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Cineplasty as a control input for externally powered prosthetic components

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Abstract—To achieve significant improvement in the function of electric-powered, upper-limb prostheses, we believe it is necessary to develop better control interfaces with inherent sensory feedback. Small cineplasties, or other surgical procedures that also externalize the force and excursion of a muscle, could potentially provide this superior control. Connecting a muscle to a prosthetic component via a controller that embodies the concept of extended physiological proprioception (EPP) would enable the physiological sensory feedback inherent in the skin, muscle, and other tissues of the cineplasty to inform the user of the state of the prosthesis. Multiple miniature forearm tunnel cineplasties, each with an EPP controller, might enable meaningful independent multifinger control of hand prostheses. At higher levels of amputation (e.g., transhumeral), small pectoral or deltoid cineplasties could augment existing control sources to improve control of multifunctional total arm prostheses. To explore the feasibility of these ideas, we quantified the control capabilities of individuals with preexisting biceps muscle tunnel cineplasties with the use of pursuit tracking experiments. A "proof-of-concept" EPP electric hand prosthesis was also successfully developed for a subject with agonist-antagonist, forearm tendon exteriorization cineplasties. The results of the tracking studies demonstrate numerically the efficacy of control by cineplastized muscles relative to other control approaches.

Key words: *cineplasty, EPP, extended physiological proprioception, kineplasty, muscle properties, prosthesis, pursuit tracking, transinformation, upper extremity.*

INTRODUCTION

The control of present day, externally powered prostheses is generally limited to sequential control of multiple joints for arm prostheses and to a single degree-of-freedom (opening-closing) of the hand replacement. Coordinated control of multifunctional prostheses requires more integrated control than is possible with myoelectricity. Although myoelectric control has been successful in many transradial fittings, this approach provides essentially no feedback to the user concerning the mechanical state of the hand components being controlled and has been used mainly in a velocity-control mode. We believe it is necessary to develop control

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interfaces with inherent sensory feedback if a significant improvement in the function of electric-powered, upper-limb prostheses is to be achieved.

We believe such interfaces can be achieved with additional surgical procedures in conjunction with physiologically appropriate, externally powered prosthesis controllers. Surgical procedures, such as the Vanghetti-Sauerbruch-Lebsche muscle tunnel cineplasty, or other surgical procedures, such as the tendon exteriorization cineplasty by Beasley (1), which externalize the force and excursion of a muscle or tendon, can provide this appropriate control. The Vanghetti-Sauerbruch-Lebsche muscle tunnel cineplasty is an evolution of the tendon “loops” and “clubs” originally advocated by Vanghetti (2–4), the muscle tunnel cineplasties advocated by Sauerbruch (5,6), and their later modification during World War II by Lebsche (7). The surgical procedure to create a Vanghetti-Sauerbruch-Lebsche muscle tunnel cineplasty was most recently described by Brückner (8).

Brückner and Thomas (9) have presented their experiences with the functional value of the Sauerbruch-Lebsche procedure. Brückner’s group, based in the former DDR (East Germany), created a total of 20 tunnels in 16 patients over a period of 6 years starting in 1988. The surgeons considered all but one of these tunnels to have been successful. They commented that the functional outcome (use of the prosthesis) was, however, dependent on the motivation and mental well-being of the patients. This was a finding that was deemed critical to the success of the procedure by others (10,11).

With the exception of Brückner and Beasley, few surgeons since Sauerbruch and Lebsche have systematically examined new ways to bring muscular forces outside the body. Surgical techniques have advanced enormously over the last 50 years, and we believe that direct or “almost-direct” connections that are simple, effective, and pleasing in appearance are possible if surgeons, engineers, prosthetists, and others work together collaboratively on this control problem.

