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Biological Stiffness Control Strategies for the Anatomically Correct Testbed (ACT) Hand

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Abstract— **With the goal of developing biologically inspired manipulation strategies for an anthropomorphic hand, we investigated how the human central nervous system utilizes the hands redundant neuromusculoskeletal biomechanics to transition between conditions. Using a experiment protocol where subjects were asked to transit between control states with equal end-effector force but different stiffness requirements, we observed that (1) some subjects used the same muscle synergy for both conditions by maintaining the same synergy throughout the transition, and (2) other subjects used two different muscle synergies to execute two conditions by transiting from one synergy to another rapidly. We hypothesize that humans typically try to use the same muscle synergy to execute two tasks when it is possible to optimize on the simplicity and speed over energy. This is a different control strategy from the way robots have been controlled in the past, and it provides a new direction in controlling an anthropomorphic robotic hand.**

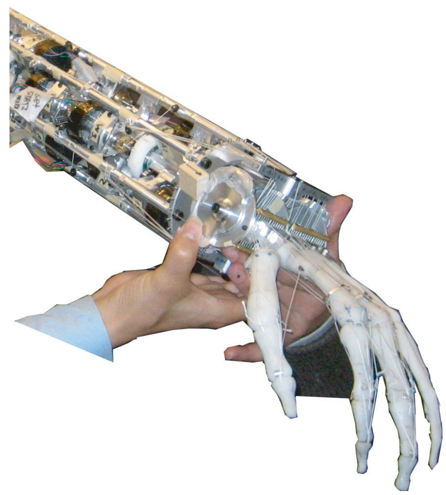

Fig. 1. The fully assembled Anatomically Correct Testbed (ACT) robotic hand, which has five fingers (and three are fully actuated) and preserves the human musculotendon structure.

I. INTRODUCTION

The human hand is skillful at manipulating objects. This is because the hand, enabled by an intricate and redundant neuro-musculo-skeletal system, is capable of controlling different aspects of a grasp, namely force, stiffness, and posture. Inspired by this, the Anatomically Correct Testbed (ACT) hand [21], [2] shown in Fig. 1 was developed with three goals. First, it is used as an experimental testbed to investigate neural control of human hand movements. Second, it is a telemanipulator or prosthetic that mimics the passive and active dynamics of the human hand. Third, it can act as a physical model of the human hand on which surgeons can test reconstruction techniques for impaired hands. For such goals, it is critical to investigate how biological systems handle redundant and tendon driven systems and compare their performance with alternate engineering solutions. In this paper, we approach this problem by exploring how humans utilize their musculature to transition between control states.

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The redundant actuation in the human hand, a consequence of each joint being controlled by several muscles, provides the central nervous system many choices to produce a desired end-effector force and stiffness. Each choice of muscular coordination is defined as a muscle synergy. For example, the index finger's three degree-of-freedom flexion-extension behavior is controlled by seven muscles that can only pull [14]. A muscle synergy for the index finger is thus a seven dimensional vector with each element representing the muscle's usage (see section II for more details), and there are many muscle synergies that could satisfy a condition.

Robotics researchers have explored the utility of redundancy in robotic manipulators for kinematic and dynamic dexterity [11], [15], while neuroscientists have explored how the central nervous system varies muscle activation to produce steady-state forces and steady-state force and stiffness states [1]. For example, muscle synergy for producing large fingertip force has been shown to be subject independent [20]. Furthermore, when subjects are told to modulate only fingertip force (without stiffness requirements), subjects achieve them by modulating the magnitude of the same muscle synergy [19]. While the importance of stiffness modulation is studied with respect to improving performance accuracy [6], [8], [16], how force-stiffness modulation is achieved in the redundant muscular control space has not been studied.

This paper focuses on the specific paradigm where a human subject is required to navigate between two states with equal end-effector force but different stiffness. After a brief review of definitions and the problem statement defining a biological controller hypothesis, section III describes the experiment procedure and results. Section IV discusses how insights into biological solutions can aid us in developing control strategies for human-like robotic hands like the ACT hand and also exploring biologically inspired controllers that could be superior and simpler.

II. BACKGROUND

A. Muscle Synergy

It has been hypothesized that the central nervous system uses muscle synergies to manage controlling a high dimensional structure (individual muscles) using low dimensional control space (a group of muscles activated in a preset combination). A muscle synergy $\mathrm{MS} \in \mathbb{R}^n$ can be defined as the fraction to which each muscle is used to achieve a certain condition [5]:

$$\mathrm{MS} = \frac{1}{\sum_i^n a_i} \begin{pmatrix} a_1 \\ a_2 \\ \vdots \\ a_n \end{pmatrix}^T, \tag{1}$$

where a_i represents the activation level of muscle i and n the total number of muscles. Normalized muscle activation (EMG measurement) is modeled to have a linear relationship to muscle force under controlled conditions such as fixed posture and no fatigue [7]. Even though having muscle synergies may reduce the control space dimension, there are still many synergies that could be used to produce the same fingertip force and stiffness.

