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CONTINUOUS POSITION AND FORCE CONTROL OF A MULTIGRASP MYOELECTRIC TRANSRADIAL PROSTHESIS

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INTRODUCTION

Dependable and efficient utilization of a multigrasp prosthetic hand requires an effective control interface. This interface should be intuitive and direct, offering continuous and proportional control of motion with negligible latency. Realization of such a controller is a challenging problem in upper extremity prosthetics research although several significant strides have been made. Prevalent approaches to multigrasp control thus far include pattern recognition [1-6] and hierarchical control [7-11].

This paper presents the design and preliminary experimental validation of a myoelectric controller that is intended to control the continuous motion of a multigrasp prosthetic hand between nine characteristic postures (reposition, point, hook, lateral pinch, opposition, tip, cylindrical, spherical and tripod). The controller, referred to as multigrasp myoelectric control (MMC) is based on an EMG supervised event-driven finite state machine. The EMG component provides user intent, and consists of a single bipolar signal acquired through two EMG electrodes, similar to EMG interfaces commonly found in commercial myoelectric prostheses. The state machine acts in conjunction with a low-level coordination controller to activate different actuator subsets (connected to digits via tendons in the prosthesis) based on the present state. The controller incorporates object detection and force estimation algorithms to allow force based state transitions and the estimation of digit forces.

To test the functionality of the controller, experiments were conducted on a healthy subject using an able bodied adapter with a multigrasp prosthetic hand. Experimental results are presented that demonstrate the ability of the MMC to provide effective movement and grasp control of the multigrasp prosthesis.

MULTIGRASP MYOELECTRIC CONTROL

The MMC consists primarily of a uniquely structured finite state machine (see Fig.1) and a coordination controller. The output of the state machine, the current hand state (posture), dictates which subset of actuators (and associated tendons) are active in the hand at any given time. The active tendons are indicated on the inset of each state in Fig.1, where T1 controls Digit II Flexion, T2 controls digits

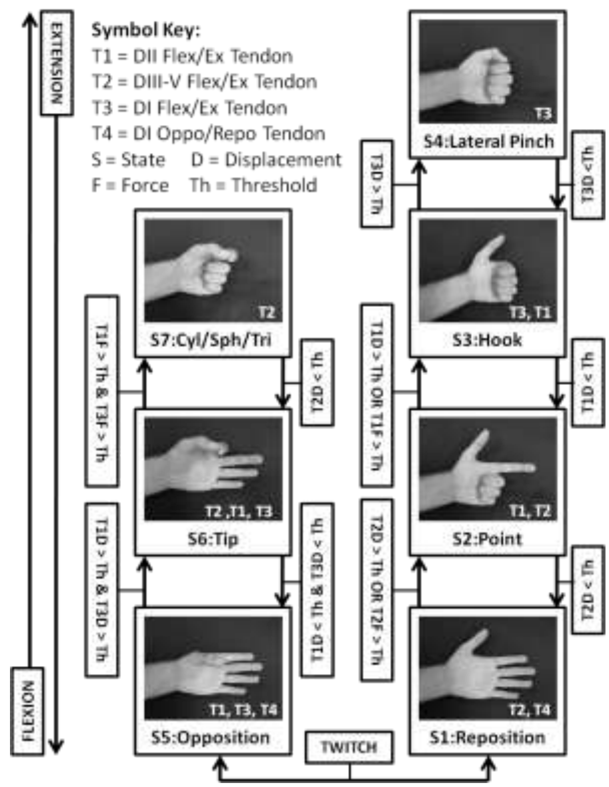

Figure 1: Structure of the MMC state-machine

III-V flexion simultaneously, T3 controls digit I flexion, and T4 controls digit I opposition. The position references for these actuators are driven by proportional signals arising from the EMG input. Changes in digit position or digit grasping force trigger transitions in the state chart based on pre-established thresholds. Twitch commands (a high intensity co-contraction of the muscles at both electrode sites) may also cause transitions among the reposition (platform) and opposition postures. Once a transition occurs, the current state of the hand changes, and a new subset of actuators and associated tendons become activated by the coordination controller. The active actuators are associated with transitions to adjacent states. This configuration is intended to leverage the benefits of traditional myoelectric control by allowing for the direct and proportional control of motion of a multigrasp hand from a single EMG input (i.e., one pair of EMG channels). A more detailed explanation of this controller may be found in [12].

