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Functionally Biarticular Control for Smart Prosthetics

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ABSTRACT

In this paper we introduce the use of force feedback in conjunction with myoelectric control to establish an improved interface for a powered prosthetic limb. The force feedback is delivered through a single-axis exoskeleton worn about the elbow, while the EMG signal is derived from the biceps muscle. This combination is intended to produce a sense of effort in the biceps that is associated with the action of the motorized prosthetic gripper. The method engages both efferent and afferent signals innervating a functional muscle with the aim of realizing a muscle that is effectively biarticular. The controlling muscle spans one joint physiologically and a second, prosthetic joint functionally. Preliminary experiments have demonstrated that force feedback can substitute for vision during grasp and lift tasks.

KEYWORDS: Myoelectric control, prosthetics, haptic feedback.

1 INTRODUCTION

New neural machine interfaces that furnish sensory feedback in lawful relationship with efferent motor commands could greatly improve voluntary control of externally powered upper limb prostheses. Supplying appropriate sensory feedback from mechatronic motion, force, and contact sensors embedded in the prosthesis would alleviate the need for constant visual tracking and enable purposeful, subconscious sensorimotor control by the user. We have developed a prototype system that uses myoelectric control from a functional muscle and provides multiple forms of sensory feedback in order to establish a "natural" interface to a motorized prosthetic limb. The sensory feedback includes tendon vibration and force feedback, which are intended to produce a sense of the movement and effort associated with the behavior of the driven prosthetic joint. Both the tendon vibration and force feedback are coupled to the same muscle from which the myoelectric signal is derived, thus providing a reflection of the reaction that arises in response to the action of the motorized myoelectrically derived command.

Sensory feedback regarding prosthesis configuration and environment interaction conditions is critical for the function and perceived ease of use of a prosthetic device [4,5]. Vision is the primary feedback modality in myoelectric prostheses, but vision generally makes a poor substitute for kinesthesia and proprioception. A user must visually monitor the opening of the prehensor and must look for deformation in grasped objects (when available) to get a sense of interaction forces. Amputees often prefer body-powered prostheses over myoelectric devices since body-powered designs provide force feedback by virtue of the direct mechanical interface between the shoulder harness and gripper joint [4]. Interaction forces developed at the gripper are transmitted through the Bowden cable to produce tension in the muscles of the shoulder girdle. To supplement vision, other forms of sensory substitution have been attempted, but they often fall short because users have difficulty associating sensations with their physical referents [5].

One principle among the tenets of prosthesis design is known as Extended Physiological Proprioception (EPP). When a prosthesis interface feeds back the mechanical response from the environment to the muscle that activated that response, then the brain seems to adopt that prosthesis as an extension of the body [4]. Body-powered designs, cineplasty, and new approaches based on nerve transfers owe their relative success to EPP. Also significant is an approach not yet explored in prostheses—tendon vibration, which induces a response in the muscle spindles that signal the brain that the muscle is lengthening. Perhaps the most promising technique involves directly stimulating afferent peripheral nerves using signals derived from the prosthesis [6]. However, to inform the development of direct interface (both to the peripheral and central nervous system), we must uncover the underlying principles that govern the brain's ability to adapt to and use new interface paradigms. These principles will also guide prosthesis development in the meantime, until direct interface is available.

2 DESIGN OVERVIEW

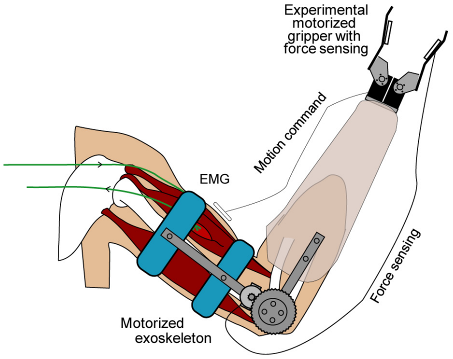
Our prototype device is designed to support experiments in which sensory feedback provided to subjects will be metered so that we may investigate the role of feedback and physiologic muscle force-length relationships for motor learning. We aim to explore a novel interface paradigm that embraces the tenets of efferent/afferent coupling and introduces related questions in motor learning. The central idea is built around transforming a uniarticular muscle on the residual limb into a muscle that is functionally biarticular, effectively spanning both the physiologic and a prosthetic joint.

