DEVELOPMENT AND ASSESSMENT OF AN AUGMENTED REALITY FEEDBACK SYSTEM FOR PROSTHESIS USERS

Lincoln Inglis[1] & Daniel Blustein[2]

[1]*Department of Psychology, Western University, London, ON, Canada.* [2]*Department of Psychology, Acadia University, Wolfville, NS, Canada*

ABSTRACT

Users of upper limb prostheses face a challenge when attempting to grasp fragile objects due to an impairment of naturalistic sensory feedback regarding grip strength. Augmented Reality (AR) has shown promise as a candidate in solving this issue. Here we present the implementation and testing of a novel AR application for the Microsoft HoloLens 2 and test it using an upper limb prosthesis simulator. Our novel AR software application displays a color overlay on top of a user's prosthetic hand that changes based on grip strength. Using a mechanical egg grasp-and-hold task, we compared grasp performance and learning between prosthesis users with and without AR grip force feedback. Using a mixed ANOVA, we observed no statistically significant difference in performance with and without AR feedback ($F(1,15) = 0.87$, $p = 0.37$) , though we did see improvement across three blocks of grasp trials ($F(2,30) = 6.58$, $p = 0.004$). The AR implementation as presented was not effective which could be explained by limitations of the HoloLens 2, our overlay visualization, a need for more user training, or the simplicity of the task. Emerging AR systems may be better suited to display useful sensory feedback for upper limb prostheses with reduced latency, higher resolution graphics, and improved hand tracking to better localize the visual overlay.

INTRODUCTION

The ability to grasp fragile objects is a key challenge faced by users of upper limb prostheses, at least partly attributed to a lack of naturalistic and intuitive sensory feedback. Without intact hand sensory structures, prosthesis users lose the valuable information that would typically be provided by the sense of touch and kinesthesia, forcing them to rely solely on visual perception when estimating how much force to apply to an object. While visual perception is a significant predictor of force perception [1], the altered internal models of prosthesis users result in inaccurate and especially variable predictions of the force required to successfully pick up a fragile object [2]. Seemingly trivial activities, such as picking up an egg without dropping or cracking it, can become quite difficult tasks.

Past research has sought to develop alternative sensory modalities by which grip force can be represented. Invasive solutions have been proposed in the form of neural interfaces, which directly stimulate peripheral sensory neurons [3], as well as reinnervation surgeries, which transfer residual nerves from the amputated limb to alternative muscle groups [4]. These solutions, however, can result in damage to peripheral nerves or unwanted tissue response [5]. Non-invasive solutions may be more widely accepted by patients with one study showing enhanced use of a prosthesis simulator when haptic feedback was applied to intact fingers [6]. However, this haptic feedback tends to be less incorporated when it is physically misaligned from its visual reference on the prosthesis [7]. Such findings suggest that this form of non-invasive feedback may not be as effective for users with more proximal amputations. Given these downsides, it may be worth investigating solutions which instead provide supplementary visual feedback.

Through Augmented Reality (AR), a visualization is superimposed over a person's view of the real environment around them, integrating digital information into a natural scene. The technology has been effective in educational [8] and stroke rehabilitation [9] settings. AR has also been proposed as an effective solution to the aforementioned grip strength perception problem. Grip strength information has been presented in the form of shape changing ellipses [10] or as visual progress bars [11]. As emerging prosthetic devices are often rejected as too much of a burden to use [12], one might fear that although effective, previous AR feedback systems may require too much attention and cognitive burden to provide real-world clinical benefit.

Our study sought to extend previous AR-based research by developing a more intuitive feedback system in which the visualized grip strength feedback is co-located with the prosthetic hand (i.e. the hand itself appears to change color). Using a between-subjects design, we investigated the effect of this system on motor learning and on grasp performance during a mechanical egg grasp-and-hold task.

METHODS

Augmented Reality Sensory Feedback System

We developed an Augmented Reality application in the Unity development platform for use with the Microsoft HoloLens 2 AR headset. The app places a colored sphere on the user's hand that tracks with hand movement. The location of the sphere can be moved between the right and left hand, and between the fingertips and the back of the hand, if desired. Every frame, or approximately 60 times per second, the application searches for incoming grip force data (in the form of keyboard input) from sensors on both the index finger and thumb. Originally two spheres were used per hand, one for each of the sensors, but this was determined to be confusing in pilot testing. The intensity of the cumulative grip force across both sensors is proportionally mapped to a color map of the visualized sphere. At no force applied, the sphere appears white. As the user applies force to an object, the sphere turns green, eventually shifting to red as maximal force is applied.