The creation of control interfaces will require surgical revisions beyond the initial amputation surgery. Preservation of residual muscle tone, length, and excursion will be of paramount importance if future revisions are to be successful at creating novel physical, muscle-prosthesis interfaces. Myoplasty and/or myodesis might be performed at the time of initial amputation surgery to retain the ability of residual musculature to easily develop tension and reduce associated muscle atrophy. In myoplasty, agonist-antagonist residual muscle pairs are tied off against each other. In myodesis, the residual muscle is stitched to the bone. Myoplasty could be performed on the superficial residual muscles while myodesis could be used on the deep residual muscles.

Attaching the externalized muscle to a prosthetic component through a controller that embodies the concept of extended physiological proprioception (EPP) (12) allows the position, speed, and force of the controlling muscle to be directly correlated (in a one-to-one manner) to the position, speed, and force of the prosthetic component. The physiological sensory feedback inherent in the skin and muscle of the cineplasty informs the user of the state of the prosthesis in a somewhat subconscious and natural manner. Using the cineplastized muscle as a control input to an EPP controller provides a method of physically linking a skeletal muscle to an externally powered device.

In the case of an electrically powered prosthetic device, the cineplasty is only required to produce a control signal; the power needed to drive the prosthesis itself comes from the batteries. In addition, the controller is flexible enough to be adjusted to accept, as its control input, the range of force and excursion available from the amputee’s cineplastized muscle. In essence, this idea of EPP control of a prosthesis can be compared to power steering for a car. This means that even small muscles of the forearm or hand could be used effectively for prosthesis control.

For persons with long transradial amputations or wrist disarticulations, we envision multiple miniature tunnel cineplasties or exteriorized tendons, each with an EPP controller, providing coordinated, subconscious, independent multifinger control of a hand prosthesis. At higher levels, such as the short transhumeral or shoulder disarticulation level, small pectoral or deltoid tunnel cineplasties could augment existing control sources to improve control of multifunctional, total arm prostheses. We are currently involved in the development of a new microprocessor-based EPP controller (13,14) for use in this application.

The idea of using a muscle tunnel cineplasty to control an externally powered prosthesis is not new; reference is made to the idea in Spittler and Rosen (15) and in Kessler (16). In the discussion section of Spittler and Rosen’s paper, Spittler mentions being approached by members of the IBM team about the possibility of using cineplasties to actuate switches to control an electric arm. IBM had been contracted by the Committee on Artificial Limbs to develop the first electric arm prosthesis in the

United States. The idea is also suggested for investigation in Alldredge et al. (17).

More recently, Filatov and Voinova (18,19) reported on modifications to the cineplastic technique and the development of original operations for fastening and controlling externally powered prostheses. Their physiological studies led them to conclude that tunnel cineplasties were a reliable source of control. In the United States, Leal and Malone (20) reviewed an arm prosthesis they made using a Veterans Affairs/United States Manufacturing Corporation (VA/USMC) electric hand that was controlled by a transradial amputee with a biceps cineplasty.

In the fitting of high-level, upper-limb amputees, the current trend is to use hybrid systems that incorporate both body-powered and externally powered components. With the use of the superior features from each technology, the number of available control sites can be used to best effect. Pectoral or other tunnel cineplasties offer a means of creating greatly needed control sites at these higher levels of amputation. Marquardt (21) described a unilateral forequarter amputee who controlled an electromechanical hand and wrist rotator with a pectoral cineplasty in conjunction with sequential switch control. Lucke, Marquardt, and Carstens (22) discussed the indications for the use of a pectoral cineplasty for amputations in the region of the shoulder girdle and described how four functions could be obtained from one muscle with the use of a four-stage switch. Murphy (23) mentioned the idea of miniature tunnel cineplasties for the control of externally powered devices as a possibility. Childress (24) first proposed the use of miniature tunnel cineplasties in conjunction with EPP control.

Toward this goal of achieving independent, multifunctional control of upper-limb prostheses, we have performed studies to quantify the control capabilities of persons with preexisting cineplasties. In addition, we have developed and fitted a "proof-of-concept" EPP electric hand prosthesis that was controlled using preexisting exteriorized forearm tendon cineplastics.