By virtue of mechanical coupling through tendon and tissue, the length and force developed within a muscle is related to the displacement and loading of any joint that it spans. Myoelectric control for motorized prostheses is usually derived from a defunctionalized muscle wrapped around a residual limb, one that no longer spans a joint. In contrast to conventional myoelectric control, we will derive the myoelectric signal from a functional muscle. Figure 1 shows a schematic of the Biceps, Brachialis, and Triceps muscles. A myoelectric signal is picked up by an EMG sensor on the Biceps muscle. When the motor at the prosthetic gripper moves (under position or rate control) in response to myoelectric signals from the Biceps it may encounter resistance to further movement, as from a grasped object. The mechatronically sensed resistance to movement or reaction force will be used to command a torque about the elbow through the action of the motorized exoskeleton. The exoskeleton will thus load the Biceps muscle, effectively transmitting the load force from the grasped object. Insofar that the action was produced by the Biceps, the reaction should be applied to the Biceps.

The central nervous system will now have to adapt to the effective "tendon transfer", learning to use other bi and uniarticular muscles as synergists. Thus the new interface requires a user to re-learn the function of the muscle and to appropriately engage antagonist and synergist muscles to select among the motions of the physiologically and mechatronically spanned joints.

We have developed an experimental apparatus for able-bodied persons that incorporates myoelectric control and force feedback for opening and closing a gripper. The device includes dry EMG surface electrodes and torque feedback integrated into a small exoskeleton worn about the elbow. To support initial experiments, we have produced a suite of prototype devices using laser-cut wood and off-the-shelf electromagnetic motors. The gripper features a motorized single-joint thumb and finger, mounted in opposition to one another on a handle to be held with a power grip in the hand of the user (Figures 2, 3). A hobby servo (Dynamixel AX-12+) drives each joint under position control, employing a potentiometer and digital controller housed in the motor unit. An approximate reading of load force on a gripper joint is available by interrogating the proportional feedback error.

The exoskeleton design (Figure 2) is rendered in laser-cut wood. Secure and comfortable capture of the upper and lower arms is facilitated by a commercial elbow brace (Aircast, Mayo Clinic Elbow Brace). Torque about the elbow, reflecting interaction forces between the gripper and grasped objects, is produced by a geared motor (Maxon RE25, with a 5:1 gearhead) coupled through a capstan drive. The mechanical advantage associated with the capstan drive is 17, yielding a maximum torque of 6 Nm.



Our approach draws the EMG signal from a functional muscle (biceps shown) and uses an exoskeleton to backdrive the joint spanned by that muscle (elbow).

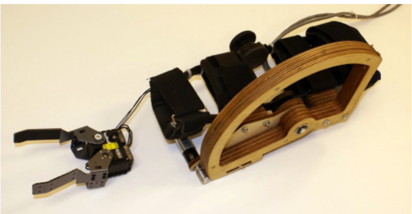


Figure 2. Hobby servomotors were used to develop the gripper while the elbow exoskeleton is based on a commercial elbow brace. A wooden capstan-driven outrigger to the brace generates the torque feedback.

Figure 3. An able-bodied user grips a soda bottle by activating his biceps muscle and feels the grip reaction force as a reaction torque about the elbow.

CONCLUSION

Providing sensory feedback that restores kinesthetic processing and gives the brain access to afferents in lawful relationship to efferents may enhance and accelerate learning of prosthetic use. There exists evidence that the human nervous system utilizes internal models of the body and of dynamical objects with which it interacts. The development of these models depends on the availability of rich sensory feedback which is lawfully related to the body's motor actions. Therefore, the lawful feedback provided by our system should facilitate the formation and/or adaptation of the human internal model that encompasses the attached prosthetic device. Further, the considerable evidence that sensory and motor areas of the brain are dynamically maintained and continuously modulated in response to activity, behavior, and skill acquisition [2,3] can be brought to bear on investigations of sensory processing. Practice can lead to an increase or decrease in activation in the brain areas involved in task performance and functional redistributions or reorganization of brain activity [1]. We believe that our novel motorized prosthetic interface presents a motor learning problem whose study might be used to develop directives for future neural machine interfaces. We are in the process of collecting pilot data using electroencephalography (EEG) and functional Near Infrared (fNIR) neural imaging techniques while subjects adapt to the presence of force feedback while performing grasp and lift tasks with our device.

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