DEVELOPMENT OF A SIMULATED SENSORY MOTOR PROSTHESIS: A DEVICE TO RESEARCH PROSTHETIC SENSORY FEEDBACK USING ABLE-BODIED INDIVIDUALS

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ABSTRACT

Sensory feedback is a desirable feature for prostheses; however, research studies are limited in scope by the relatively small proportion of persons with upper-limb amputation. This impedes our ability to study the effect that various forms of sensory feedback have on device control and function. A Simulated Sensory Motor Prosthesis (SSMP) was developed to allow able-bodied users to perform functional tasks similar to a transradial amputee using a prosthesis, with the addition of somatotopically matched mechanotactile haptic sensory feedback. The intent is to assess the impact of relevant prosthetic sensory feedback on functional task performance.

This paper reports the design and development of the SSMP, which mimics the function of a prosthetic device, while also providing optional mechanotactile feedback. The device passed through many rapid iterations using 3D modelling and 3D printing, combined with traditional manufacturing techniques. The control of the device is similar to traditional transradial myoelectric prostheses, and required the development of training and testing protocols for new users. Data from twelve participants was collected and preliminary results are presented. A standard training protocol was successful at improving skill level to allow performance of 4 functional tasks. Participants gave higher ratings for confidence in grip security with the sensory feedback, compared to without. Two of the four tasks showed lower error rates using the sensory feedback. The SSMP provides flexibility to test and iterate different feedback modalities and control strategies as a first-pass with able-bodied participants. This offers the potential to save significant clinical and amputee participant time.

INTRODUCTION

Sensory feedback is listed as a desirable future feature for powered prosthetic devices [1]. Various approaches to providing sensory feedback in upper limb prosthetics are being pursued [2], including somatotopically matched feedback [3]. However, it can be challenging to recruit large enough populations of upper-limb amputee participants to reach statistical significance when evaluating sensory feedback strategies. As a result, many studies are case-specific and can be difficult to reproduce. Moreover, the method of introducing feedback is generally unique between studies, further decreasing reproducibility. Researchers have previously used simulated prostheses with able-bodied participants in the study of motor control to give greater statistical power by increasing participant numbers [4, 5]. Our goal was to develop a Simulated Sensory Motor Prosthesis (SSMP) for able-bodied participants, to study the potential impact of prostheses with sensory feedback. The SSMP was developed to specifically investigate the effects of mechanotactile haptic sensory feedback during functional tasks. Herein, “simulated” refers to the device simulating how a prosthetic device functions; “motor” refers to the control of the terminal prosthetic device; and, “sensory” refers to the mechanotactile haptic sensory feedback given to the user. This paper describes the SSMP device design and development, training protocol, and initial report on use during functional task testing.

DESIGN OVERVIEW

The SSMP was designed to simulate as closely as possible the function of a transradial prosthetic device for use with able-bodied participants. Because the SSMP is controlled through myoelectric signals in the forearm of the user, the weight of the device had to be minimized to not

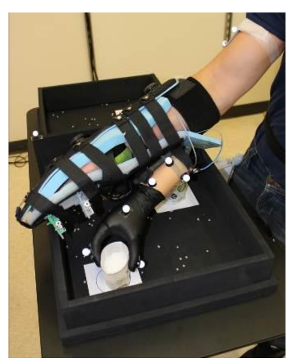

Figure 1: Side view of SSMP during use in cup transfer task

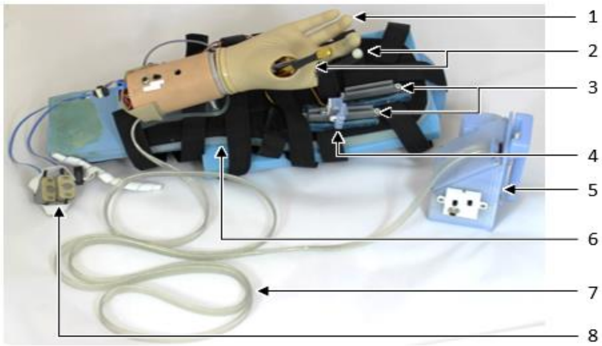

Figure 2: The SSMP with all required components, shown palmar side up, (1) sensorized Ottobock hand, (2) sensorized fingers with glove removed, (3) tracks for tactor adjustment, (4) tactor system, (5) electronics enclosure with belt clip, (6) hand brace, (7) cable connecting prosthetic hand to electronics enclosure, and (8) Ottobock electrodes.