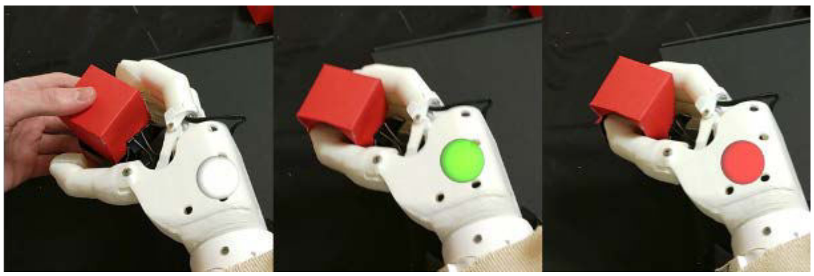

Figure 1: Augmented reality grip force display. Increasing grip force strength, from left to right, changes the visualized color across a gradient from white (no force) to green (low force) to red (high force).

Strain gauge sensors (Interlink Electronics FSR 400) on the pads of the index finger and thumb of a prosthesis simulator [13] measured force applied. The sensors interfaced with a 3.3V Arduino Micro microcontroller which converted the voltage input into the keyboard output necessary to bring data into the closed Microsoft ecosystem. The character string consisted of three digits for each finger (000 to 255), followed by a single-character delimiter, which was primarily used to signify the end of a given string, but could be altered to change user settings, such as enabling a color-blindness mode or switching the feedback location. A USB connection passed the output from the Arduino to the HoloLens 2 approximately once every 100ms, much slower than other AR prosthesis feedback systems [10], [11]. Faster transmission rates and Bluetooth transmission both resulted in data loss, a limitation of the Hololens 2.

Participants controlled the 3D-printed prosthesis simulator [13] via electromyographic (EMG) signals measured by a Thalmic Labs Myo armband. Flexor and extensor muscle activity during wrist movements was mapped to open and close the hand. EMG-driven velocity control of the prosthetic hand was calibrated using brachI/Oplexus software [14], with extreme velocities mapped to maximally comfortable wrist movement in both directions.

Participants

Seventeen participants were recruited from a research participant pool at Acadia University of undergraduate students who had intact limbs and corrected-to-normal color vision. Fourteen identified as female, two as male, and one as non-binary. The mean age of participants was 20.7 years (ranging from 18 to 32 years). Two participants indicated a left-hand dominance. Participants were compensated for their time with bonus credit towards their Psychology courses. All work was completed under the oversight of the Acadia University Research Ethics Board.

Experimental setup

The prosthetic hand simulator was mounted to the table and remained stationary throughout testing, with only one degree of freedom: hand open/close. Pilot testing with a donned simulator and multiple free degrees of movement led to tracking issues. The Hololens 2 could not automatically detect the prosthetic hand in certain orientations, leading to intermittent tracking of the visualization. Participants remained seated with their arm hanging at their side while controlling the prosthesis (Figure 2a) to grasp a mechanical egg (Figure 2b): a small paper cube (5cm x 5cm x 5cm) with two mechanical fuses inside, mounted perpendicularly between opposing graspable surfaces. The fuses were pieces of angel hair pasta that would 'break' if too much force were applied, generating an audible signal to indicate a failed grasp [15]. Each egg's mass was adjusted by attaching weights inside to equal two ounces.

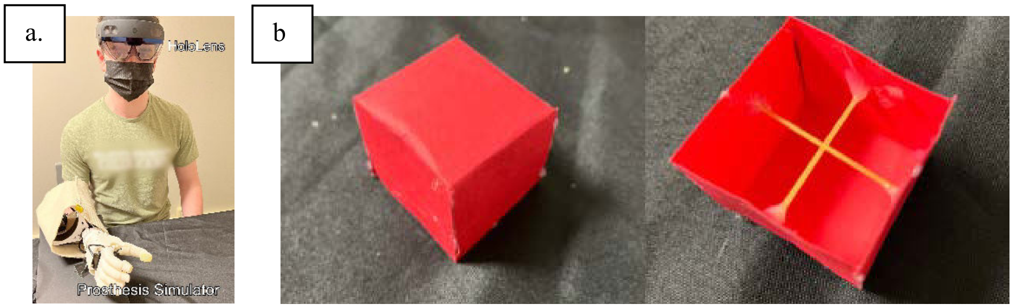

Figure 2: Experimental setup. A. Participants wore the HoloLens 2 while controlling a prosthesis simulator. b. Mechanical egg in grasp-and-hold task. *Left,* participant view. *Right*, underside showing intact pasta fuses [15].

