A NOVEL METHOD FOR ACHIEVING DEXTEROUS, PROPORTIONAL PROSTHETIC CONTROL USING SONOMYOGRAPHY

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ABSTRACT

Although myoelectric upper limb prostheses have been commercially available for decades, many patients who receive these devices abandon them due to their limited functionality. Some of these functional limitations are related to the difficulties in sensing activity in different muscle compartments with surface electromyography. We believe it is possible to overcome the limitations of myoelectric control through use of sonomyography, or ultrasound-based sensing of muscle deformation. Sonomyography can better distinguish individual muscle activity and provides access to control signals that are directly proportional to muscle deformation, which has the potential to significantly improve prosthesis functionality. In this paper, we will describe our work towards developing a low-power wearable imaging system that will enable sonomyographically-controlled prostheses.

INTRODUCTION

Major upper limb loss affects more than 41,000 individuals in the United States alone [1] and can cause significant functional deficits. Despite recent advances in electromechanical design for prosthetic hands, development of control strategies has not kept pace. Surface electromyography (EMG) remains the predominant method for sensing muscle activity in order to actuate a prosthetic hand. As a result of the poor amplitude resolution and low signal-to-noise ratio [2], [3] for EMG signals, it can be challenging for prosthesis users to control a hand having more than one degree of freedom (DoF). More sophisticated signal processing algorithms relying on pattern recognition (e.g., [4]) can enable control of multiple DoFs but do not avoid the inherent problem of poor amplitude resolution. Alternative strategies such as targeted muscle reinnervation [5] or implanted electrodes [6] offer access to a richer set of control signals at the expense of surgical intervention and may not be tolerated by all individuals [7].

To address these problems, we propose the use of a different sensing modality based on ultrasound. Sonomyography (SMG), or ultrasound-based imaging of muscle contractions, is a non-invasive technique that can spatially resolve individual muscles with sub-millimeter precision. Other research groups (e.g., [8], [9]) have demonstrated that SMG is a viable option for classifying individual finger motion. We believe our group is the first to develop a low-power wearable imaging system for SMG that ultimately could be incorporated into a prosthesis socket, and demonstrate the ability of SMG to enable proportional positional control in amputee subjects. In this paper, we will describe our prior work in this area, present some new previously-unpublished results, as well as describe the anticipated directions for our future work.

BASICS OF SONOMYOGRAPHY

Sonomyography involves real-time ultrasound imaging of muscle contractions during voluntary movement. For different movements that the individual performs, a unique group of muscle compartments are activated and undergo mechanical deformation. Ultrasound images capture a spatially- and temporally-resolved view of the forearm muscle deformation over time as the users perform different motions (Figure 1A). Individual ultrasound scanlines can be visualized over time as M-mode images, which can be used to track deformation of specific muscle compartments (Figure 1B). By applying custom-developed image analysis and machine learning methods to these images, we can extract control signals and use them to drive a prosthetic hand (Figure 1C).