METHODS

Quantification of Control Capabilities of Persons with Preexisting Biceps Cineplasties

Quantification of cineplasty performance was measured with the use of pursuit tracking experiments. We also recorded the mechanical properties for the muscle tunnel cineplasty of each subject by measuring the length and tension characteristics of the cineplastized muscle. The tracking abilities of three persons with biceps cineplasties were examined (25). Their cineplastic tracking ability was compared with their ability to track through biscapular abduction with the use of the harness and Bowden cables commonly used in body-powered prostheses (figure-of-nine harness). The subjects' tracking capabilities using their intact contra-lateral elbow was also measured.

In pursuit tracking tasks, a band-limited, Gaussian distributed, randomly moving "target" was displayed on a screen (the oscilloscope in **Figure 1**). The subject tried to maintain a "follower," which was under his control (the cineplasty in inset of **Figure 1**), superimposed on this moving target. Both target and follower paths were recorded and then compared during postprocessing. By modeling the human operator as an information channel with additive noise, we derived a measure (the transinformation rate) of how well the follower matched the target. This process was repeated for a number of target signals of differing bandwidth. The experimental procedure was similar to that used by Doubler and Childress (26) and can be found in Weir (25). See Results section.

The mechanical properties for cineplastized muscle of each subject were also obtained. These measurements were taken from isometric length-tension, isotonic load-excursion, and force-velocity relationships found for the cineplastized muscle of each subject (25). These relationships give an indication of the condition of the cineplastized muscle and are valuable for prosthesis design

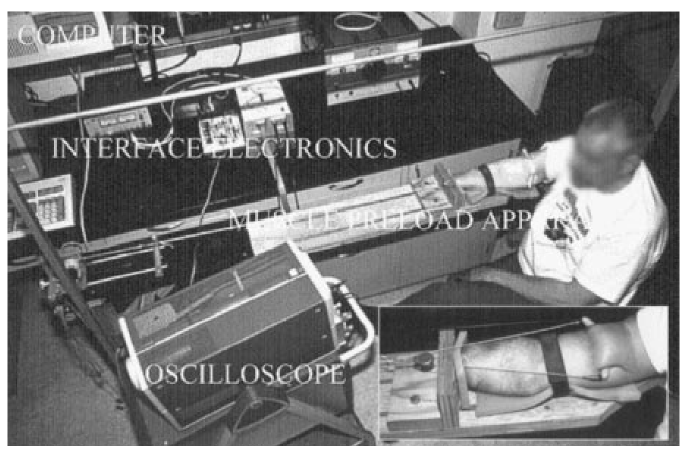

Figure 1.
Experimental setup used to quantify biceps muscle tunnel cineplasty control capabilities. The inset shows how the muscle tunnel cineplasty was interfaced to the apparatus.

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because they provide an idea of the range of forces, excursions, and velocities available for control inputs. The mechanical properties for each subject's cineplastized muscle are summarized in **Table 1**.

Development of an EPP Prosthesis with Direct Muscle Attachment

In anticipation of favorable quantification results and the potential advantages of direct muscle attachment, we developed, and subsequently fitted, a "proof-of-concept" prosthesis (27,28). An Otto Bock System Electric Hand (Otto Bock Healthcare, Duderstadt, Germany) was used. This hand was modified to incorporate a cable-actuated electronic EPP controller. These modifications take advantage of the inherent sensory apparatus of the tendons and muscles, as well as that of the skin lining the tendons. The prosthesis is controlled by pulling on cables that mechanically link the tendon loops to a force transducer mounted to the thumb in the hand (**Figures 2** and **3**). An electronic controller converts the force on the sensor into a drive signal for the hand mechanism. The position and speed of movement of the tendon (and the muscle) directly control the position and speed of movement of the fingers and thumb of the electric hand. Movement of the flexor tendon causes the hand to close a distance proportional to the shortening of the muscle. Movement of the extensor tendon causes the hand to open a distance proportional to the shortening of that muscle.

