DEVELOPMENT OF A MODULAR SIMULATED PROSTHESIS AND EVALUATION OF A COMPLIANT GRIP FORCE SENSOR

Eric D. Wells [1], Shealynn Carpenter [2], Michael R. Dawson [3], Ahmed W. Shehata [3], Jason P. Carey [1], Jacqueline S. Hebert [3, 4]

[1]*Department of Mechanical Engineering, University of Alberta, Edmonton, Alberta, Canada*
[2]*Department of Medicine, University of Alberta, Edmonton, Alberta, Canada*
[3]*Division of Physical Medicine and Rehabilitation, Department of Medicine, University of Alberta, Edmonton, Alberta, Canada*
[4]*Glenrose Rehabilitation Hospital, Alberta Health Services, Edmonton, Alberta, Canada*

ABSTRACT

Grip force sensory feedback is commonly stated as a desirable feature for upper-limb myoelectric prosthetics. Many techniques for non-invasive grip force feedback are being investigated. However, the choice of force sensor, feedback location, and experimental apparatus typically vary between research studies, making it challenging to compare results. A standardized device where individual parameters can be adjusted would allow researchers to evaluate the impact of each variable on results. An example of such a device is a simulated prosthesis. Simulated prosthesis devices enable non-disabled individuals to participate in myoelectric prosthesis research experiments while ensuring consistency in experimental apparatus between participants. We developed a lightweight, modular, and inexpensive simulated myoelectric prosthesis capable of delivering sensory feedback to fingertips and proximal forearm. We integrated mechanotactile feedback devices to deliver modality matched feedback to the forearm and somatotopically matched feedback to the fingertips. We compared a commercial force sensor before and after being encapsulated within a compliant material under a variety of loading conditions. The encapsulated force sensor outperformed the standard sensor in all non-ideal loading conditions by a large margin. The use of this encapsulation technique dramatically increases accuracy in sensor readings when loading conditions differ from calibration conditions. This device will help facilitate myoelectric research by providing a consistent experimental apparatus between non-disabled participants for various control and feedback-oriented studies.

INTRODUCTION

Upper limb amputation results in loss of both motor and sensory function of the hand, harming an individual's economic, psychological, and social well-being [1]. Prosthetic technology attempts to mitigate these effects by restoring functionality to the lost limb. Current research in the upper limb prostheses field focuses on electrically powered devices controlled by the muscle signals in the residual limb, termed myoelectric prostheses [2]. Myoelectric devices utilize the existing neural pathways in an open-loop fashion, without specific feedback on the outcome of the action.

Upper limb myoelectric prostheses users commonly state sensory feedback as a desirable feature, with grip force ranking as the highest priority sensory input [3]. Many methods of non-invasive grip force feedback implementation are being investigated with promising results [4]. However, parameters such as feedback location, force sensors, and experimental apparatus are typically unique to each experiment, making comparisons between studies difficult. There is an ongoing need for devices capable of adjusting these parameters to allow researchers to evaluate each variable independently.

In previous studies, simulated prosthesis devices have been used to investigate myoelectric control [5] and sensory feedback techniques [6]. An evaluation of a simulated prosthesis device showed that it resulted in motion kinematics and performance metrics similar to those found in myoelectric users [7]. A Simulated Sensory Motor Prosthesis previously constructed within our lab allowed for somatotopically matched mechanotactile feedback during myoelectric control [8]. However, initial testing with the device showed various issues that justified a revision. The large size, non-modularity and weight of the device (1.3 kg) made it difficult to move naturally, causing discomfort over long periods.

The objective of this work was to optimize the size, weight, and comfort of the Simulated Sensory-Motor Prosthesis while maintaining the ability to provide sensory feedback to both the forearm and fingertips. This allows for both modality and somatotopically matched feedback to be used on the same experimental apparatus. An additional focus was placed on modularity to allow for interchangeable components for various user sizes or experimental conditions. The device was fit with inexpensive compliant force sensors to measure the grip force of the end effector reliably. These sensors were evaluated and compared to standard sensors under various loading conditions to ensure accurate grip force measurement.