fatigue the user's arm during use. The prosthetic prehensor was aligned under the palmar side of the user's hand with the fingers of the prehensor and the user as close as possible to each other. This was chosen to lower the moment arm from the elbow and still have intuitive and visible control (Figure 1). The forearm of the prehensor was also angled in the direction of the user's elbow to help the user associate with the device. The user's hand was restricted with the use of a rigid splint to ensure their hand did not move and would receive feedback at the same location throughout the testing protocol.

The device is controlled using myoelectric signals on the forearm of the user, with wrist flexion controlling prehensor hand close and wrist extension controlling hand open. Signals from two Ottobock electrodes (Electrode model: 13E200=60 Otto Bock Healthcare Products; Duderstadt, Germany) were fed directly to the Ottobock hand (MyoHand VariPlus Speed model: 8e38=9-R7 ¼ Otto Bock Healthcare Products; Duderstadt, Germany), where simple proportional dual site differential strategy was applied for control.

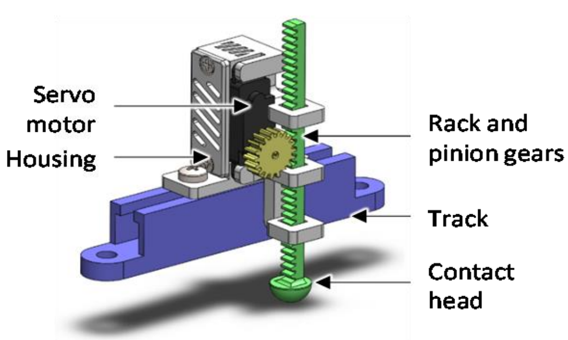

Figure 3: Tactor device within mounting track of the SSMP.

Most of the electronics and processors were placed within an electronics enclosure on the user's belt to reduce the weight acting on their arm. Electronic components were connected to each other via a durable flexible cable. The components of the SSMP are shown in Figure 2.

To measure the grasping forces of the prehensor, the fingers were fitted with strain gauge sensors (HDT Expeditionary Systems, Inc. a division of HDT Global; Solon, OH, USA,). Bending strain information from the sensors was converted to a force using the manufacturer's calibration. These forces were mapped to the tactors to provide matched feedback from the prosthetic fingers to the fingers of the able-bodied participant. The tactor system [3] (Figure 3) was driven using a HS-35HD Ultra Nano Servo (HITEC RCD; Poway, CA, USA); as forces are measured on the prosthetic hand, the servo motor rotates, causing the rack-and-pinion gear to push into contact with the user's fingertip. The device was untethered to improve ease of use during functional tasks, where settings could be manipulated wirelessly via Bluetooth.

MECHANICAL CONFIGURATION

To rapidly iterate SSMP designs, 3D modelling with SolidWorks 2016 and 3D printing were used. Specifically, the forearm and hand brace, prosthetic device attachment, electronics enclosure, tactor system, and strapping system were rapidly prototyped using PLA and flexible polyurethane filament. The final forearm and hand brace, as well as prosthetic device attachment were manufactured using polypropylene heated and shaped to the bottom of the brace and firm EVA foam for the hand brace. The rigid splint used a series of straps and Boa laces (Boa Technology, Inc.; Denver, CO, USA) which were attached to the brace to secure the user's hand and forearm.

