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Design of a Hand Prosthesis with Precision and Conformal Grasp Capability

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Abstract— **This paper presents the design of an anthropomorphic prosthetic hand that provides both precision and conformal grasp capability. Specifically, the design of the hand dedicates three actuators in a direct-drive manner to achieving precision grasp capability. The design additionally dedicates one actuator and six degrees of freedom, in addition to a compliant coupling, to providing a conformal grasping capability to the amputee. The design of the hand is described in this paper, and the various degrees of actuation are characterized with respect to grasp forces and finger speeds.**

I. Introduction

Traditionally, upper extremity prosthetic devices have been limited to single degree-of-freedom devices. In contrast, the human hand has approximately 20 degrees of freedom (DoF), and can perform a large amount of complex grasps and postures. Recent advances in mechatronics technology enable the development of multigrasp prostheses, which contain multiple actuators and multiple degrees-of-freedom. Presumably, these "multigrasp" prostheses are able to provide enhanced capability to the amputee. For a recent survey of multigrasp prosthetic hands, see [1]. Some multigrasp hand designs are described in [2-10]. These hands contain between one and six independent actuators and between eight and sixteen joints distributed in various ways in the digits (thumb, index, etc.). In each device, the discrepancy between the number of independent actuators and the number of joints is accommodated either by differential drives, which prescribe a given torque distribution between joints, kinematic linkages, which prescribe a given relative motion between joints, variable compliance couplings, which prescribe given relative compliance between joints, or by a combination of these. Of these devices, the most highly underactuated is the hand described by [2], which is composed of 15 joints and 5 digits, which are differentially driven via a single independent actuator (and as such could be used with current myoelectric interfaces). The Oxford and Manus hands described in [3] contain eight and nine joints, respectively, which are kinematically linked within three (active) digits (two of which are coupled) and driven by two actuators. The HIT/DLR hand described by [4] includes 13 joints, which are kinematically linked within the five digits (three of which are coupled), driven by three actuators either directly or through a combination of differential and compliant transmissions. The Cyber Hand and Smart Hand described by [5] and [6] contain 10 and 16 joints, distributed over 3 and 5 compliantly linked digits, respectively. Each of these devices is driven by four independent actuators either directly (as in [5]) or by a combination of differential and compliant transmissions (as in [6]). The fluidic hand described by [7] utilizes five independent commands to actuate eight joints via a miniature hydraulic actuation system. The prosthetic hand described in [8] incorporates 11 joints within five kinematically linked digits, driven by six independent actuators. The Southampton hand described in [9] incorporates 16 joints distributed over 5 kinematically linked digits, which are driven by six independent actuators. Finally, the hand described in [10] incorporates 16 joints driven by four actuators, in a somewhat similar configuration to the hand in [6].

As indicated by the variety of configurations described in [2-10], the manner in which to configure the degree of underactuation in a multigrasp prosthesis is highly variable. In particular, the degree and nature of underactuation is highly dependent upon the functional objectives of the hand, and the control system and user interface that controls it. The paper describes a configuration for a multigrasp hand that provides potential advantages with respect to the stated functional objectives of the design, and to the authors' knowledge, has not been previously presented in the engineering literature. In particular, the configuration of underactuation is designed to explicitly provide both precision and conformal grasp capability. A set of four actuators drives nine degrees of freedom, which enables a set of eight grasps and or postures. This paper provides a description of the major design layout and features, and presents an experimental characterization of the performance capability of the hand, indicating that the design achieves biomechanically appropriate levels of force and speed.

