A Mixed-Reality Training Environment for Upper Limb Prosthesis Control

Avinash Sharma*, Christopher L. Hunt*, Asheesh Maheshwari‡, Luke Osborn*,
György Lévay§, Rahul R. Kaliki§, Alcimar B. Soares¶, and Nitish Thakor*‖
*Department of Biomedical Engineering, Johns Hopkins University, Baltimore, MD 21218 USA
‡Department of Biomedical Engineering, Vellore Institute of Technology, India
§Infinite Biomedical Technologies, LLC, Baltimore, MD 21218 USA
¶Department of Electrical Engineering, Biomedical Engineering Lab, Federal University of Uberlândia, Brazil
‖Singapore Institute for Neurotechnology, National University of Singapore, 119077 Singapore
Email: avinash@jhmi.edu

***Abstract*—Adjusting to an amputation can often times be difficult for the body. Post-surgery, amputees not only have to incur expensive rehabilitation treatment costs, but also have to wait for up to several months before receiving a properly fitted prosthesis. We developed a mixed-reality training environment where amputees can train, at their own time and convenience, and interact with holographic objects, while also receiving tactile and proprioceptive feedback. We incorporate positional information through inertial sensors, touch and proprioception information through vibrational feedback, all integrated into an augmented-reality (AR) environment viewed through the Microsoft HoloLens™. Training tasks were designed to account for limb rotation and object relocation in a three-dimensional space with a correct palm orientation essential for an intuitive grasp and release of objects. Our results showed an improved performance in training time, overshoot and completion rate with vibratory feedback (of both touch and proprioception) over without feedback. Furthermore, EMG activity was analyzed to estimate the muscular effort during each task.**

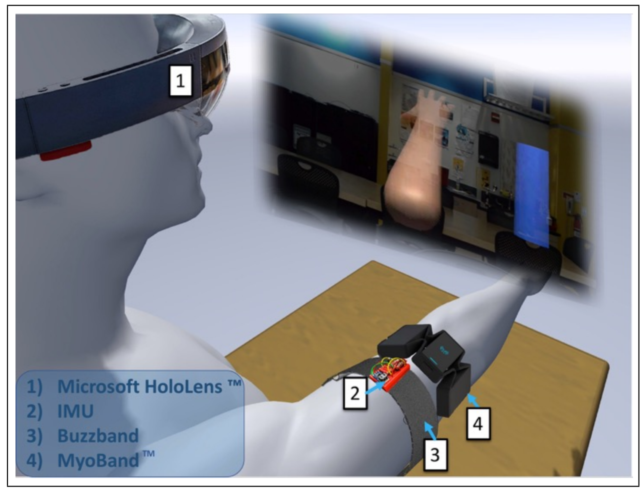

Figure 1. The mixed-reality setup with 1) Microsoft HoloLens™ for AR environment display, 2) Inertial Measurement Units (IMUs) for augmented limb control, 3) a proprioceptive armband for limb position feedback, 4) Myo™ armband for touch feedback. A perspective of the user is also shown in the figure.

I. Introduction

While prosthesis technology has improved on several fronts in the past few decades, their abandonment rates still remain high at about 35% [1]. This suggests that there is a disconnect between the efficacy of prosthesis technology and its utility. From the time of amputation to the first prosthesis fitting, an amputee has to wait for an average of 165 days, with no functional prosthesis training during this time [2]. Early prosthesis fitting has been shown to increase prosthesis adherence; however, it is patient-specific and usually applicable to certain types of amputations [2]. With delayed fitting, amputees often feel their use of prosthesis as unnatural and troubling [2].

On the technology front, extensive research is currently being done on building a closed-loop control system through sensory feedback and substitution [3]. Sensory substitution is primarily aimed at replacing the lost sensory function through a pathway that both senses relevant external information and also feeds it to the amputee. In a 2012 survey, about 88% of upper limb prosthesis respondents realized the need for sensory substitution in various degrees [4]. Contact grip and proprioceptive information were voted most important, with the first contact during grasp and the end of contact duringrelease of an object as useful information for object manipulation. When naturally grasping objects, mechanoreceptors send tactile information to the brain, which enables proper perception and interaction with objects [5]. Mechanical vibration on the upper limb stump when reinforced with a visual feedback through a virtual limb has been shown to stimulate the sensory-motor centers in the cortex [6]. Proprioception is another important type of feedback that is lost after amputation with amputees relying mostly on visual cues. Proprioceptive feedback along with visual cues have been shown to improve adherence rates and ease of use of prostheses [7].