B. Iso-Torque, Iso-Stiffness, and Iso-Effector Spaces

In order to have the ability to describe the redundancy in muscle control space mathematically, we define iso-torque, iso-stiffness, and iso-effector spaces in muscle activation space. Details of these definitions can be found in [1].

The iso-torque space is the space of actuation solutions that produces a specific end-effector force for a given configuration. The muscle forces f_m that produce a specific end-effector force f_e is given by

$$f_m = R^{-T} J^T f_e + f_n, \tag{2}$$

where J represents the mechanism's Jacobian [4], f_e the external force that the finger applies, R^{-T} the Moore-Penrose pseudo-inverse of the transpose of the moment arm matrix R, and f_n a vector belonging to the right nullspace of R^T, $N_r = \{x | R^T x = 0\}$[13]. As an example, an index finger has seven muscles and four degrees of freedom. The iso-torque space for a given finger configuration is a three dimensional hyperplane in a seven dimensional space.

The iso-stiffness space is the space of actuation solutions that produces a specific end-effector stiffness and can be described as

$$K_m = R^{-T} J^T K_e J R^{-1} + K_c + K_r, \tag{3}$$

where K_m represents the diagonal muscle stiffness matrix, K_e the end-effector stiffness matrix, K_c represents a matrix whose columns belong to the right nullspace of R^T and K_r a matrix whose rows are one-forms that belong to the left nullspace of R. The left nullspace of R is defined as $N_l = \{x | xR = 0\}$.

By intersecting the iso-torque and iso-stiffness solution space, we get the set of muscle forces that produce a specific end-effector force and stiffness for that configuration. This solution space is called the iso-effector space. For the index finger, the iso-effector space is a two dimensional manifold residing in a seven dimensional space. This indicates that many different synergistic muscle activities exist to produce a given endpoint force and stiffness at a specific finger configuration.

C. Problem Statement

When manipulating objects, often one has to modify the grasp. With the goal of creating net changes in end-effector force and stiffness, the central nervous navigates in the control space of muscle actuation. What are the the salient features of such a transition? Can we quantify the transition?

We asked subjects to transit quickly between two conditions (two iso-effector spaces) with the same end-effector force but different stiffnesses that could be accomplished with the same muscle synergy (see Fig. 2).

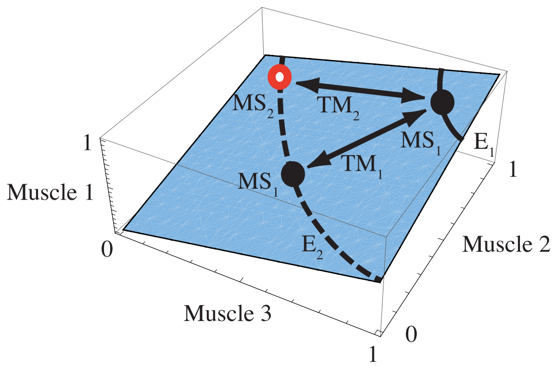


Fig. 2. Transitioning between two iso-effector conditions E_1 (bold curve) and E_2 (dashed curve) on the same iso-torque plane: transition mode 1 (TM_1) uses the same muscle synergy (MS_1) for both conditions, while transition mode 2 (TM_2) uses different muscle synergies (MS_1 for E_1 and MS_2 for E_2).

We investigated three points. First, we investigated whether the central nervous system would use the same synergy for those two conditions. Second, we investigated whether the same synergy is used throughout the transition period when the same synergy is used at the beginning and the end. Third, we investigated how the transition occurs from one synergy to another if the two conditions used different synergies.

III. Experiment Procedure and Results

A. Materials and Methods

Four subjects (two male and two female) participated in our experiment. The subject sat in a chair and placed their hand on the table so that the index finger flexion-extension plane was in parallel with the table surface. The subject's arm was strapped to isolate the index finger movement, and the index finger was maintained at a prescribed flexed posture (the three joint angles from knuckle to tip: 45, 45, and 10 degrees respectively). A force sensor (Flexiforce sensor A201; Tekscan, Boston, MA) was positioned normal to the fingerpad to measure fingertip force.

Muscle activations from three muscles that control the index finger—the flexor digitorum superficialis (FDS), the flexor digitorum profundus (FDP), and the extensor digitorum (ED)—was recorded using the Bagnoli-8 surface EMG system (Delsys, Boston, MA). Care was taken to minimize interference from muscle activations of other fingers and joints, and the subjects were instructed to keep the other fingers and joints as relaxed as possible. Force and EMG signals were recorded at 250 Hz.