An experimental fitting (**Figure 3**) of this hand was performed on a subject with a transcarpal amputation of the right hand, for whom forearm tendon exteriorization cineplasties (1) had been performed (by Robert Beasley) 19 years before this study. The exteriorized tendons appear as skin-lined loops (**Figure 3a**), one on the ventral surface (flexor muscles) and one on the dorsal surface (extensor muscles) of the forearm. When the muscles associated with the tendons are contracted, the loops move a short distance proximally (toward the elbow). Each loop can be controlled independently of the other or both loops can be controlled simultaneously.

Although the subject had not used the tendons for prosthetic control for a number of years, he was able to demonstrate fair to good control of the prosthesis. The device was adjusted to operate with 6 mm of tendon excursion and with an actuation force of 225–500 g.

RESULTS

Quantification of Control Capabilities of Persons with Preexisting Biceps Cineplasties

Average results for pursuit tracking data obtained for three persons with biceps tunnel cineplasties are shown in **Figure 4**. The transinformation rate is a measure of tracking performance that varies with the bandwidth of the signal tracked. Essentially, the higher the transinformation rate, the better the tracking performance. The graph shows that tracking using the contralateral intact elbow is superior to tracking using either a tunnel cineplasty or a conventional figure-of-nine harness. However, the differences shown between the tracking performance with a cineplasty and an figure-of-nine harness are not statistically significant. The variability of the control with the use of the figure-of-nine harness is far greater than that associated with the tunnel cineplasty. This suggests that the control with the cineplasty is more consistent than that associated with a figure-of-nine harness.

We believe this result to be encouraging. It indicates that because control by tunnel cineplasty is on a par with current body-powered positioning methods, it is superior to velocity-control techniques: the techniques currently favored for commercially available myoelectrically controlled prostheses. Previous work (26) has shown the superiority of position control over velocity control in tracking tasks. Both tunnel cineplasty prosthesis control and cable-actuated prosthesis control are examples of position control.

The only other study to look at control using a cineplasty as opposed to a conventional harness was conducted by Mount and Bernberg (29) who found that control using a cineplasty was superior at discriminating the

Table 1.
The mechanical properties for each subject's biceps muscle tunnel cineplasty.

Subject	Maximum isometric tension (N)	Maximum speed of shortening (m/s)	Excursion of tunnel (mm)
1	163	0.37	47
2	129	0.58	50
3	127	0.54	53