Based on the issues and needs mentioned above, we devised a training environment for upper limb amputees that is portable, affordable, and incorporates sensory substitution for touch and proprioception in a mixed-reality environment (Fig. 1). Vibrational feedback was provided to both give a sense of contact of the augmented limb with holographic objects and also assist users in achieving the correct limb orientation for grasping/releasing objects. As proprioceptive feedback is another useful piece of information for amputees, we designed a vibrational armband — a proprioceptive band, to provide information about the position of the augmented limb in space. It consists of a set of four vibrational motors that wraps around the user's limb.

Several augmented and virtual reality (AR and VR) training systems have been developed in the past for stroke rehabilitation [8]. In this work, we present an upper limb prosthesis training system that incorporates sensory substitution for touch and proprioception in an AR environment. In the following section we describe the hardware setup and the experiments conducted to gauge the performance of the system and finally present the results.

II. Methods & Experiment

For the purpose of testing and evaluation, two able-bodied volunteers served as subjects and the experiment was conducted with their informed consent. The experiment protocol was approved by the Johns Hopkins Medicine Institutional Review Board. The setup was comprised of 1) sensors, to both record biosignals and provide sensory substitution feedback for touch and proprioception and 2) a Microsoft HoloLens™ based AR environment to allow manipulation of holographic objects with an augmented limb.

A. Augmented Reality Environment

The environment was designed as a modified version of the Prosthetic Hand Assessment Measure (PHAM) setup [9]. The scene comprised of a first person view of an augmented limb which, was projected through the Microsoft HoloLens™ (Fig. 2). Holographic 3D objects, in the shape of a cylinder, appeared at a reachable distance from the subject's augmented limb at different locations and orientations. There were primarily two types of objects in the scene - target and goal object. Target object (in blue) appeared at the beginning of a task and corresponded to the object that needed to be picked up. Goal object (in green) appeared only after the target object was picked up and denoted the region where the target object had to dropped. A visual display (in red text) provided positional information of the augmented limb in space, relative to the subject. This reinforced subjects' proprioceptive feedback with the visual feedback to facilitate learning based on the work shown in [7]. Furthermore, to provide motivation to the subject, a score ticker (in green text) displayed the number of times the subject was able to complete the task within 10 s in the previous 4 tasks.

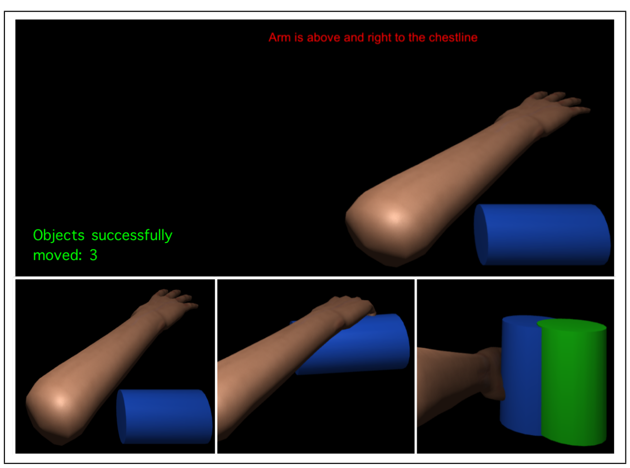

Figure 2. [Top] Scene with the augmented limb, score ticker (bottom left in green) and limb position display (top in red), [Left] limb reaching for target object (in blue), [Center] grasp to pick and move target object, [Right] dropping target object on the goal object (in green). During pick and drop the hand was required to be oriented to the surface normal of the objects. For clarity we show the scene on a dark background in this figure.

B. Hardware and Sensors

1) Inertial Sensors: Orientation of the augmented limb relative to the subject's limb position was calculated with two 9-axis MPU9250 (InvenSense, San Jose, CA) inertial measurement units (IMUs), one placed on the bicep and the other placed on the shoulder. The shoulder IMU was used as the reference node. In order to maintain inter-subject consistency, calibration was performed at the beginning of training routine. Relative orientation was recorded for the first 10 s while the subject kept their limbs fully extended to the sides of their trunk. With a Bluetooth Low Energy (BLE) adapter connected with each IMU, inertial data was streamed wirelessly to the Microsoft HoloLens™ through a User Datagram Protocol (UDP) server.

2) Vibrotactile Feedback: The information of touch or contact of the augmented limb with the holographic objects was conveyed through vibrotactile feedback with a gentle vibration provided by the Myo™ armband (Thalmic Labs, Canada). A stronger vibration (of a higher amplitude) was provided to the subject if the limb was oriented to the surface normal of the target/goal object and was within its close proximity. This was to assist the subject in object grasp and release.