II. Design Objectives

The design objectives for the hand described in this paper are similar to a previous hand design discussed in [10]. These design objectives are briefly restated here. A large majority of activities of daily living (ADLs) can be attained via six hand grasps, which are the tip, tripod, hook, spherical, cylindrical, and lateral pinch grasps [11, 12]. Cutkosky further characterizes these grasps as either precision grasps with emphasis on dexterity and sensitivity (tip, lateral pinch, tripod) or conformal grasps with emphasis on security and stability (hook, spherical, cylindrical, lateral pinch) [13]. Note that a distinguishing feature of the latter is the ability to conform to an object being grasped, and the maximization of contact area between the hand and object. Such grasps are generally used for the grasping of objects of a size on the order of the hand. In the performance of such grasps, one would like the shape of the object to principally determine

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the configuration of the hand. Conversely, precision grasps are generally used to handle or manipulate objects that are much smaller than the size of the hand. Such grasps are non-conformal (indeed, the notion of conforming to an object much smaller than the hand is kinematically ill-posed), and therefore the hand must determine its final configuration, rather than the object. In such cases, underactuation should be avoided. Ideally, a prosthetic device should be capable of both types of grasps for it to effectively perform ADLs. In addition to these grasps, the pointing and platform postures are very useful for certain activities. The pointing posture enables an amputee to use their prosthesis to press buttons or type on a keyboard, and the platform posture allows for carrying a plate, or placing the prosthesis in a pocket.

In addition to forming these grasp shapes and hand postures, the hand should be capable of exerting sufficient forces while grasping objects and moving at sufficient speeds to achieve ADLs. A discussion of speed and force requirements as related to ADLs is given in [10], and the specifications remain the same for this iteration. Specifically, of the 12 precision grasp tasks studied by [14], 9 required pinch forces less than 10.5 N; one required a pinch force of 15 N (large zipper, such as that used on a suitcase); one required a pinch force of 18 N (pulling an electrical plug out of a socket); and one required a pinch force of 25 N (pushing a plug into an electric socket). Thus, the digits associated with precision grasp (digits I and II) should be capable of at least 11 N, and ideally up to 25 N. A study of conformal grasp forces [15] indicates that the maximum measured fingertip forces for digits III, IV, and V were 6 N, 4 N, and 4 N, respectively. As such, the composite capability of these three digits should be at least 14 N. With regard to speed of movement, based on estimates presented in [16], the hand should be capable of joint angular velocities of at least 4 rad/s, which on average corresponds to a bandwidth of 1.5 Hz over half of the range of motion of each joint.

I. Hand Design

A. Allocation of Actuation

The allocation of actuation in the hand is illustrated in Fig. 1. The current version of the hand uses 4 brushless DC motors to control 9 DoF. In particular, 3 of the motors are allocated to control digits I and II in a direct drive manner. Specifically, one motor drives digit I (thumb) opposition/reposition; one motor drives digit I flexion; and one motor drives digit II (forefinger) flexion. The remaining motor drives digits III-V (the middle, ring, and little fingers) in flexion in an underactuated manner. Specifically, the flexion axes of digits III-V entail six degrees-of-freedom, which are underactuated through a combination of moment isotropy (within each digit) and parallel compliance (between the three digits). Thus, the configuration of digits I and II are determined uniquely as commanded by the motor units, while the configuration of digits III-V are determined by a combination of the motor unit command and the nature (i.e., shape) of the object being grasped. Thus, the hand is able to explicitly provide both precision grasp capability, in addition to whole hand conformal grasp capability.

B. Nature of Actuation

In digits I and II, actuation is achieved via a pair of opposing tendons: one for flexion, and another for extension. This use of bi-directional tendons makes torsional springs for digit extension unnecessary, reducing the physical complexity of the part, and allowing higher flexion and extension forces. To provide improved force resolution during grasping a spring is used in series with the flexion tendon, while the extension tendon is attached directly to the digit.

Since it is generally unnecessary to execute the opposition/reposition motion while the thumb is under load, the force required by this DoA is much lower than for the rest of the DoAs. Thus, for simplicity of design, the thumb opposition/reposition joint is connected directly to the output shaft of the respective motor unit.