A quick disconnect wrist allowed for the use of various prosthetic hands and provided adjustability in the rotation of the prehensor. We chose to provide mechanotactile haptic feedback to the pad of the fingertip on the user's thumb and index finger, matched to the instrumented thumb and index fingers on the sensorized prosthetic hand, to imitate ideal somatotoptic feedback locations. To account for variance in user's hand sizes, slots were cut on the palmar side of the brace and a track for the tactor was mounted next to the slots to allow for alignment of the position of the tactors to the fingertip. Slot sizes and brace size were determined based on NASA anthropometric data [6] and accommodate users across the 5th to 95th percentile of the population. This meant the SSMP accommodated different sizes of forearms so that multiple users could be tested using the same device.

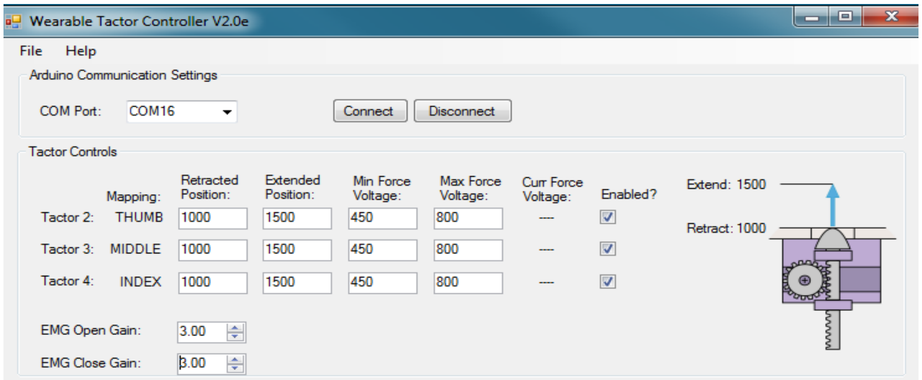

Figure 4: Wearable Tactor GUI

Straps were adjustable to account for different hand sizes and tactor positions. This was accomplished by lining the entire open area of the palmar side of the brace with hook and loop. The straps, once placed, could then be tightened using the Boa laces (by Boa Technology, Inc.; Denver, CO, USA). In previous iterations, discomfort was found to limit perception of sensory feedback. To improve comfort for the user, the inside of the brace was lined in PPT (patient protective technology) foam and polyurethane, foam (McMaster Carr; Aurora, OH, USA).

SOFTWARE DESIGN

A graphical user interface (GUI) was developed to change settings wirelessly and save the settings for each user (Figure 4). Each tactor can be enabled individually. Real-time force voltage is displayed in the GUI. The ranges of force voltage used for mapping can be adjusted, as well as the retracted and extended positions of the tactors.

The GUI does not need to be used for the system to operate, if adjustment of settings is not required. The overall time delay between force inputs to tactor output was quantified on a similar system to be less than approximately 150 ms. Users did not report a noticeable delay in the system.

The SSMP was required to measure sensory feedback even at low forces, i.e. when grabbing something very compliant, such as a wax cup. To enable the user to feel the sensory feedback with an object with little stiffness, a nonlinear mapping from measured force to delivered force was used (Figure 5). We used a series of linear maps with the greatest change (or sensitivity) in tactor movement at the lower end of the measured force, and less sensitivity at higher measured force.

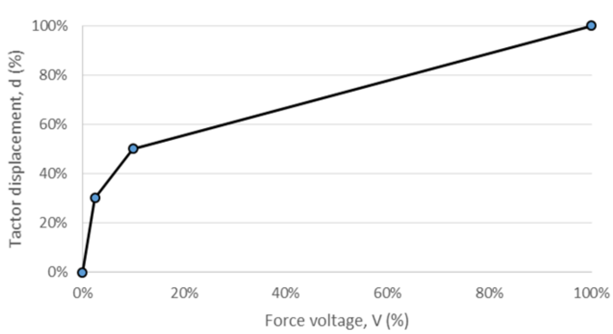

Figure 5: Tactor mapping trend line.

As both the index and middle finger of the prehensor measured force and the fingers moved in unison, it was reasonable to assume either or both fingers of the prehensor would contact an object during grasp. Therefore, the greater measured force from either the prehensor index or middle finger was mapped to the displacement of the tactor providing feedback to the user's index finger.

