Sonomyography Combined with Vibrotactile Feedback Enables Precise Target Acquisition Without Visual Feedback

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Abstract— **Upper limb prosthesis users currently lack haptic feedback from their terminal devices, which significantly limits their ability to meaningfully interact with their environment. Users therefore rely heavily on visual feedback when using terminal devices. Previously, it has been shown that force-related feedback from an end-effector or virtual environment can help the user minimize errors and improve performance. Currently, myoelectric control systems enable the user to control the velocity of terminal devices. We have developed a novel control method using ultrasound sensing, called sonomyography, that enables position control based on mechanical deformation of muscles. In this paper, we investigated whether the proprioceptive feedback from muscle deformation combined with vibrotactile haptic feedback can minimize the need for visual feedback. Able bodied subjects used sonomyography to control a virtual cursor, and performed a target acquisition task. The effect of visual and haptic feedback on performance of a target acquisition task was systematically tested. We found that subjects made large errors when they tried to reacquire a target without visual feedback, but in the presence of real-time haptic feedback, the precision of the target position improved, and were similar to when visual feedback was used for target acquisition. This result has implications for improving the performance of prosthetic control systems.**

I. INTRODUCTION

Upper limb amputation affects 600,000 individuals in the US [1]. Although approximately 35-45% of upper limb prosthesis users discontinue use of their prosthesis [2], 74% of those individuals would reconsider using a prosthesis if technological advancements were made to improve their usability [3]. Apart from problems with the physical attributes of the hand (weight, power consumption, etc.), clinical professionals working with prosthesis users rated lack of continuous proportional feedback of force and position as top priorities for future development of prosthetic hands [4].

Existing myoelectric prostheses are limited in their ability to provide multi-sensory feedback (visual, proprioceptive, and haptic) to the user. Thus, myoelectric prosthesis users are primarily reliant on visual feedback and must fixate their gaze on the prosthetic hand during task performance [5]. This is problematic when performing activities of daily living, as delays in processing the visual feedback contribute to difficulties in accurately controlling the prosthesis [6] and a higher cognitive load [7].

It has been shown that force-related feedback from an end-effector or virtual environment can help the user minimize errors and improve performance [8], [9], [10]. Users have also been shown to improve performance while controlling a prosthetic limb, if they are given haptic feedback proportional to the force being sensed by the hand during object manipulation [10]. Several types of haptic feedback have been investigated for such tasks, ranging from simple ON/OFF vibrotactile or skin stretch feedback, to more complex event-based neuromimetic feedback [11].

However, haptic feedback in myoelectric prostheses is typically delivered based on grip force of the end-effector, rather than its position. This is because myoelectric control does not provide reliable proportional position control due to the low signal-to-noise caused by random fluctuations in the surface electromyography (sEMG) signal [12] and low specificity between individual muscles resulting from cross talk [13]. To compensate for these problems, myoelectric systems control the velocity of the terminal device based on muscle contraction level. As a result, the proprioceptive feedback from the residual muscles is not congruent with the visual feedback of the position of the end effector. This makes it particularly challenging to accomplish tasks requiring precise manipulation and wrist rotation.

Previously, our laboratory developed a proportional positional control paradigm using ultrasound sensing (sonomyography) [14]. Through continuous recording of ultrasound cross-sectional images of the forearm, participants with and without limb loss were able to control a virtual cursor's position just by flexing their forearm muscles to the desired extent. We have shown in prior work that there exist large errors when subjects are asked to reacquire a presented target by proportionally flexing their muscles, without visual feedback of the cursor or their own hand [15]. In this current work, we investigated whether the precision of the cursor position can be improved by adding real-time proportional haptic feedback based on the position of the cursor. We hypothesized that the errors between the user controlled cursor and the presented target would decrease after addition of haptic feedback but in the absence of visual feedback.

II. MATERIALS AND METHODS

A total of 5 able-bodied young adult participants, ages 19-22 years, volunteered for the experiment. Participants were compensated for their time, and all subjects gave written consent. All study procedures were approved by the George Mason University Institutional Review Board.