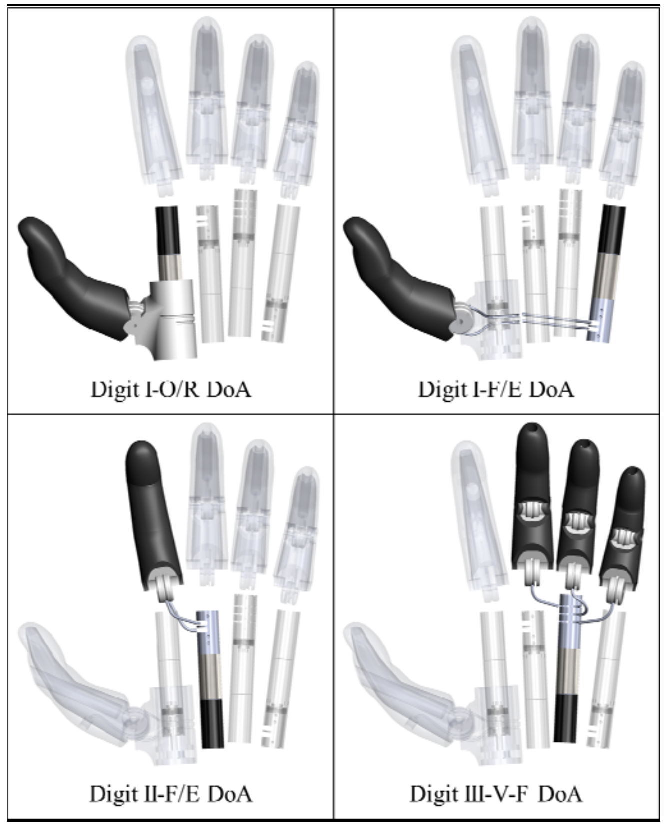

Fig. 1. Degrees of freedom corresponding to each degree of actuation (Note that O/R refers to Opposition/Reposition, F/E refers to Flexion/Extension, and Digits III-V are only actuated in Flexion).

Digits III-V utilize unidirectional tendon actuation. Each digit contains a torsional spring in each joint (parallel elasticity) and a compression spring in the fingertip (series elasticity). Since the tendons only actuate the digits in flexion, the equilibrium point of the torsional springs is set such that they will provide a restoring (extensive) force to open the hand when the tendons unwind. As with digits I and II, the compression springs in the respective fingertips of digits III-V enable both force control and passive compliance (i.e., a compliant differential between the digits). That is, for any given motor position, the digits can move relative to one another (as determined by the shape of object being grasped), with the difference compensated by the compression of the spring. To achieve an appropriate degree of passive compliance to enable conformal grasping, the stiffness of the springs in digits III-V is lower than in digits I and II.

Fig. 2. Vanderbilt hand performing the eight described grasps and postures

C. Fabrication

As with previous designs, additive manufacturing processes are utilized in the construction of the device. This enables complex interior part geometries, especially regarding tendon paths, which would be expensive or impossible for conventional machining or molding. Additionally, a composite manufacturing process is utilized, which allows parts consisting of multiple materials to be produced in a single process. Thus, in one process a part can be made that contains a rigid structure overlaid with a soft, rubber-like surface which can be anthropomorphic in shape. Thus the cosmesis is an integral component of the hand design.

II. Experimental Characterization of Hand Performance

A. Grasp and Posture Configurations

The assembled hand prototype is shown in Fig. 2, along with its ability to achieve the aforementioned grasps and postures under motor control. To achieve these grasps and postures the hand utilizes a controller which is described in detail in [17]. In order to determine if the prototype design is capable of biomechanical levels of force and speed, the hand performance was experimentally characterized, as described in the following sections.

B. Fingertip Forces

The fingertip forces were measured by applying the maximum allowable current (with a factor of safety) to the motor unit for a duration of one second. Note that each motor unit incorporates a two-way clutch, and as such it is presumed that sustained grasping would be performed passively, first by squeezing the object for a short period (e.g., one second), then turning off the motor current and allowing the combination of the series elasticity and two-way clutches to passively hold the respective grasp force. A force gauge was attached orthogonally to the fingertip to measure the resulting fingertip force. Three trials were taken at each finger position, and the average force value for each DoA is reported in Fig. 3. For digits III-V, the force gauge was attached to all three fingers at once, and the combined force provided by the three fingers was measured together.

