CONTROL OF A MULTI-FINGER PROSTHETIC HAND

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ABSTRACT

Our novel prosthetic hand is controlled by extrinsic flexor muscles and tendons of the metacarpal-phalangeal joints. The hand uses tendon-activated pneumatic (TAP) control and has provided most subjects, including amputees and those with congenital limb absence, control of multiple fingers of the hand. The TAP hand restores a degree of natural control over force, duration, and coordination of multiple finger movements. An operable hand will be demonstrated.

BACKGROUND

While modern robotic hands are highly dexterous, having many degrees of freedom, prosthetic hands function much as they did over a century ago, by single-joint grasping. Available hand prostheses are either 'body powered', or 'myoelectric' devices that restore prehension. Standard body powered prostheses are controlled by a harness that couples shoulder movements to opening/closing of a prehensile hand. While harness-type controllers have proven reliable and robust for thousands of amputees over decades [1], their versatility is limited by the number of independent control motions practically possible: one. Myoelectric controllers may eventually offer more degrees of freedom (DOF), but this number is limited by the ability of the user to learn unnatural movements to activate hand motions and the ability of the controller to decode the resulting electromyographic (EMG) signals [2,3]. Perhaps due to these limitations, myoelectric controllers still provide only one practical DOF, directed by flexion-extension of arm muscles. Accordingly, intensive efforts are underway to extract more independent channels from EMGs, with advanced signal processing techniques, tactile feedback, complex user control schemes, or surgical re-innervation [4,5].

Even the most advanced controllers available today do not fully exploit the residual functions possessed by persons with missing limbs. These include the ability, at least in below elbow amputees, to possibly control their extrinsic muscles and tendons that flex the metacarpal-phalangeal joints. A controller that could transduce these volitional motions would thus restore, at least partially, the natural link between volition and movement, and would hence be biomimetic. Beyond providing finger control for hand prostheses, the TAP controller may facilitate the transition to more complete hand restorations via surgery.

METHODS

System Design

The overall design goal was to use natural tendon movements in the forearm to actuate virtual finger movement. A volitional tendon movement sliding within the residual limb causes a slight displacement of air in foam sensors apposed to the skin in that location. The resulting pressure differential is transduced, processed, and used to control a multi-finger hand.

Subject Screening

Twelve subjects filled out a questionnaire (minors with parental assistance) intended to provide demographic and consumer information. All subjects reported interest in multi-finger control and proportional control of force and velocity. Four had congenital deficiencies (2 female/2 male), and eight had acquired amputations (all male). Eight (including three with congenital ULRD) were myoelectric users, one used a body-powered hook, one had a cosmetic hand, and one had a cineplasty APRL hook. There is intense interest in this research as a result of media attention, and our database now includes over 80 potential candidates internationally, as well as many providers and physicians.

Residual and sound limbs were examined and measured. Subjects were asked to perform finger flexions while the examiner palpated the limb. Successful detection of movement on 9/12 subjects indicated acceptance into the next phase.

Six successful candidates, 10 to 40 years of age, having a minimum of 1/3 the original length of the forearm and at least 3 tendons and/or muscle sites were selected for further testing. Two had congenital ULRD, and the rest had acquired amputations. Tests were performed to evaluate the sensitivity and specificity of the system, the ability of subjects to activate individual fingers, and the degree of control over the signals.

Smart Socket Fabrication

Sensor sites determined during the initial screening were optimized using a transparent test socket. Following optimization of the measurements and the final sensor locations, the sites were transferred back to a positive cast of the limb. A soft silicone sleeve was custom fitted to the cast, with the sensors embedded inside at predetermined locations. An acrylic laminate was fabricated over the silicone, with a wrist unit mounted on the distal end to allow for direct attachment of a prototype mechanical hand.

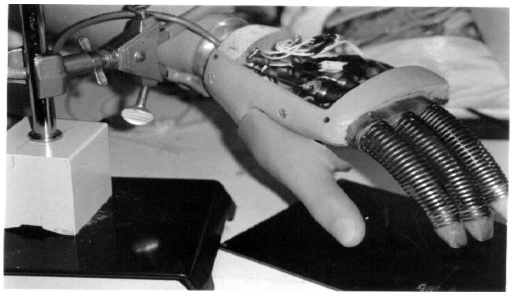
Alternate smart sockets were made by affixing single TAP sensors with Velcro or glue at selected points on the socket.

RESULTS

Virtual and Mechanical Hands

Initial demonstrations of finger tapping were done using a computer program which displayed the TAP signals, along with a virtual hand having fingers that could be lit independently when the corresponding finger volition was detected. Some subjects, especially children, seemed to enjoy operating the virtual hand, and also watching their TAP signals on the computer screen [6]. The virtual hand proved to be a valuable training tool.

The first 2 versions of our mechanical hand were simple robotic hands that allowed users to observe finger activations. The version 3 prototype hand was a laminated shell to which were attached fingers obtained from a commercial wooden hand (Becker Imperial, Hosmer-Dorrance), as shown below:



A 2-position thumb was attached to permit either keyboard use or grasping. Linear actuators provided movement of 3 independent fingers, each having approximately 30 degrees of flexion, with a maximum of about 4 N of force. Software, written in 8051 code controlled the hand. The version 3 hardware microcontroller for the portable hand was the ***Log-a-Rhythm***® (Nian-Crae, Inc.) wearable computer. Because of the simplicity of the requested movements, a straightforward decoding algorithm was used.