3) Proprioceptive Feedback: Positional information of the augmented limb was conveyed with a custom vibratory armband that was developed for this purpose. The armband has four vibrating motors that actuate, in combination, to provide subjects a proprioceptive feedback of the location of the augmented limb in front of them. The stimulus frequency is 12 Hz with the feedback application time being pulse width modulated with a center frequency of 10 Hz. The positional information was received from the IMUs and transmitted wirelessly to a battery powered Arduino Mini that was used to drive the four vibrating motors. The vibratory armband was placed at the distal end of the bicep, as vibration at this region has been shown to induce strong illusionary movements [10]. However, in our experiment, the users didn't perceive illusory movements, rather they relied on the vibrational information as a substitution for limb position.

4) EMG Sensor and Classifier: Myoelectric decoding was incorporated to record subject's intent of grasp and release of the augmented limb. A Myo™ armband was placed at the proximal end of forearm which was used to record and classify EMG signals into three-classes (hand rest, open and close). EMG data was streamed from the armband at 200 Hz and

Table I
FEATURE PARAMETERS OF TASKS

Task No.	1	2	3	4	5	6	7	8
d_0	-1	-1	-1	-1	1	1	1	1
Δd	0	-1	0	-1	0	0	1	1
$\Delta\theta$	0	0	1	1	0	1	0	1

was used for both hand classification and muscular activity estimation.

C. Experiment

The entire experiment was divided into two modules - 1) with tactile and proprioceptive feedback, and 2) without either feedbacks. Each module was split into three trial sets, with each trial set consisting of 8 set of tasks (Table 1). These tasks required the subject to manipulate the augmented limb; pick a target object and drop it on the goal object. A total of 48 tasks were performed, 24 with feedback and 24 without feedback, randomly conducted without notifying the subject. Each of the eight tasks in each trial set was unique and was designed keeping in mind the positional and rotational effect of the limb during training. A task $T(d_0, \Delta d, \Delta\theta)$ was parameterized by three features - 1) initial position (d_0) of the target object with respect to subject's chestline (above or below), 2) relative 2-D position (Δd) and 3) relative angular position ($\Delta\theta$) of the goal object with respect to the target object. Initial position of the target object determines if the target object was below (d_0 = -1) or above (d_0 = 1) the subject's chestline. Relative 2-D position determines whether the object has to be moved vertically ($\Delta d = -1$), diagonally ($\Delta d = 1$) or along the same level ($\Delta d = 0$) from the target position while the relative angular position describes the orientation of the goal object with respect to the target object and whether the user would be required to rotate the augmented limb clockwise/anticlockwise ($\Delta\theta = 1$) or maintain the orientation ($\Delta\theta = 0$).

The goal of the experiment was to show the feasibility of our AR training system with the effects of feedback (vibrotactile and proprioceptive) on the performance of object manipulation. A target object was gripped by the augmented hand if and only if the limb was orientated in a manner such that the hand faced the surface normal of the object (Fig. 2). During the movement of the target object towards the goal object the subject was required to continuously keep the hand in the closed position. In case the object was dropped during the task, the target object had to be picked up again from its original position.

For comparison, four performance metrics were used - 1) time, 2) normalized integrated muscular effort, 3) overshoot and 4) completion rate. While the subjects were allowed to perform the task at their own pace, time taken for each task was recorded by the system for later performance evaluation. Muscular effort during a task was estimated from raw EMG signal based on the technique described in [11] . The method estimates the envelope of the EMG signal. The area under the envelope is integrated to get the estimated integrated muscular effort. For comparison, we normalized the efforts with the peak value. Overshoot was defined as the number of times the augmented limb made contact with the target or goal object while failing to pick or drop the object due to misalignment of the palm with the object's surface normal. Completion rate was defined as the fraction of tasks in a trial set that were performed within 10 s.