Procedure

After obtaining informed consent and demographic information, participants donned the Myo armband on their right forearm and completed the calibration procedure. Once the prosthesis' motor velocity maximum had been calibrated to match the strength of the participants' forearm muscles, participants donned the HoloLens 2 headset. Participants were randomly assigned to one of two conditions, as early testing indicated that the task was learned too quickly to use a within-subjects design. In one condition (unaided feedback, n = 9), the HoloLens headset was worn, but was not turned on. In the other (AR-assisted feedback, n = 8), the HoloLens was powered on with the AR application running. After being provided instructions, participants completed the grasp-and-hold task. In each trial of the grasp-and-hold task, participants were handed an intact mechanical egg on a spatula and were asked to hold the egg for two seconds, attempting to keep the egg intact. After two seconds, the participant was prompted to drop the egg intentionally, which represented a successful movement. Each movement block consisted of 20 egg holds, and participants completed three movement blocks, with a two-minute rest break between each block. The number of successful and unsuccessful (breaks and drops) egg grasps were recorded for each block.

Data analysis

We analyzed overall grasp performance with supplementary AR feedback and visual feedback only, as well as the change in performance across blocks. A mixed ANOVA was run with block number (within) and condition (between) as predictor variables, and the number of egg breaks+drops as the outcome variable.

RESULTS

A summary of results by block and condition can be found in Figure 3. Participants completing the first block failed an average of 7.25 egg grasps when using AR feedback (SD = 2.76), and an average of 5.56 without AR (SD = 2.13). In the second block, AR condition participants recorded an average of 6.12 egg failures (SD = 4.19), while their unaided counterparts failed an average of 4.22 (SD = 3.77). In the final block, participants using AR failed 4.25 eggs on average (SD = 2.25), while those without AR failed an average of 3.89 eggs (SD = 3.95).

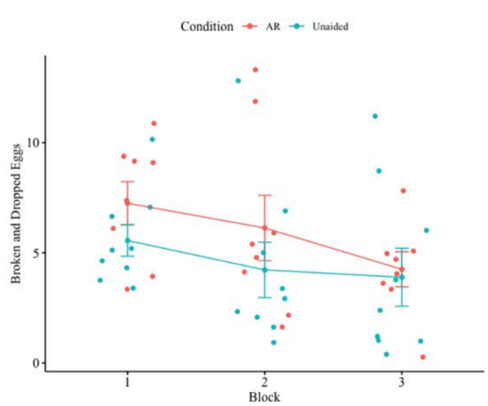

Figure 3: Failed egg grasps by feedback type and block. Error bars represent standard error of the mean.

Mauchly's Test for Sphericity showed no violations of the sphericity assumption, W = 0.98, p = 0.86. The mixed ANOVA showed a statistically significant main effect of Block, $F(2,30) = 6.58$, $p = 0.004$, and no statistically significant effect for Condition, $F(1,15) = 0.87$, $p = 0.37$, or the interaction between Block and Condition, $F(2,30) = 0.84$, $p = 0.44$. This suggests a statistically significant learning effect but does not provide support for the hypothesis that co-located AR feedback would change motor performance.

DISCUSSION

The HoloLens 2 implementation of an AR visual overlay conveying fingertip force feedback on a prosthetic hand did not significantly affect performance during grasping of a fragile object. These results are inconsistent with previous AR grip strength feedback systems [10], [11] using physically offset visualizations. Some possible explanations for why there was no improvement with our AR system include: 1) low resolution grip force feedback; 2) feedback latency issues; 3) graphical limitations of the HoloLens 2; and 4) a moving visualization relying on hand tracking (although movement was minimized due to a stationary hand, it did occur with participant head movement). Perhaps the task was too simple and the AR feedback added no useful information, as has been reported with haptic feedback systems [16]. We consider this work a pilot study to help inform future methodology and suggest using a more modern AR system to provide higher fidelity feedback. Many questions remain regarding the usability of AR feedback systems to improve user operation of prostheses and how to best implement it for maximum effectiveness.

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