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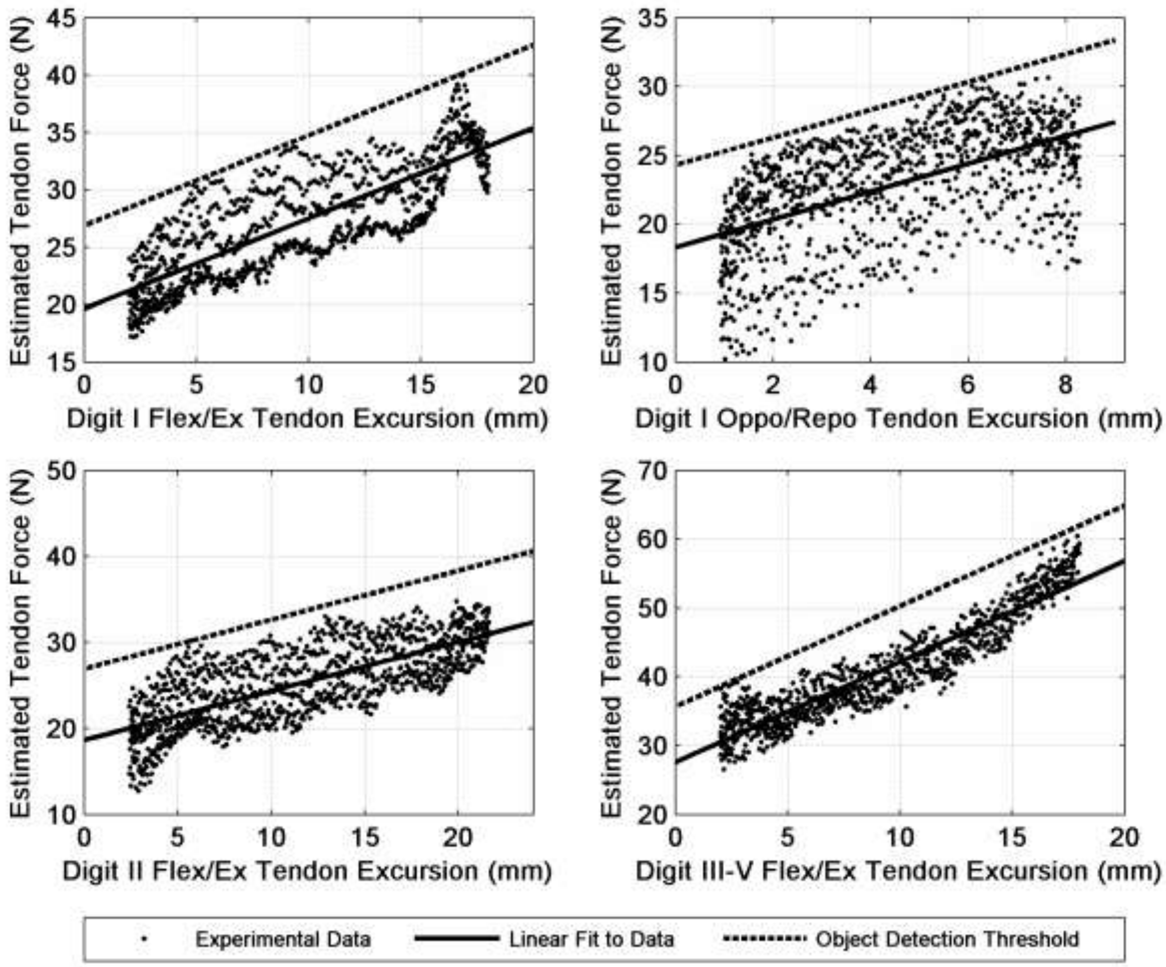

Figure 2: Estimated Tendon Force versus Tendon Excursion for Flexion of Digits I-V and Opposition of Digit I

OBJECT DETECTION AND FORCE ESTIMATION

Object detection and force estimation were implemented in the MMC to enable force-based transitions in the state chart and allow for proportional force control. To do this, the digits of the hand described in [13] were driven repeatedly through their full range of motion with a chirp signal whose frequency increased exponentially from 0 Hz to the motion bandwidth of each digit (or joint, in the case of the digit I opposition degree of freedom). The current command and tendon excursion were recorded during these motions. The tendon force, F_T, was then estimated as $F_{T=\frac{u_m k_t N}{r}} = \frac{u_m k_t N_G}{r}$, where u_m is the motor current, k_t is the motor torque constant, N_G is the gearhead ratio, and r is the pulley diameter of the hand described in [13]. The graphs in Fig. 2 depict the force required to either flex the digits or oppose the thumb as a function of tendon excursion. A linear fit was then applied to these data (ignoring the first and last 10% range of motion) and offset by the maximum difference between the experimental data and the linear fit. Note that, by using the chirp signal to generate this data, dynamic effects due to variations in velocity (i.e. friction) and acceleration (i.e. inertia) are accounted for. This being said, the spread of the data for a given excursion is usually on the order of 10 N. As this represents at most approximately 4% of maximum tendon force (270 N for short-term operation) this variation is assumed to be insignificant, and a quasi-static characterization may have been sufficient. Nevertheless, this process established a conservative characteristic baseline for unimpeded motion which was utilized as an object detection threshold for each degree of actuation, respectively. An object was detected when the instantaneous tendon force estimate during operation (based on the above equation and dependent on motor current) exceeded the object detection threshold (dependent on tendon excursion).