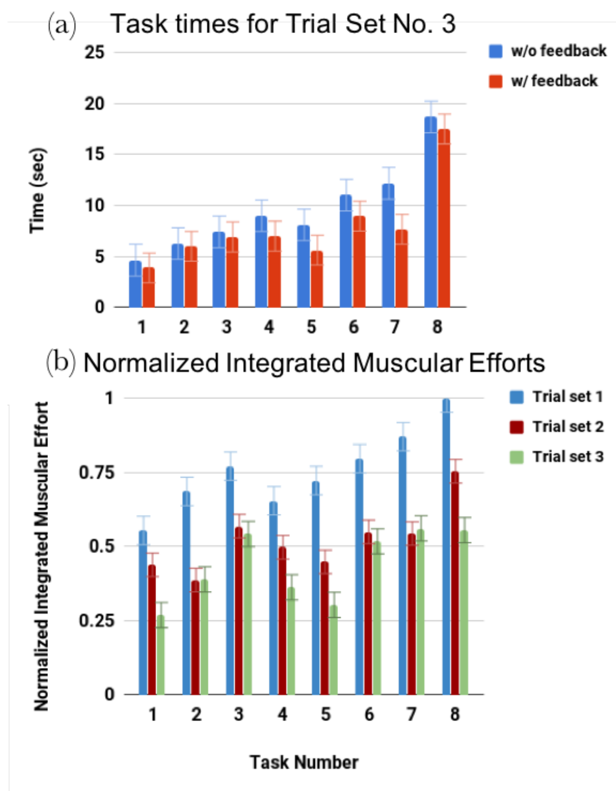

Figure 3. (a) Task time comparison for trial set 3, with and without feedback (both vibrotactile and proprioceptive), (b) normalized integrated muscular effort estimated from EMG signals and averaged across both modules for each task. The error bars represent the standard error of mean.

III. RESULTS

Average of the performances across all subjects are reported. In Fig. 3a. we compared the time performance for each task in the last trial set (Trial 3). On average, task times were shorter or comparable across all tasks with feedback. Across the three trials conducted for each subject, the best times were achieved in the last trial (Fig. 4a) with 7.79% and 31.30% reduction in time between the first and the last in the corresponding modules (with and without feedback). Overall, there was an average time reduction of 18.01% with the highest time reduction of 37.14% which was recorded for task no. 7. The integrated muscular effort over both modules is shown in Fig. 3b. There was a general decline in the effort over subsequent trial sets. Furthermore, we observed an increased likelihood for overshooting without feedback (Fig. 4b). With feedback however, there was a substantial reduction in the tendency to overshoot while picking and dropping objects in the correct orientation. Completion rates (Fig. 4c) were comparable within

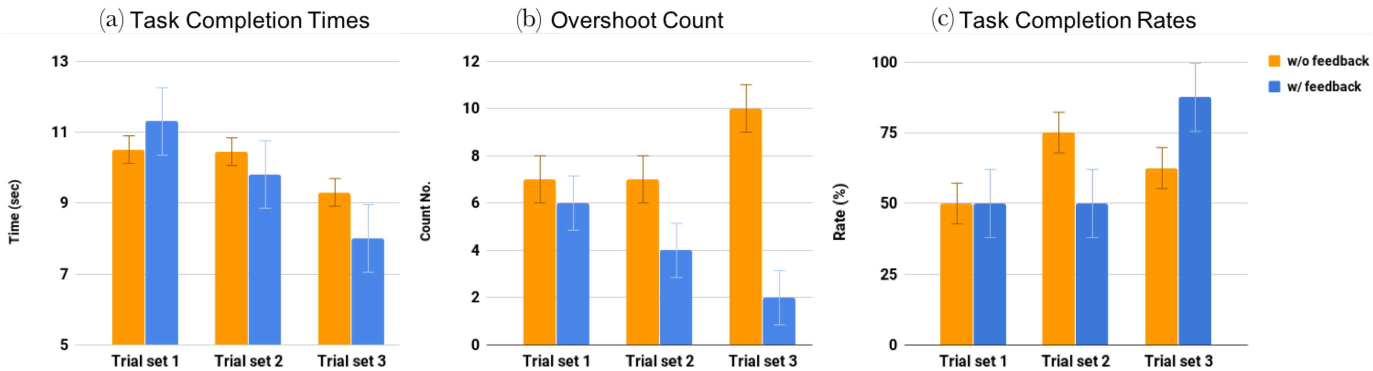

Figure 4. (a) Average task times (over eight tasks), (b) overshoot count (mean across subjects rounded up to the nearest integer), (c) task completion rates, across three trial sets, with and without feedback (both vibrotactile and proprioceptive). The error bars represent the standard error of mean.

trial sets and were within 50% to 75% range without feedback and within 50% to 87.5% with feedback.