Subject's end-effector force was taken from the force sensor and then normalized by the subject's maximum voluntary force (MVF) measured during calibration. Subject's end-effector stiffness was estimated as the smallest of the three instantaneous muscle activations, which measures the extent of co-activation of muscles [18]. The "low" level of stiffness was calibrated by asking subjects to relax the muscles at a given force level. The "high" level of stiffness was calibrated by asking subjects to stiffen up their index finger at a given force level. The subject was given real-time feedback of the normalized force and stiffness levels.

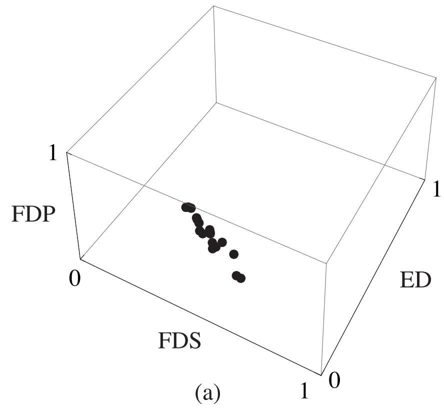
The experimental protocol required a subject to maintain four force-stiffness conditions: 10% MVF–low stiffness (10L), 10% MVF–high stiffness (10H), 30% MVF–low stiffness (30L), and 30% MVF–high stiffness (30H). The subject was also required to transition between low and high stiffness conditions within the same same force levels (that is, 10L↔10H and 30L↔30H) when given a cue. The transition had to be completed within 1.5 seconds from the time the cue was given to be considered a successful trial. *However, the subject was not instructed how to move between conditions.* The experimenter ensured that the subject maintained the required configuration and was not fatigued. The subject was allowed one or two practice trials, followed by four trials for each transition.

Before analyzing the data, we eliminated trials where subjects did not follow the instruction using the following four criteria: 1) Force standard deviation greater than 20% MVF, 2) Mean force during a condition or during transition lay outside a 15% window around the target, 3) Stiffness standard deviation greater than 10% maximum muscle activation, and 4) Stiffness levels during the conditions were not significantly different ($p > 0.05$).

B. Experimental Results

Using automatic clustering methods on the muscle synergy data, we found that different force-stiffness conditions were executed using either only one or two muscle synergy clusters for all subjects. Fig. 3 shows the example of subject 2 who had only one cluster and another example of subject 3 who had two clusters.

We further analyzed the data to pay attention to the transition between two conditions. We found a total of two types of transitions for all subjects: Transition Mode 1 (TM_1) where the central nervous system transitioned within one synergy to produce two force-stiffness conditions; and Transition Mode 2 (TM_2) where the central nervous system transitioned to a different synergy to execute a different force-stiffness



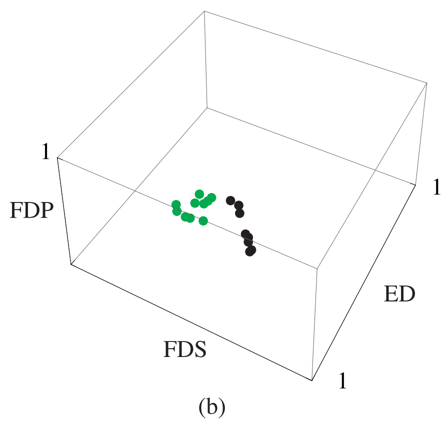


Fig. 3. Muscle synergies expressed in the muscle activation space. Automatic clustering method was used to identify the number of synergies used by subjects. (a) Subject 2 had one cluster showing the use of only one muscle synergy (black), while (b) Subject 3 showed two different clusters (black and gray).

condition.

In TM_1, the same synergy was maintained throughout the transition (average absolute slope across muscles was 0.15 ± 0.02 (se) per second). Fig. 4a shows a typical set of data including force, muscle activation, and muscle synergy for TM_1.

In TM_2, muscle synergy changed from the first one to another rapidly. While subjects were allowed a transition duration of 1.5 seconds, the average transition duration of muscle synergy was only 0.27 ± 0.04 (se) seconds. The slope during the transition was on average 0.46 ± 0.004 (se) per second. Fig. 4b shows typical time histories of force, muscle activation, and muscle synergy for TM_2.

IV. Discussion

Modulating stiffness and force is crucial for robust manipulation, since it provides flexibility to handle a variety of objects, such as a hammer or a soft toy, in the presence of disturbances [9], [17], [22]. In robotics, force and stiffness modulation was implemented, for example, using impedance control using endpoint force feedback [10], joint and Cartesian stiffness synthesis using screw algebra [3], and velocity control using pseudo-inverses for redundant controllers [12]. In order to develop more dextrous and human-like ways to transit between different iso-effector space under redundant structure, we explored how humans choose and use muscle synergies.