It should be noted that the precision grasps illustrated in Fig. 2 occur in the tendon excursion range of 40 to 90% tendon excursion. In this range, digits I and II each provide approximately 12 N of finger force, which as previously discussed, provides sufficient force to conduct approximately 75% of representative precision grasp tasks. Further, it should be noted that, due to the presence of the two-way clutches, the tip grasp force provided by digits I and II will be the larger of the respective fingertip force capabilities (i.e., the digits are self-locking). As such, the hand is capable of up to an 18 N tip grasp force, which according to [14] is sufficient for all but one of the representative grasps tested (i.e., for 92% of the grasps tested). For the case of conformal grasps shown in Fig. 2, the tendon excursions required are generally in the 20 to 60% range. As such, as per the data in Fig. 3, digits III-V are fully capable of the objective of 14 N stated previously.

C. Speed Characterization

To measure the speed of the hand, the motors were driven by a sinusoidal position command with a magnitude of half the total tendon excursion. The gain of the response as compared to the commanded input is shown in Fig. 4 as a function of the frequency of the input. As can be seen from the graph, all DoAs have a bandwidth higher than the specified 1.5 Hz. Specifically, the respective -3 dB bandwidths range from 4.5 Hz (digits III-V) to approximately 11.5 Hz (digit I-O/R).

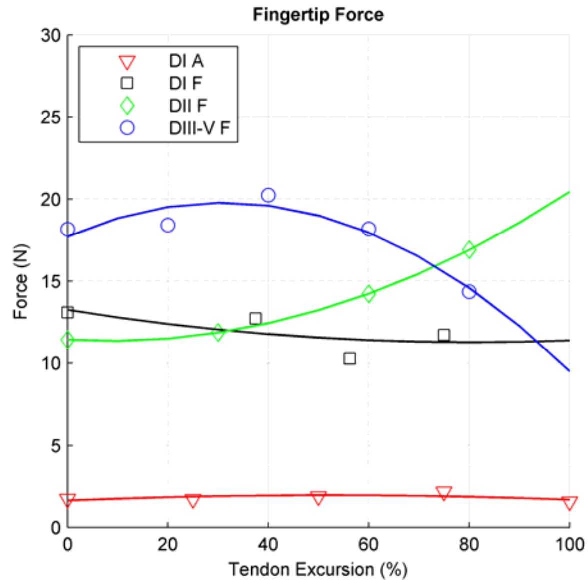

Fig. 3. Fingertip force capability for each DoA

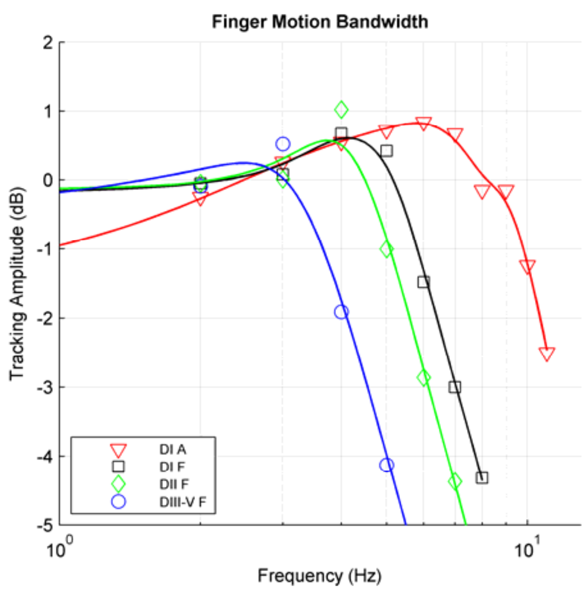

Fig. 4. Finger motion bandwidth for each DoA

III. Conclusion and Future Work

This paper describes a novel hand design in which degrees of actuation are allocated explicitly to provide capability for precision and conformal grasping. The authors demonstrated the ability of the hand to achieve both the configurational and performance objectives appropriate for a multigrasp hand prosthesis. Future work will involve fitting the hand to transradial amputee subjects and assessing the ability of the hand to provide the precision and conformal grasps required in ADLs.

IV. References

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