A proportional signal was generated by subtracting the instantaneous tendon force estimate from the object detection threshold. The normalized finger force was then found by dividing this quantity by the maximum force

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achievable given the thermally induced current limits of the motors.

EXPERIMENTAL PROCEDURE

To test the MMC with object detection and force estimation, the multigrasp prosthesis described in [13] was attached to a healthy subject using a custom built, able-bodied-adapter, depicted with the prosthesis in Fig. 3.

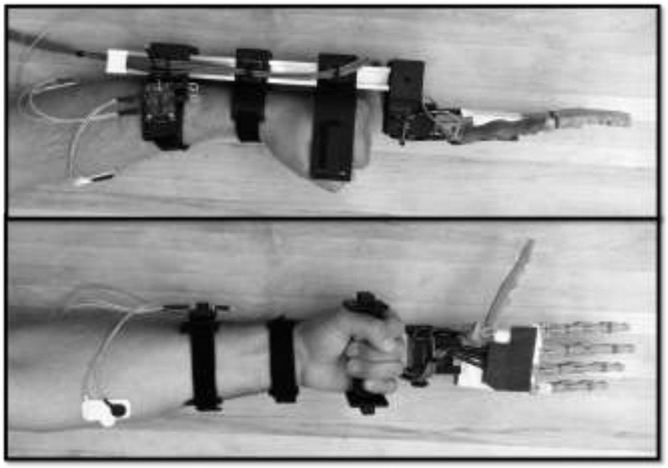

Figure 3: Prosthesis and able bodied adapter

To verify the efficacy of the object detection algorithms, the subject was required to traverse the state chart while grabbing various objects to impose both position and force based state transitions. Specifically, a roll of electrical tape was grasped while in the point state to impede motion of digit I, and a 6 cm (2-3/8 inch) diameter PVC pipe was grasped while in the tip state to impede motion of digits III-V (see Fig. 4).

RESULTS AND DISCUSSION

Figure 5 shows EMG control input, hand state, tendon excursion, and normalized finger force during the experiment. This figure demonstrates several important characteristics of the MMC. First, the same EMG input can affect positional references for different actuators based on the current state of the hand (EMG channel 1 commands T2 around the reposition state and controls T3 around the lateral pinch state). Second, a single EMG input may govern multiple actuators, (EMG channel 1 simultaneously controls actuators T1 and T3 in the opposition and tip states). Third, a high intensity co-contraction of the forearm flexor and extensor muscles results in a twitch. The twitch event causes automated opposition and reposition of the thumb (note the behavior of T4 after the occurrence of a twitch). As can also be seen in Fig. 5, response to user intent is immediate. That is, movement occurs as soon as elevated EMG signal levels are detected.

Figure 5 also verifies that force-based transitions were successfully executed as indicated in the figure by arrows. It can be seen that a force-based state transition occurred between the point and hook states when the estimated tendon force for T1 exceeded the object detection threshold as the electrical tape was grasped. This transition then allowed T3 to flex and further enclose the grasped object. Similarly, a force-based transition occurred between the tip and cylinder/spherical/tripod grasps as tendons 1 and 3 began to close around the 6 cm (2-3/8 inch) diameter PVC pipe. Although these fingers were able to close sufficiently to cause a transition to the tip state, the occurrence of object detection allowed further transition to the cylinder/sphere/tripod grasp state. This, in turn, allowed T2 to flex, causing digits III-V to close, and adding further stability to the grasp. While previous work [12] had demonstrated the efficacy of this controller in a virtual environment, with tendon excursion based transitions only, this was the first demonstration that the controller was effective with hardware, and that force based transitions could be executed successfully in the presence of grasped objects. Finally, Fig. 5 also shows that the normalized finger force increases with continued EMG input after object detection has occurred, providing a signal which may be utilized for user feedback.

CONCLUSION

This paper demonstrates that the MMC provides direct access to multiple grasps and postures with negligible latency. By grasping a variety of objects while traversing the state chart, it was seen that the object detection and force estimation algorithms are functional and allow for continuous force and position control. This was the first physical (as opposed to virtual) demonstration of the controller's effectiveness. In future work, the MMC and multigrasp prosthesis will be functionally assessed on amputee subjects. Additionally, normalized finger force will be utilized to provide some form of feedback to the user.