TRAINING AND TESTING

While most prosthesis users have substantial experience in operating their devices, this training is lacking in able-bodied participants. To ensure comparable results, it was desirable to train SSMP users to be able to reliably perform tasks and prevent a learning curve between trials from compromising the analysis. We developed a training protocol for the SSMP which included a myoelectric control strategy session, a general use of the SSMP guide, a

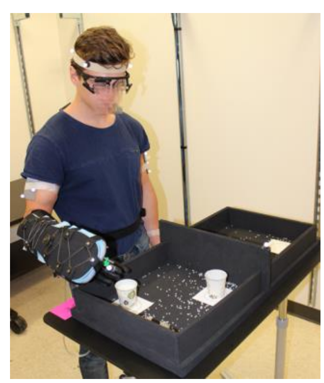

Figure 6: SSMP in use during cup transfer task, with the motion capture and eye tracking setup.

functional task training with and without sensory feedback, an object stiffness test, and an applied feedback location discrimination test. The total time for the training was approximately 1-2 hours.

Testing of the device included functional tasks evaluated using a 3D motion capture and eye tracking analyses, and a questionnaire. Four tasks were specifically designed to test the impact of sensory feedback. The tasks included were a pasta box transfer task, a cup transfer task (Figure 6), a cup pouring task and a shape sorting task. During training and testing short breaks were taken between trials and longer breaks were given if the user felt fatigued.

The total time for functional task testing was approximately 2-3 hours. This time included 3D motion capture and eye tracking measurement setup.

OUTCOMES TO DATE

The SSMP was used to test twelve able bodied subjects. The subjects underwent one setup and training session between 1.5 and 2 hours in duration, with a subsequent testing session using the protocol described above between 2 and 3 hours in duration.

At the end of each training session, participants were administered a questionnaire, and asked to rate their perception of using the SSMP with and without sensory feedback. In general, participants gave higher ratings for confidence in grip security with the sensory feedback, compared to without.

After the testing session, participants were asked to rank the difficulty and realism of the tasks performed. The tasks involving the wax cups (cup transfer and cup pouring) were rated as the hardest. This indicates that fine grip control is difficult, as excess grip would squeeze the cups and spill their contents, detrimental to task performance. For both the shape sorting and pasta box tasks, excess gripping force does not change task performance, so they were perceived as easier to perform. Furthermore, the wax cup tasks were also rated relatively high in terms of realism, meaning they represent tasks users would likely perform in daily life. The highest rated task for realism was the cup transfer task. Overall, there was no difference in average error between sensory feedback and none, but there were task specific differences. The pasta and cup transfer task both showed less errors with sensory feedback, but the easiest task (shape sorting) showed no difference and the most difficult task (cup pouring) had greater errors with sensory feedback.

CONCLUSIONS AND FUTURE WORK

An SSMP was designed and used successfully with twelve able-bodied participants to evaluate the impact of providing mechanotactile haptic sensory feedback on simulated prosthetic function. These trials have inspired several future design changes. The device should have more advanced data filters and an alternate method of mapping measured force to applied feedback, to reduce noise and relay feedback more effectively. There is potential to evaluate different modes of haptic sensory feedback using this device; for example, vibratory feedback as opposed to mechanotactile stimulus. Future revisions could provide access to more digits of the hand and possibly other areas of the arm, to evaluate alternate feedback locations. The device should also include grasping aperture measurement and data logging, with the potential to provide more effective feedback and control options.

Testing demonstrated that participants can successfully use the SSMP to perform functional tasks. Initial evaluation suggested that sensory feedback improved their confidence and performance for some tasks. Future work will involve a statistical comparison of the SSMP user data collected during the testing sessions compared to prosthetic users performing the same tests, to determine the similarities and differences in movement strategies and perception. Further comparisons of performance using the SSMP with and without sensory feedback will also be undertaken.

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