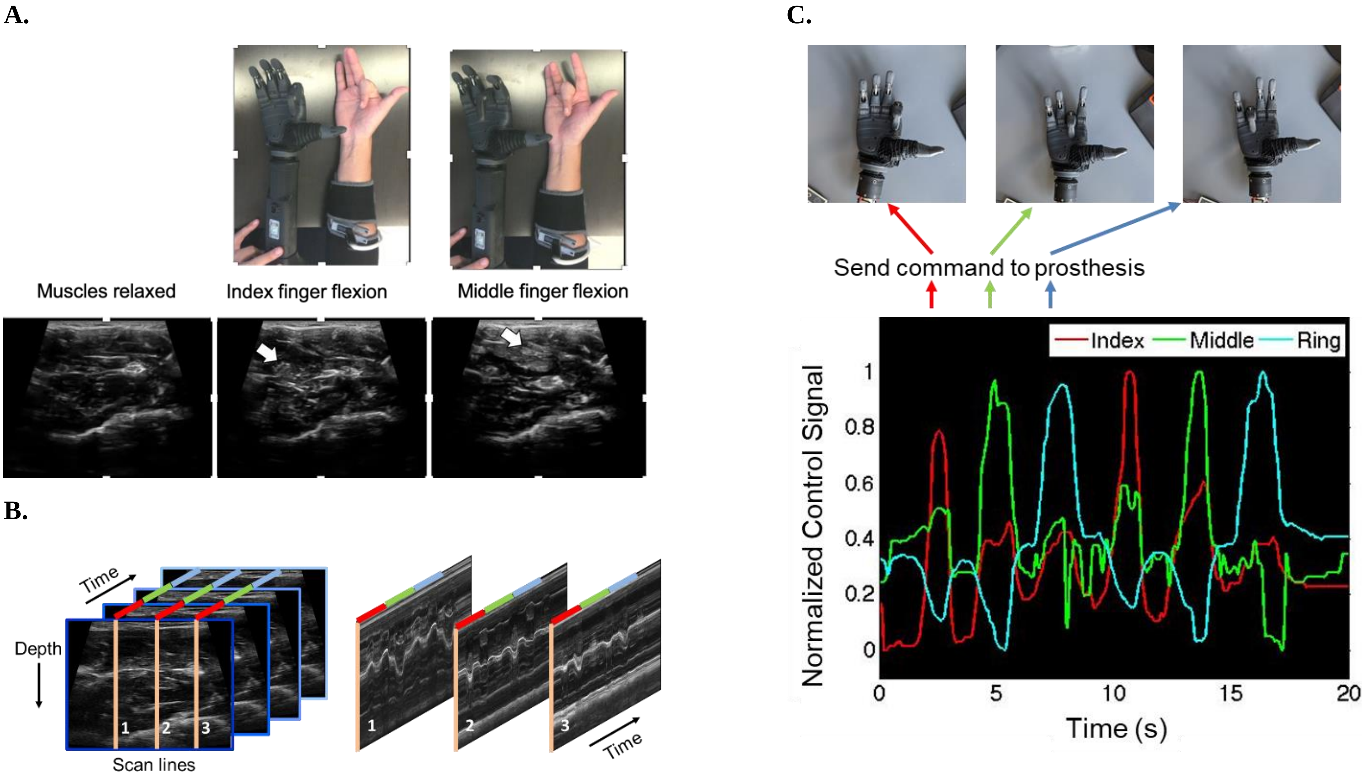

Figure 1. Schematic showing our approach to prosthetic control with SMG. (A) Muscle deformation over time is tracked with an ultrasound transducer placed on the forearm. The figure shows an able-bodied subject performing index finger flexion and middle finger flexion. The corresponding ultrasound images show different muscle compartments deforming for each movement. (B) M-mode images (depth over time) show deformation of different muscle compartments over time corresponding to individual finger movements (red, green, blue segments). (C) Control signals are extracted based on the muscle deformation associated with individual finger movements (red, green, blue traces) and are then mapped to movement of a prosthetic hand.

GRASP CLASSIFICATION USING SONOMYOGRAPHY

Ultrasound systems are becoming increasingly inexpensive and portable, and probes can now be connected to a laptop or smartphone through USB (e.g., Philips Lumify, Butterfly iQ, Mobisante). To demonstrate the feasibility of using these systems as part of a wearable prosthesis system, in a previous study, we recruited 10 able-bodied individuals and attached a handheld ultrasound probe to their forearm. Participants were asked to move each individual digit (thumb, index, middle, ring, little fingers) multiple times in sync with an auditory cue from a metronome. Activity pattern images corresponding to each movement were saved in a training database and were used to train a k-NN algorithm. Leave-one-out cross-validation revealed the offline classification accuracy to be 98.33%. We also demonstrated that ultrasound echogenicity changes proportionally in response to different levels of thumb flexion, showing the potential for achieving proportional digit control. Taken together, these results show that inexpensive handheld ultrasound probes are adequate for sensing and classifying muscle activity [10].

We have also explored the use of low-resolution binary activity patterns as features for classifying complex grasping gestures [11]. In a group of six able-bodied individuals, we demonstrated an average offline classification accuracy of 91% for 15 different grasps. Additionally, we showed that simultaneous wrist and hand movements (e.g., power grasp with wrist pronation) can be classified with > 90% accuracy. These results indicate that low-resolution imaging can be a viable option in a wearable ultrasound system.