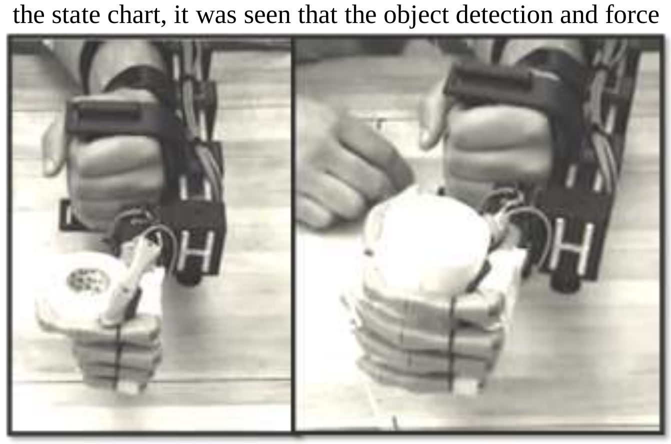

Figure 4: Objects grasped during experimentation

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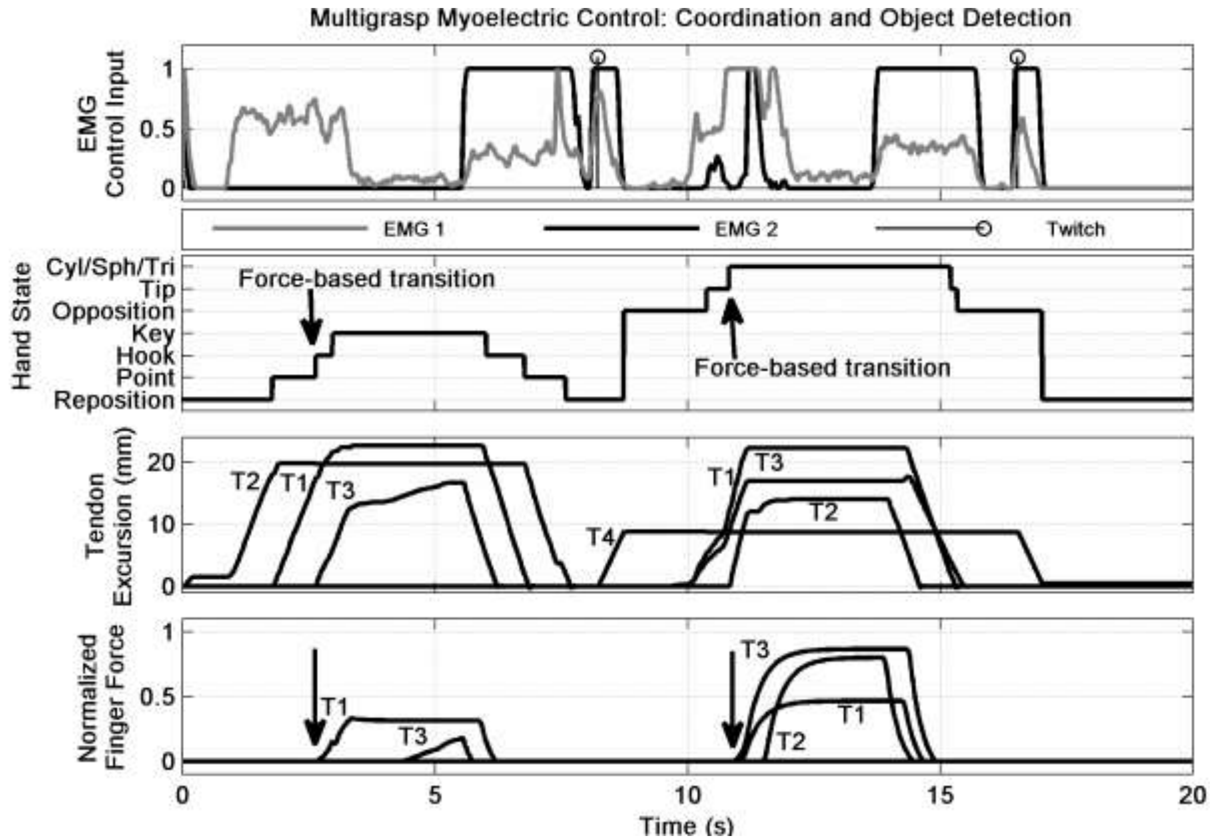

Figure 4: EMG input, hand state, tendon excursion, and normalized finger force during state chart navigation

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