series of simplified pulley-based tendon mechanisms, and a pneumatic actuation system with low friction and inertia and high force output. We also presented models of the joint and tendon kinematics and air dynamics, as well as preliminary work on control strategies that utilize our models to achieve accurate control of the new robot.

Our results to date show that the new robotic finger is very capable, but also requires advanced control techniques and accurate modeling. In future work we will refine our models, and apply optimal control techniques to overcome the complexity and nonlinearity of the system.

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