As a step towards further reducing the instrumentation footprint, we investigated the effect of using a sparse set of ultrasound scanlines for gesture classification [12]. We recorded ultrasound images from the forearms of five able-bodied subjects performing five grasps (power grasp, pinch, index point, key grasp, wrist pronation) using a 128-element linear array transducer. We then selected different subsets of scanlines to quantify the extent to which classification accuracy was affected. Even with a subset of only four scanlines, classification accuracy was virtually unchanged (94 ± 6% for 128 scanlines, 94 ± 5% for 4 scanlines). This demonstrates the feasibility of using a small number of single-element transducers rather than a full array, which

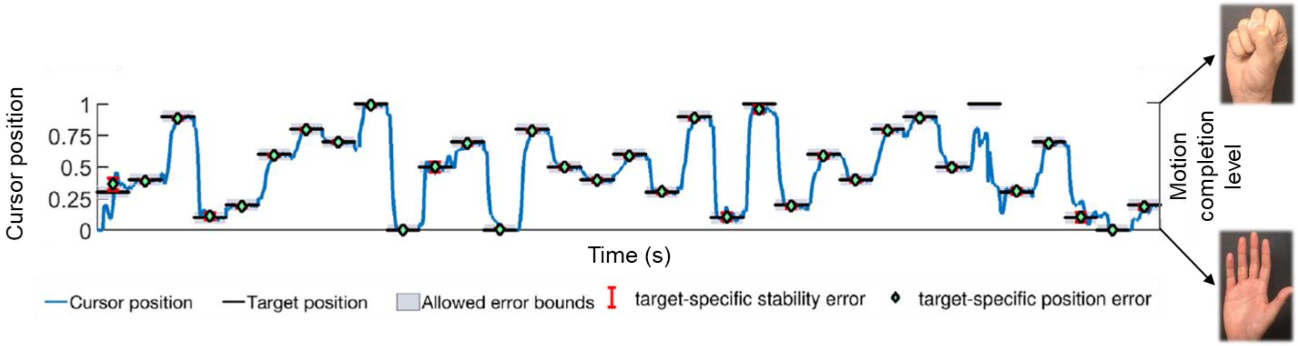

Figure 2. Representative time series plot showing an amputee performing the target acquisition task using power grasp. A cursor position of "0" corresponds to a fully relaxed state and a cursor position of "1" corresponds to motion completion.

simplifies the instrumentation that would need to be incorporated into a prosthesis socket.

SONOMYOGRAPHIC CONTROL IN AMPUTEES

Musculoskeletal anatomy can differ significantly between the forearm of an able-bodied individual and the residual limb of an individual with transradial limb loss. It is therefore important to demonstrate that our methods for classifying finger movements and complex grasps in able-bodied individuals are applicable to amputees as well.

We tested the ability of our system to distinguish between five different hand motions (power grasp, wrist pronation, tripod, key grasp, and point) in a group of five able-bodied controls and five transradial amputees. Average cross-validation accuracy was 100% for able-bodied controls and 96% for amputees, indicating that the system could reliably predict motions in both groups [13].

Having demonstrated that real-time classification of motion endpoints is possible in amputees, we next sought to implement an extended version of our algorithms that would enable proportional position control [13]. Participants were asked to perform a target acquisition task in which they manipulated a computer cursor that moved vertically in response to the degree of grasp completion (Figure 2). A series of targets were presented at 10 different levels of grasp completion and we quantified participants' ability to reach each target and stay within the target bounds. The task was repeated for each of the five hand motions. There were no differences in performance between groups, showing that sonomyography can enable proportional position control for both amputees and able-bodied individuals.

WEARABLE LOW-POWER ULTRASOUND SYSTEM FOR PROSTHETIC CONTROL

In our most recent work, we have developed a low-power ultrasound imaging system using a novel signalling method that uses low-voltage (5V peak to peak) transmissions. The system consists of a wearable band of 4 single element transducers (Figure 3) weighing less than 2 ounces, and benchtop instrumentation powered by a 7.4 V battery. This system consumes 350 mW/channel and provides comparable results to conventional pulse echo imaging and is well below FDA guidelines for acoustic exposure.