IV. Discussion and Conclusion

While the primarily results look promising, a closer look would give greater insights into the effects of feedback (touch and proprioception) and positional effect in prosthesis training. Manipulation of objects that were above the chestline ($d_0 = 1$) were harder to perform. This could likely be due to the limb position effect in the EMG classification. For the same initial position of target object, tasks that required limb rotation, generally took longer to perform in comparison to those tasks which had no relative angular position difference ($\Delta\theta$) between the target and goal objects (task no. 1 vs 3 or 5 vs 6). Relative 2-D position (Δd) also had an effect on time, with tasks that had the target and goal object along the same levels/heights ($\Delta d = 0$) requiring shorter time to perform than otherwise (task no. 1 vs 2 or 6 vs 8). Task no. 8 took the longest times in both modules of our experiment. This task involved both limb rotation and diagonal movement of the augmented limb. It was challenging for the subjects to perform both limb rotation and diagonal motion of the target object while maintaining muscle tension for the hand close pose. As subjects were required to maintain the hand close grip during tasks, integrated muscular efforts were strongly correlated to task times. Therefore, certain tasks not only took longer but also required greater muscular efforts (Fig. 3). Fatigue likely resulted in reduction in muscular efforts with also an increased tendency to overshoot during trials with no feedback. The vibrotactile feedback, which was designed to assist the subject in closing and opening the hands at the correct orientation proved to be useful. This potential benefit can be attributed to the cueing effect of the feedbacks.

In this work we showed the feasibility of our mixed-modality prosthesis training system and the combined effect of tactile and proprioceptive feedback. Future work could involve multiple grip classes which in turn would enable manipulation with more types of objects (e.g. sphere, pyramid, etc.). Adaptive task sequences can be incorporated to account for muscle fatigue to encourage training for long periods of time. Finally, a long-term experiment to study the effects of feedback in AR training in pre-prosthetic training and vocational rehabilitation will be conducted in the near future.

V. Acknowledgment

The authors would like to thank the human subjects who participated in this study and Johns Hopkins University Applied Physics Laboratory for providing the Microsoft HoloLens$^{\text{TM}}$.

References

[1] E. A. Biddiss and T. T. Chau, "Upper limb prosthesis use and abandonment: a survey of the last 25 years," *Prosthet. Orthot. Int.*, vol. 31, no. 3, pp. 236–257, 2007.

[2] L. E. Pezzin, T. R. Dillingham, E. J. MacKenzie, P. Ephraim, and P. Rossbach, "Use and satisfaction with prosthetic limb devices and related services," *Arch. Phys. Med. Rehabil.*, vol. 85, no. 5, pp. 723–729, 2004.

[3] C. Antfolk, M. DAlonzo, B. Rosén, G. Lundborg, F. Sebelius, and C. Cipriani, "Sensory feedback in upper limb prosthetics," *Expert Rev. Med. Dev.*, vol. 10, no. 1, pp. 45–54, 2013.

[4] S. Lewis, M. F. Russold, H. Dietl, and E. Kaniusas, "User demands for sensory feedback in upper extremity prostheses," in *IEEE Int. Symp. Med. Meas. Appl. Proc.*, 2012, pp. 1–4.

[5] R. S. Johansson and A. Vallbo, "Tactile sensibility in the human hand: relative and absolute densities of four types of mechanoreceptive units in glabrous skin." *J. Physiol.*, vol. 286, no. 1, pp. 283–300, 1979.

[6] M. Kurzynski, A. Jaskolska, J. Marusiak, A. Wolczowski, P. Bierut, L. Szumowski, J. Witkowski, and K. Kisiel-Sajewicz, "Computer-aided training sensorimotor cortex functions in humans before the upper limb transplantation using virtual reality and sensory feedback," *Comput. Biol. Med.*, vol. 87, pp. 311–321, 2017.

[7] K. J. Kuchenbecker, N. Gurari, and A. M. Okamura, "Effects of visual and proprioceptive motion feedback on human control of targeted movement," in *IEEE Int. Conf. Rehabil. Robot.*, 2007, pp. 513–524.

[8] G. Tieri, G. Morone, S. Paolucci, and M. Iosa, "Virtual reality in cognitive and motor rehabilitation: facts, fiction and fallacies," *Expert Rev. Med. Dev.*, pp. 1–11, 2018.

[9] C. Hunt, R. Yerrabelli, C. Clancy, L. Osborn, R. Kaliki, and N. Thakor, "Pham: prosthetic hand assessment measure," in *Proc. Myoelec. Controls Symp.*, 2017, p. 221.

[10] J. S. Schofield, M. R. Dawson, J. P. Carey, and J. S. Hebert, "Characterizing the effects of amplitude, frequency and limb position on vibration induced movement illusions: Implications in sensory-motor rehabilitation," *Technol. Health Care*, vol. 23, no. 2, pp. 129–141, 2015.

[11] T. J. Roberts and A. M. Gabaldón, "Interpreting muscle function from emg: lessons learned from direct measurements of muscle force," *Integr. Comp. Biol.*, vol. 48, no. 2, pp. 312–320, 2008.