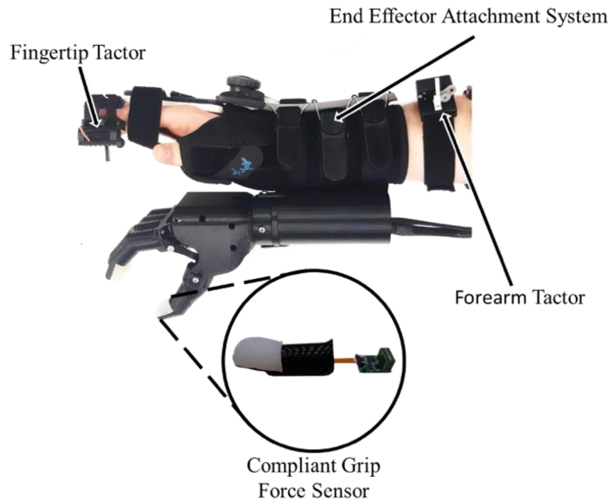


Figure 1: The MSP Overview

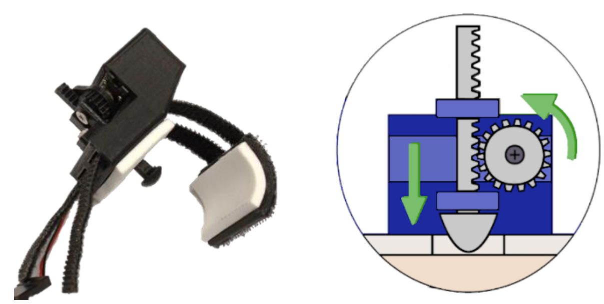
MECHANICAL DESIGN

Figure 1 shows an overview of the Modular Simulated Prosthesis (MSP) that was developed. A wrist and thumb support brace (MedSpec, USA) restrains the user's hand to ensure isometric contraction during electromyography (EMG) control. This commercially available product is designed to be comfortable, lightweight, adjustable, and leaves adequate space on the proximal forearm for EMG sensors and other devices. Additional finger flexion restraints were required to prevent the fingertips from colliding with the end effector. This was achieved by extending the existing metal supports within the brace with 3D printed PLA supports.

In previous simulated prosthesis devices, the prosthetic hand is typically mounted with a distal, radial, or ventral offset. Any combination of these offsets places the additional weight of the prosthetic hand off the axis of the user's arm, resulting in an undesired torque. Because the human hand width is much smaller than its length and breadth, this torque is minimized by offsetting in the ventral direction. An adjustable offset in the radial direction was also added to the MSP to resolve any line of sight issues that may arrive for specific tasks. An end effector attachment system was developed to attach the prosthetic hand to the brace while accommodating a variety of arm shapes and sizes. The system consists of a 3D printed bracket that rests midline on the ventral surface of the wrist brace and a cable tightening system (BOA, USA) that rests midline on the dorsal surface of the wrist brace. Attached to the bracket is a 3D printed wrist adapter for end effector mounting. The bracket is temporarily secured to the ventral side of the arm using a large Velcro strip. The cable tightening system is then wrapped around to the dorsal side, where 3D printed quick-connect clips are connected, completing the loop around the arm. The interlocking cable system is tightened to create a snug fit between the end effector and the participant's forearm to minimize the relative movement of the device.

A 3D printed, anthropometric, single-degree-of-freedom end effector was designed (Solidworks, 2018). The hand is driven by a Dynamixel MX-64AT servo motor (Robotis, Inc.). The fingers and thumb are actuated simultaneously using a linked bar mechanism, giving a gripping aperture of 100 mm. This end effector has a mass of 298 grams with a maximum continuous grip force of 11 N. The total mass of the MSP is 691 g with the end effector included, can be comfortably worn for 3 hours, and costs less than $1000 CAD. The end effector, feedback devices, and attachment system are all independent units creating a highly modular design that can be easily customized to fit specific needs.