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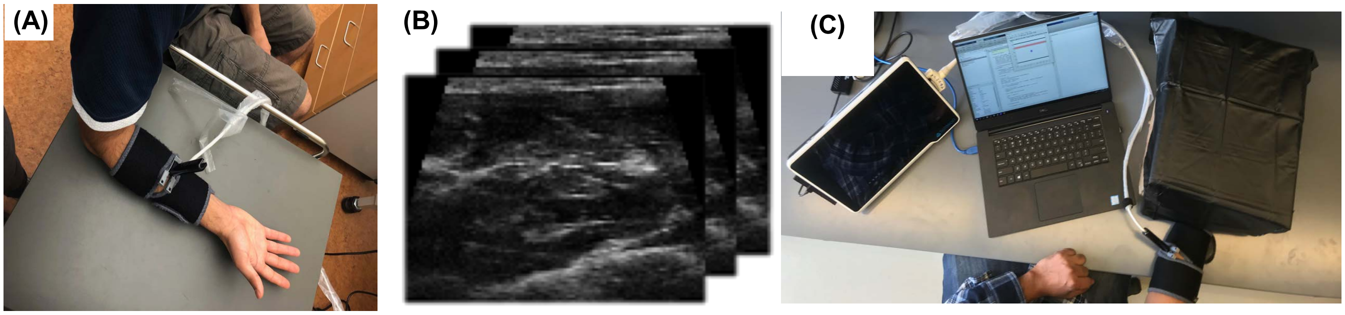


Fig. 1: (A) Ultrasound transducer strapped onto the volar aspect of the subjects' forearm and connected to a clinical ultrasound system (B) Cross-sectional ultrasound image sequences are continuously recorded from the forearm and used by the algorithm to derive a proportional signal for controlling the cursor. (C) User's arm is instrumented with an ultrasound transducer and the hand is kept inside an opaque enclosure while the subject is controlling a cursor on a computer screen.

The apparatus consisted of a low-profile, high-frequency, linear, 16HL7 ultrasound transducer strapped onto the volar aspect of the subjects' forearm with a stretchable cuff (Figure 1A) and connected to a clinical ultrasound system (Terason uSmart 3200T, Teratech Corporation, Burlington, MA). Each subjects' hand was placed inside an opaque enclosure that prevented direct observation of hand movements below the elbow (Figure 1C). Ultrasound image sequences from the clinical ultrasound system (Figure 1B) were acquired using a video grabber (DVI2USB 3.0, Epiphan Systems, Inc.) and processed using a custom-developed MATLAB script (The MathWorks, Inc., Natick, MA).

The vibrotactile haptic feedback was delivered on the subject's bicep using a 10mm vibrating mini motor disc (Adafruit, ID: 1201, New York) paired with a brushed DC motor driver carrier (Pololu, DRV8838, Nevada). The motor and the drivers were interfaced with an Adafruit Feather M0 board microprocessor (Adafruit, ID: 3061, NY) which was paired with a Featherwing Proto board extension (Adafruit, ID: 2884, New York). Serial communication was used to interface the microprocessor with a computer.

In this experiment, the subjects controlled the height of a cursor on a screen in front of them by proportionally flexing their forearm muscles to the appropriate level. Ultrasound cross-sectional images were continuously recorded from the users' forearm and used by the algorithm to derive a proportional control signal. The cursor moved up when they flexed their muscles and it moved down when the muscles were relaxed.

Three equispaced target positions (at 25%, 50% and 75% of motion completion) were presented to the subjects, 3 times each. They were first asked to acquire the target (reach the target and be within $\pm$ 5% of the target for 3 seconds continuously), and then hold at that position (hold the position for 10 seconds). The order of target positions and feedback conditions were randomized

Three conditions were tested as the subject was performing the task:

1) Visual and proprioceptive feedback (V+P): In this condition, subjects had visual feedback of the cursor position at all times as well as proprioceptive feedback of the level of muscle contraction. Subjects were asked to acquire the target and hold at the target for 10 seconds.