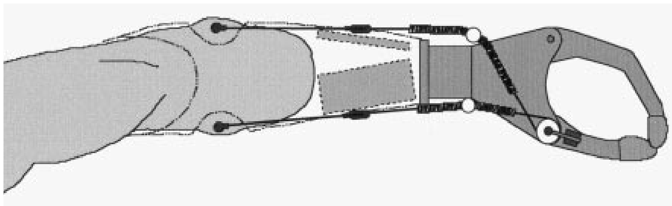
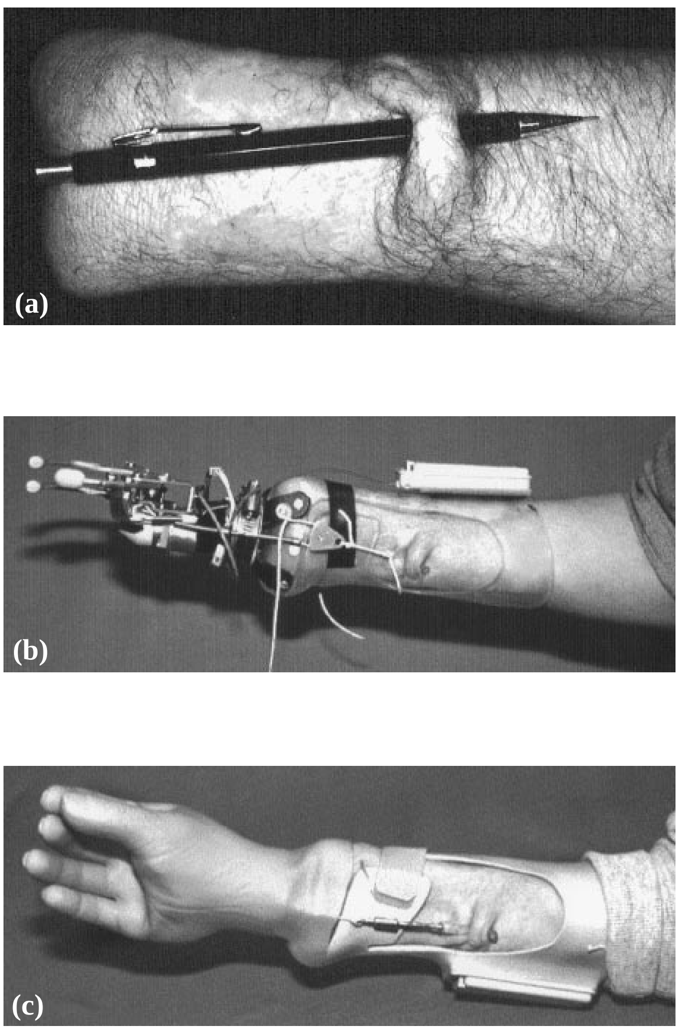


Figure 2.
Schematic of the modified Otto Bock Hand and how it could be interfaced for direct muscle attachment. This is an example of an "unbeatable" position servomechanism.



Figures 3.
(a) Picture of the subject's exteriorized tendon cineplasty showing a pen passing through the skin-lined tendon loop, **(b)** picture of a prototype version of the "proof-of-concept" prosthesis, and **(c)** picture of the finished "proof-of-concept" prosthesis.

shape of different objects grasped. The authors commented that this result could have been in part because of the practice of using voluntary closing terminal devices (Army Prosthetics Research Laboratory [APRL] hook and hand) with cineplasty prostheses as opposed to using voluntary-opening devices with harness-controlled prostheses of the day.

DISCUSSION AND CONCLUSIONS

A large body of data was obtained that characterizes human performance with the use of muscle tunnel cineplasties. The results show numerically the efficacy of control by cineplastized muscles relative to other control approaches. It was important to collect the human factors data on cineplasties at this time because the number of subjects available for such tests is declining rapidly in the United States. World War II veterans who had cineplasty procedures are generally in their seventies and the numbers of cineplasties done after the Korean and Vietnam wars were relatively small in number. Cineplasty procedures essentially ended in the United States about 1974 with the retirement of those surgeons who were the main proponents of the procedure and the rise of myoelectric control.

The first clinical fitting (to our knowledge) of a powered hand prosthesis, controlled directly by antagonist muscles (via exteriorized tendons) in a physiological manner, was accomplished. An electronic EPP controller was developed and incorporated with an Otto Bock adult electric hand. This was a new approach to control of upper-limb prostheses. Advantages of direct muscle attachment used in conjunction with EPP controllers are that it provides:

- Force and excursion amplification
- Additional control sources
- Freedom from proximal harnessing
- Natural feedback to the central nervous system
- The possibility of a meaningful multidigit control of hand prostheses
- Immunity from elctromagnetic interference.