We observed two different ways to transit from one iso-effector space to another. For TM_1, while there must have been a lower energy solution to execute the second condition, the human strategy was to use the same combination of muscle activations and simply increase the magnitude as a whole. Similar strategy was observed when subjects were instructed to produce different fingertip forces with no constraints on stiffness [19]. We hypothesize that for hand muscles, it is more important to transit from one iso-effector to another as fast and easy as possible rather than to conserve energy. Hand muscles are small enough that the energy consumption may not be as critical as a larger limb such as a leg.

It is interesting that we observed TM_2, which has not been observed in the past. When we further analyzed the second muscle synergy (as shown as the muscle synergy in Fig.4b), we saw that the subject minimized the use of FDP which is the largest of the three muscles we recorded from. It appears that for some conditions, and for some subjects, it is more advantageous to change the synergy between two iso-effector space transitions. The reason for this change could be dependent on the specific subject's hand size, kinematics, or musculotendon size and routing, that makes it difficult to use the same synergy for multiple conditions. We need to further analyze the iso-effector space location, shape, and size in muscle synergy space to check why these individual differences exist.

V. Conclusion and Future Work

This paper explored biological controllers for an anthropomorphic robotic hand by analyzing how humans modulate their hand musculature when transitioning between control states. We investigated specific questions regarding the use of muscle actuation to perform different force-stiffness conditions and present results that highlight the role of muscle synergies when transitioning between conditions. Future work includes expanding our analysis to find more complete mappings between force-stiffness conditions, muscle usage, and

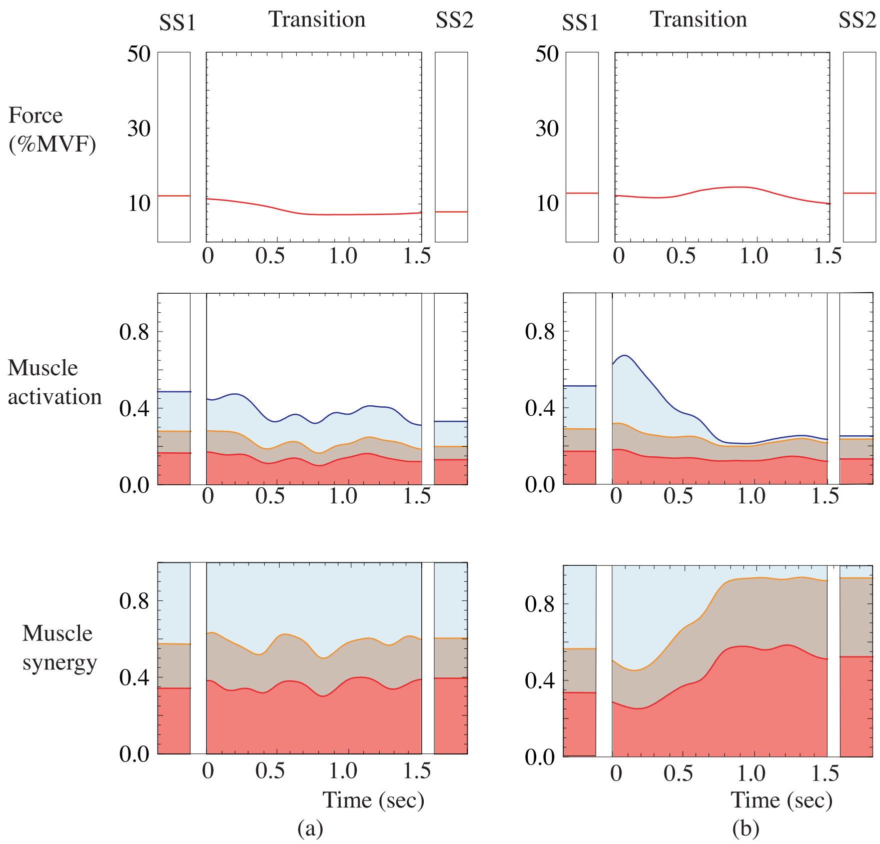


Fig. 4. Time histories of force, muscle activation, and muscle synergy during two different transition modes from condition 10H to condition 10L: (a) muscle synergy is same for both conditions and during transition (TM_1, subject 2); (b) muscle synergy is different for the two conditions and the transition is rapid (TM_2, subject 3).

posture. In particular, it would be interesting to identify the region of optimality for a muscle synergy and also understand how synergies are chosen across different postures.

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