2) Proprioceptive feedback only (P): In this condition, once the target was acquired with visual feedback of the cursor, the screen went blank and the subject was asked to hold at the target position for 10 seconds, using only their sense of proprioception. In the next trial, visual feedback was turned back on, and once the target was acquired with visual feedback of the cursor, the screen went blank and the subjects were asked to go back to rest. They were then asked to acquire the same target, but this time without any visual feedback, using only their proprioceptive sense of the previously acquired target.

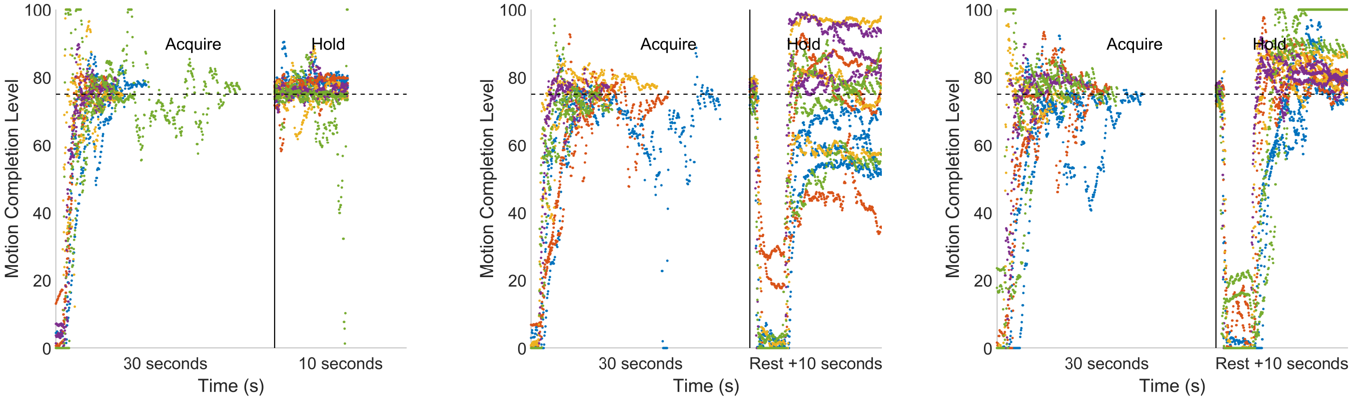
3) Proprioceptive and haptic feedback (P+H): In this condition, the tasks described in the "P" condition above were repeated but haptic feedback was turned on. Before the experiment, the minimum and maximum vibration levels were calibrated for each subject. While performing the task, there was no vibration as long as the subjects' cursor was below the target. At the target, the vibration was turned on at the minimum level. As the cursor moved higher than the target, a increasing level of vibration was delivered, proportional to the distance of the cursor from the target.

For each of these conditions, we quantified the bias in the cursor position (average signed difference between target and cursor) and the precision (standard deviation of the average cursor position between trials) for target acquisition and the target holding stability (standard deviation of the cursor position with time) was quantified for each subject.

Separate one-way ANOVAs were performed to test the effect of feedback condition (visual+proprioceptive, proprioceptive only, proprioceptive + haptic) on acquisition bias, acquisition precision, and holding stability. Post-hoc comparisons were performed with Tukey's HSD test. Significance for all comparisons was set at α = 0.05.

III. RESULTS

There was a statistically significant difference between feedback conditions for acquisition bias as determined by the one-way ANOVA (p = 0.0241). Posthoc tests revealed



(a) Visual + proprioception (b) Proprioception (c) Proprioception + haptics

Fig. 2: Real-time traces of subjects' cursor position. The traces before 30 seconds represent the target acquisition segment. The traces over the next 10 seconds represent the three conditions: (a)visual + proprioception, (b) proprioception only, and (c) proprioception + haptics. Each color represents a different subject. All the traces show the data acquired when the presented target was at 75% motion completion.

there was a significant difference (p = 0.022) between 'P' (Fig. 2b) and 'P+H' (Fig. 2c). The average acquisition bias for 'P' (-2.14 ± 6.44) was lower than for 'P+H' (7.40 ± 5.32), see Table I.