We are currently exploring individual control of powered fingers and supplemental control at shoulder disarticulation prostheses through direct muscle interfaces. In addition, we are involved in trying to stimulate

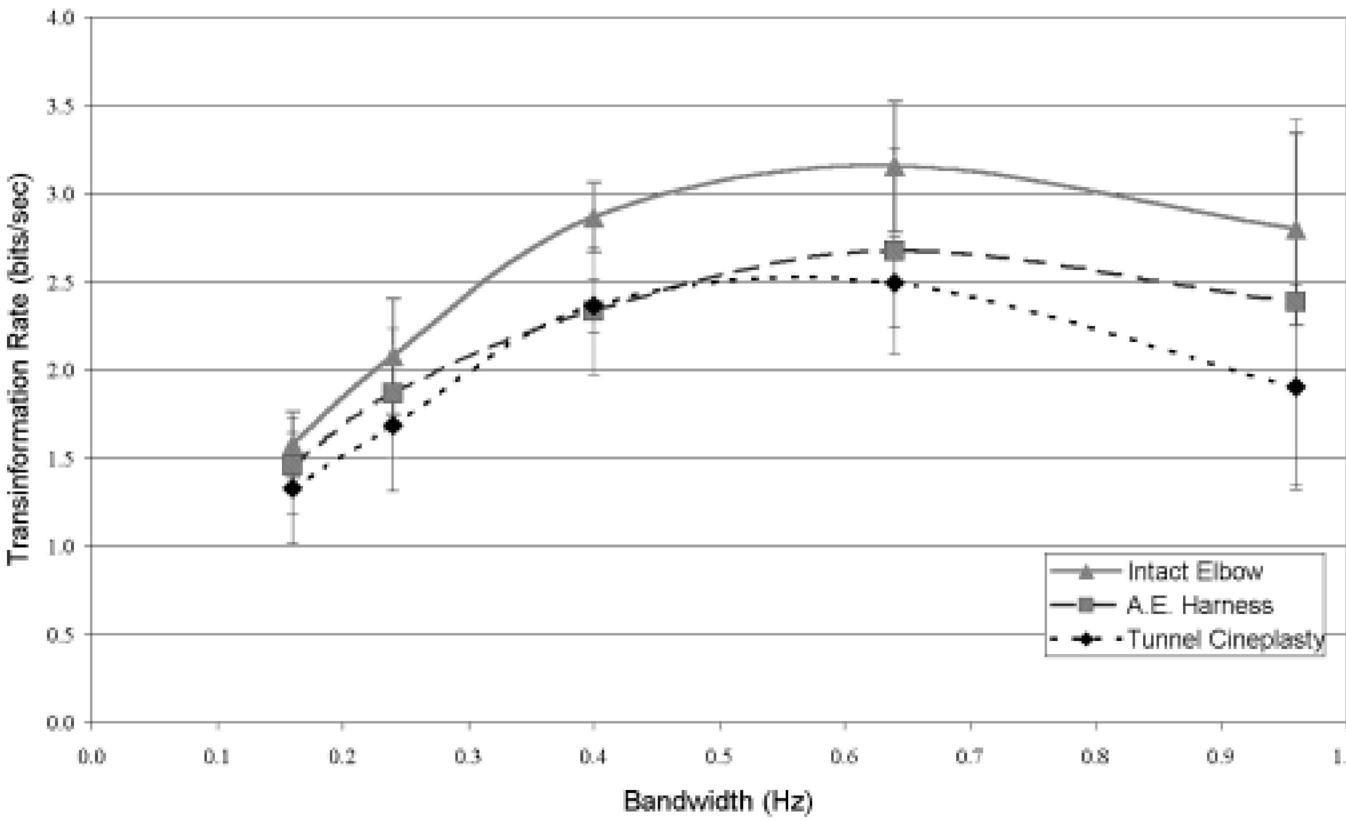


Figure 4.
Graph of mean transinformation rate versus bandwidth, for three subjects performing pursuit tracking experiments. It compares control with the use of their cineplasty *versus* a figure-of-nine control harness *versus* their intact contralateral elbow.

new ideas in surgery so that interface methods between muscles and prostheses might be improved.

Preservation of muscle tone, length, and excursion is of paramount importance if future surgery is to be successful at creating novel physical muscle-prosthesis interfaces. Myoplasty and/or myodesis procedures are probably important to ensure the ability to develop tension when voluntarily contracted. This would serve to preserve muscle tone and reduce muscle atrophy.

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