In a preliminary study (previously unpublished), we tested the performance of this system. All study procedures were approved by the George Mason University Institutional Review Board, and we obtained an abbreviated Investigational Device Exemption to test this system on human subjects. We recruited 5 able-bodied subjects, who were asked to perform 9 different motions: key grasp, pinch and power grasp in three different wrist orientations: supine, neutral and prone. The acquired data from the 4-channel system were then analysed offline to calculate the confusion matrix and classification accuracy. Our results show that the system can differentiate between 9 movements with 94.7% classification accuracy on average. The key grasp in supine position was the motion with the lowest classification accuracy overall.

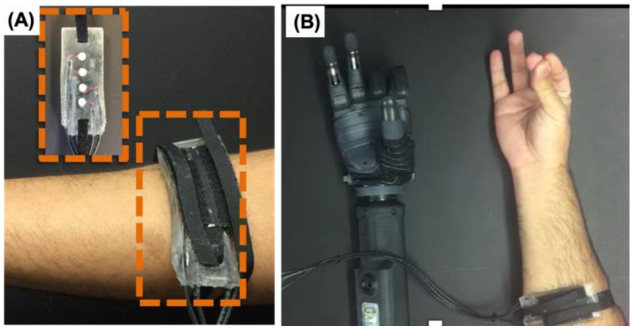

Figure 3. Wearable low-power 4-channel ultrasound system (A) for controlling a prosthetic hand (B).

DISCUSSION

We believe our research thus far demonstrates numerous advantages of SMG compared to EMG, making it a promising modality for restoring dexterous movement to individuals using upper limb prostheses. One of the primary benefits of SMG is that muscle activity can be sensed with high spatial specificity, even in deep-seated muscle compartments. As a result, cross-talk from muscles that are not associated with the intended movement is effectively suppressed. We have shown that SMG can classify five individual digit movements with 97% accuracy [10] and 15 complex grasps with 91% accuracy [11] in able-bodied individuals. Importantly, similarly high classification rates can also be achieved in transradial amputees [13]. It is also noteworthy that full-resolution ultrasound imaging is not required to achieve these outcomes. Classification accuracies are not affected even when a subset of only four ultrasound scanlines are used. Single-element transducers may be used instead of a full array, reducing the instrumentation required for implementing SMG control in a standalone prostheses.

Furthermore, the control signals derived from muscle activity using SMG have high signal to noise and are able to resolve sub-millimeter muscle deformations, so the resultant control signals enable finely-graded proportional positional control. We have demonstrated that individuals with transradial amputation can consistently achieve 10 different graded positions using SMG [13].

Unlike the control signals derived from EMG that must be mapped to velocity of a terminal device, the control signals from SMG can be mapped to position. This strategy is similar to natural motor control and doesn't involve learning a new strategy, which is required for conventional myoelectric control. We have shown that learning to use SMG requires minimal training. In fact, transradial amputees were able to achieve 96% classification accuracy for 5 grasps after only a few minutes of training time [13].

CONTINUING WORK

The majority of our work to date has been implemented in a benchtop setting. As a next step toward demonstrating the utility of SMG control, we are now working to translate our technology to a standalone research-grade prototype that can be integrated into a prosthetic socket. This will ultimately enable functional assessment in a laboratory setting.

There are several critical questions that still need to be addressed as part of our continuing work. First, it is necessary to demonstrate whether adequate signal quality can still be maintained when the transducers are integrated into a socket and used for long periods of time. We have shown that classification accuracy is robust to changes in arm and wrist position for able-bodied individuals [11], but it remains to be seen whether coupling between the residual limb and transducer will be affected by changes in arm position, sweating, or loading introduced by the socket and terminal device. In future studies, we plan to investigate this systematically. Additionally, we will explore the extent to which use of SMG contributes to functional improvements compared to EMG. In particular, we will test whether higher scores on standard clinical tests, improved quality of movement, greater patient-reported satisfaction, and reduced cognitive load can be achieved through use of SMG.

Despite these remaining questions, we believe our work demonstrates the feasibility of using SMG to achieve real-time proportional positional control with limited training. Importantly, these outcomes can be achieve using a low-power wearable imaging system for SMG that can incorporated into a prosthesis socket. We anticipate that this approach will ultimately enable intuitive proportional control of multi-articulated prosthetic hands and will contribute to improved acceptance of these devices.

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