There was a statistically significant difference between feedback conditions for acquisition precision as determined by the one-way ANOVA ($p < 0.001$). Posthoc tests revealed there was a significant difference ($p < 0.001$) between 'V+P' (Fig. 2a) and 'P', as well as between 'P' and 'P+H' ($p < 0.001$). The average acquisition precision was lowest for 'V+P' (1.91 ± 0.47) compared to 'P' (11.41 ± 1.88). The average acquisition precision improved for 'P+H' (4.09 ± 1.95) compared to 'P' (11.41 ± 1.88).

There was a non-significant difference between feedback conditions for holding stability as determined by the one-way ANOVA, p = 0.1355. The average holding stability for 'V+P' (1.15 ± 0.56) was lowest, but comparable to holding stability for 'P' (1.82 ± 0.35). In the 'P+H' condition, the stability was slightly worse (2.17 ± 1.11), with more variability between subjects.

IV. DISCUSSION

In the current experiment, we implemented a virtual target acquisition task in which the cursor position was manipulated through sonomyographic control. Sonomyographyh relies on mechanical deformation of muscles to control the position, and therefore, we believe that this control method is congruent with the proprioceptive feedback from muscles. In previous work, we have shown that prosthesis users can utilize sonomyographic control to robustly control a virtual cursor as well as a terminal device [14]. We have also shown in prior work [15] that proprioception alone is not enough to compensate for lack of visual feedback. In this study, we evaluated whether the combination of sonomyography and vibrotactile haptic feedback can minimize the reliance on visual feedback.

Our main finding is that adding haptic feedback significantly improves the precision of position control without any visual feedback. In our study design, we provided haptic feedback only after the subject exceeded the target height. This inherently introduced a positive bias, which was borne out in our results as well. The bias was highly variable among subjects, which indicates that some subjects are more sensitive to the variation of the level of vibrotactile feedback than others. However, precision of all 5 subjects improved and reached a level just slightly higher than the condition with visual feedback. There was no significant difference in holding stability by adding haptics, as subjects were able to rely on their proprioceptive sense to hold a target position with low stability error not significantly different from when visual feedback was present.

This study was limited by a small sample size. Thus,

TABLE I: Acquisition bias, acquisition precision, and holding stability for all subjects

	Acquisition Bias			**Acquisition Precision**			**Holding Stability**		
Subject #	V+P	P	P+H	V+P	P	P+H	V+P	P	P+H
1	0.87	-11.6	0.4	1.69	8.99	1.33	1.45	1.51	1.4
2	1.47	-5.12	7.16	1.87	10.83	3.09	0.96	2.12	2.26
3	-0.17	4.23	6.6	1.28	11.3	4.24	0.98	2.26	2.36
4	-0.11	3.02	7.48	2.26	11.75	5.93	0.45	1.48	0.97
5	0.68	-1.25	15.39	2.49	14.22	5.89	1.94	1.74	3.87
Pooled	0.54±0.69	-2.14±6.44	7.40±5.32	1.91±0.47	11.41±1.88	4.09±1.95	1.15±0.56	1.82±0.35	2.17±1.11

future work should assess whether the trends reported here continue to exist in a larger sample. Additionally, we will explore more efficient and reproducible methods for setting the maximum and minimum vibration levels for each subject (for example, [16]), which could help account for differences in sensitivity to vibration between subjects. Future experiments will investigate whether event-based haptic feedback to prosthesis users while they are using a physical prosthetic hand can lead to less reliance on visual feedback and lower cognitive load.

V. CONCLUSION

In this study, we investigated the role of visual, proprioceptive and haptic feedback for cursor control tasks using sonomyography. Our results show that adding haptic feedback enables able bodied subjects to control a cursor position with high precision even without visual feedback. These results can have implications for improving the intuitiveness of prosthetic control systems using sonomyography.

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