SENSORY FEEDBACK DESIGN



(a) (b)

Figure 2: Mechanotactile Tactor Overview: (a) Fingertip Mounting System, (b) Motion Illustration

Sensory feedback is integrated into the MSP using small, inexpensive mechanotactile tactors modified from our earlier work [9]. The tactor devices use a lightweight Dymond D47 servo motor (Dymond, USA) with a 3D printed rack and pinion system to apply force to the user. We developed two mounting systems to apply somatotopically accurate feedback to the fingertips, or modality matched feedback to the forearm. The tactors are secured to the user with Velcro straps. Washable foam provides cushioning to prevent irritation to the user. The tactor with the fingertip mounting system is shown in Figure 2. The tactors can provide up to 12 N of force with a throw of 14 mm.

SENSORIZATION DESIGN AND EVALUATION

Measurement of grip force can be done through small force sensors placed on the fingertip of the prosthetic hand. Capacitive force sensors have previously been shown to perform better than commonly used force-sensitive resistors for this application [9]. These sensors are designed to be attached to a flat surface, with the force loading evenly distributed across its surface area. However, prosthetic hands undergo a variety of loading conditions that do not represent this ideal situation. Prosthetic fingertips with barometric pressure sensors embedded in elastomer [10] have previously been shown to provide pressure sensitivity in non-ideal loading conditions. It was hypothesized that encapsulating a capacitive force sensor in a compliant material would disperse the force evenly throughout the sensor, allowing for more robust measurement to various loading conditions.

Methods

A SingleTact S8-10 capacitive based force sensor (SingleTact, USA) was compared before and after being encased in Dragon Skin 10NV, a compliant silicone rubber based material (Smooth-On, USA). The two configurations are shown in Figure 2. A load cell (Omega LCM703 calibrated to a maximum error of 0.1N) was placed in line with an HS-35HD servo motor (Hitec RCD, USA) to apply force to the sensor through a PLA indenter. The load cell was read using Simulink Real-Time (Matlab 2014a) through a National Instruments data acquisition system (NI PCI6259). A force was applied between 0 and 10 N in a sinusoidal pattern for five total periods, similar to earlier work [9]. Loading periods of 0.5, 1, and 5 seconds were tested to account for dynamic loading effects. Each measurement was repeated three times to ensure repeatability between trials, for a total of 9 trials for each condition.

An indenter was made with a circular flat contact surface (10 mm diameter) and covered in a 2 mm thick foam to ensure even force distribution over the entire surface area of the sensor. Loading of this indenter directly aligned with the sensor acted as the ideal condition for both the baseline and the encapsulated configurations. All other conditions were compared to the ideal condition to evaluate the sensor's ability to adapt to various circumstances. An indenter with a 10 mm diameter curvature was tested to represent grasping a curved surface. The indenter position was moved by 4mm in both the proximal and distal directions to evaluate the effect of a non-central loading condition. For only the encapsulated configuration, a centred applied loading condition at a 15-degree angle was also evaluated.