Structural design of the version 3 hand proved effective. It consisted of an acrylic/carbon fiber shell to form the palmar structure, to which was attached fingers, thumb, and a wrist unit. The carbon fiber shell was a mirror image of the sound hand of an amputee, and was strong, light, and easily machined. Actuators were mounted in the shell, and linked to fingers. The finger 'bones' were 2 bars articulating at an M-P and a P-P joint, inserted in a spring for passive extension. Two types of finger bone materials were tested: steel bars and nylon rod. Also tested was the return spring design: either internal or external to the bones. The thumb was mounted on a spring-loaded ratchet that had 2 stable positions: abducted and adducted. Structural and actuator designs are currently being further developed.

Biomimetic Control

A signal response matrix was generated for each subject, consisting of three rows, representing requested finger motions, and three columns, representing the three sensor locations, as shown below:

	Site →	**T**	**I**	**L**
Intention ↓				
T		TT	TI	TL
I		IT	II	IL
L		LT	LI	LL

TT, for example, represents signal energy from the thumb sensor for an intended thumb movement; IT is from the same sensor for an intended index movement, and so on. To maximize the diagonals, subjects were instructed to use less force to help avoid cross signals. Several response matrices were obtained from each patient. An example is shown below. All subjects were able to produce at least one matrix comparable to the one shown.

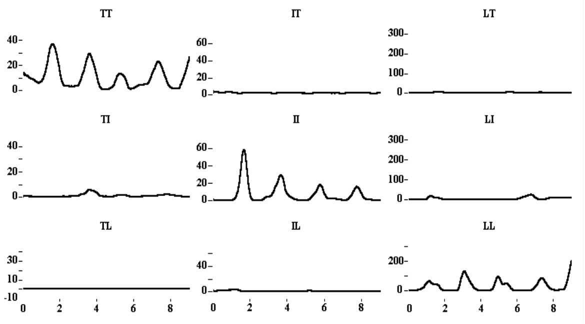


Figure 1: Response Matrix

Traces represent squared signals derived from TAP sensors over a 9-second period of repetitive finger flexions. Using the response matrix, the levels of signals received from the requested (diagonal) channels and the cross-talk (off-diagonal) channels were compared. Ratios of energy levels were expressed in decibels (dB):

$$R_{ij} = 10 \log \frac{\sum (D_i)}{\sum (O_{ij})}, \quad i=1,2,3;\ j=1,2$$

where R_{ij} is signal energy of sensor i with respect to sensor j, D_i is the energy of diagonal sensor i, and O_{ij} is the energy of the off-diagonal sensors with respect to each diagonal. Energies were calculated for the duration of each protocol, representing about 6 sequential finger commands. Results showed that diagonal signal energies were all well above zero and ranged from 1 to 22 dB above noise.

Sensitivity and specificity data were summarized as the percentages of true positives for diagonal sensors and true negatives for off-diagonal sensors, respectively. Within 3 or 4 sessions, each subject could elicit independent signals from each channel, with sensitivities and specificities approaching 100%. Some subjects acquired sufficient dexterity to play simple piano pieces with the hand.

Representative sensitivity data are shown below for 3 subjects. Similar results were found for specificity (not shown).

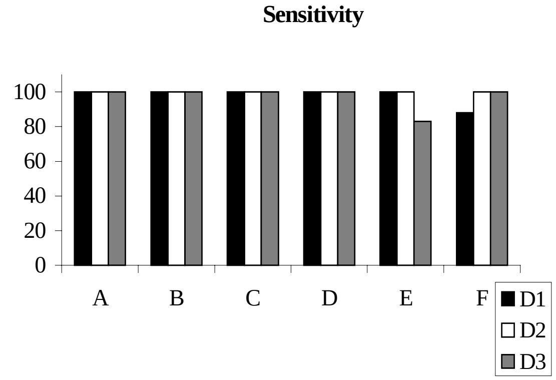


Figure 2: Sensitivity of TAP System.
Sensitivity data was summarized as the percentage of true positives for each diagonal sensor on each subject. Bars represent "diagonal" values (D_i) for each subject. Sensitivity was 100% for all subjects on at least two channels. Five or six data points were used in each case.

Dexterity Limits

Requested movements (3 subjects) consisted of individual finger taps and grasping. Subjects were asked to sustain signal movements for variable times, and to apply forces of low, intermediate and high intensity. Average frequency of tested tapping movements was 2.5 Hz. Subjects were able to sustain supra-threshold signals for up to 3 seconds.

Both grasping and sequential finger tapping were accomplished. When prompted to grasp an imaginary object at increasing levels of force, signal energy increased in approximate proportion to force perception and volition. Traces typical of 3 amputee subjects tested are shown below:

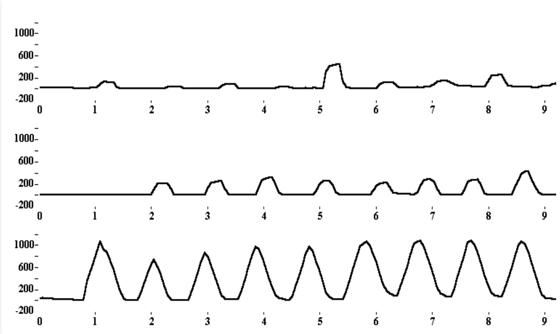


Figure 3: Proportional Control.
Subjects were prompted to grasp an imaginary object at increasing levels of force, subjectively determined. Signal energy increased in approximate proportion to force perception from low (top) to high (bottom).

DISCUSSION

The TAP hand offers amputees control of finger flexion using natural motor pathways. Most subjects, including those with relatively short and scarred residua, quickly gained control over several mechanical fingers. Slow typing and piano playing were demonstrated. Beyond providing dexterity, the TAP controller may facilitate the transition to more complete hand restorations.

Acknowledgements

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