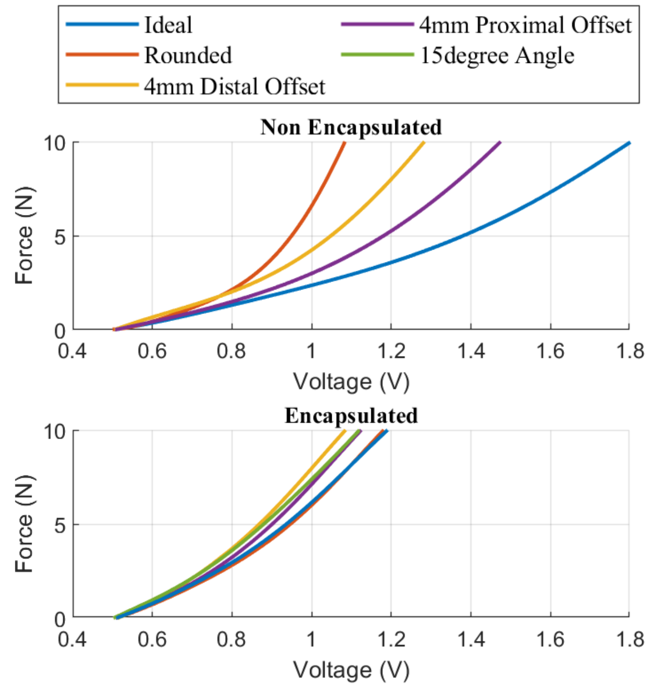


Figure 3: Loading Curve Comparison Between Various Conditions

The baseline and encapsulated sensors voltage to force relationship was calibrated using a 5th-degree polynomial curve fit to all trials under the ideal condition. This calibration curve was used to predict force outputs under all other conditions.

Results

The results for all conditions are summarized in Table 2. In the ideal condition, both sensors performed within the manufacturer's specifications at root mean square error (RMSE) of 2.2% and 2.5% of full-scale range (FS) for the baseline and encapsulated sensor. The RMSE of the baseline sensor was much more sensitive to changing conditions than the encapsulated sensor. The curved indenter condition produced a substantial decrease in performance for the baseline sensor, giving an RMSE of 36.4% FS. The encapsulated sensor was relatively unaffected with an RMSE of 2.9% of FS. Similarly, when the ideal indenter was shifted by 4mm, the RMSE for the baseline rose to 25.5% FS (distal offset) and 15.5% FS (proximal offset). The encapsulated sensor RMSE increased to 10.5% FS (proximal offset) and 7.2% FS (distal offset). Finally, the encapsulated sensor showed an RMSE error of 7.6% FS during the 15-degree angled loading scenario. Figure 3 shows each sensor's loading curve fit with a 5th-degree polynomial curve. The baseline sensor's loading curves are much more varied when contrasted with the encapsulated sensor, illustrating the dependency on environmental conditions. For example, at a load of 10 N, the baseline sensor voltage output varies by 0.72 V (50.7% FS over 10 N) depending on the condition, while the encapsulated sensor only varies by 0.11 V (14.4% FS over 10 N).

Table 1: Summary of Experimental Results for Grip Force Sensor Comparison

Loading Condition	Baseline Sensor RMSE (N)	Encapsulated Sensor RMSE (N)
Ideal	0.22	0.25
Rounded	3.64	0.29
4 mm Distal Offset	2.55	1.05
4 mm Proximal Offset	1.55	0.72
15 Degree Angle	-	0.76

SOFTWARE DESIGN

BrachI/Oplexus, an open-source graphical user interface (GUI) designed for myoelectric prosthesis control [11], enables the EMG signal interpretation and end effector motion. A microcontroller (Arduino Uno, R3) controls the mechanotactile tactors and grip force sensors. Data logging capability is enabled at a frequency of 50 Hz. A custom GUI (Visual Studio, 2015) was created to communicate with the microcontroller for quick customization of tactor parameters.

CONCLUSIONS AND FUTURE WORK

A lightweight, modular simulated prosthesis was developed with integrated modality and somatotopically matched mechanotactile feedback. Grip force sensors were compared before and after being encapsulated in a compliant material under various loading conditions. In all non-standard loading conditions, the encapsulated sensors outperformed the baseline sensor. This device will help enable researchers to study feedback and control techniques in myoelectric prosthetics by providing a reliable test apparatus that easily allows for the manipulation of various parameters.

Future work includes evaluating the performance of the MSP to ensure that the device is an accurate representation of a myoelectric user and evaluate the effectiveness of various sensory feedback techniques. More modular components, such as alternative feedback devices of various modalities, could be designed to fit onto the device. The device is currently tethered to a one-meter long power cable, which may be restrictive for some studies. A wireless version of the MSP would make the device more flexible.

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