A TRANSRADIAL MODULAR ADAPTABLE PLATFORM FOR EVALUATING PROSTHETIC FEEDBACK AND CONTROL STRATEGIES

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ABSTRACT

Novel multi-modal and closed-loop myoelectric control strategies may yield more robust, capable prostheses which improve quality of life for those affected by upper-limb loss. However, the translation of such systems from an experimental setting towards daily use by persons with limb loss is limited by the cost and complexity of assessing all the possible sensor and feedback configurations. The comparison of different control strategies is further complicated by the use of disparate prosthetic socket and simulated prosthesis designs across experiments. This study aims to address these issues through the development and preliminary assessment of a Modular-Adaptable Prosthetic Platform (MAPP) system for use in experimental control strategy evaluation. The MAPP system is compatible with a variety of commercially available control and feedback devices and can be used in experiments involving participants with either intact or amputated limbs. The modular design enables compatibility with novel devices and quick reconfiguration of components. We compared EMG and FMG data acquired with the MAPP system to a previously characterized transradial simulated prosthesis, using able-bodied subjects. The MAPP was shown to match or exceed the control accuracy achieved using a rigid simulated prosthesis, while providing the added benefits of modularity. This device shows promise as a research tool which can catalyze the deployment of advanced control strategies by enabling comprehensive and standardized assessment of control and feedback strategies.

INTRODUCTION

Recent developments in robotic prostheses have yielded many advancements including multi-articulated hands [1], [2], machine learning based controllers [3]–[5] and sensory feedback systems [6]–[8]. However, translating these improvements to wearable prosthetic devices remains challenging. Before translating these advancements to clinical use, thorough assessment and validation of the potential benefits are required. A significant bottleneck for assessment arises due to the tradeoff between experiment scale, representativeness of real-world conditions, and time/resource costs [9]. Numerous factors besides the control strategy itself, including end-effector loading, sweat, limb-position, and acceleration can affect the performance of a prosthetic system, and these conditions must be recreated during the experimental assessment to provide accurate insights into real-world performance [8], [10]. Simulating a realistic physical limb-socket interface within a participant- and control strategy-specific prosthesis requires a custom-designed and manufactured socket [10], [11], which is not easily adapted for various control and feedback systems.

An alternate strategy to custom-designing prosthetic sockets for testing persons with amputation is often pursued by having able-bodied persons wear a simulated prosthesis with or without an end-effector attached. Researchers have used various versions of simulated prostheses to investigate performance of commercial prosthetic hands [12], performance of novel control strategies [13], [14], kinematic movement trajectories when using prosthetic hands [15], and the effect of providing sensory feedback to users on performance in functional tasks [7]. There is, however, an incomplete understanding of how well results collected from these studies translate to daily use in a prosthesis by a person with limb loss. Furthermore, comparisons across studies are limited due to the disparate versions of the prostheses utilized. There is thus a need for a modular platform that accommodates multiple sensors and feedback systems and can be worn by both able-bodied persons and persons with amputations to facilitate these crucial comparisons. This study aims to address this gap through the design and assessment of an inexpensive and easy-to-use 3D-printed transradial Modular-Adaptable Prosthetic Platform (MAPP).

Figure 1: *Overview of the 3D-printable MAPP with a HANDI-hand attached to it* [2].

Table 1: *Design specifications for MAPP system*

Item	Design Specification	Achieved Specification
Length adjustability	10 – 40 cm	Achievable with multiple exterior panels
Fit intact limbs	Achieve Target	Target met
Prosthesis interface	Compatibility with iLimb, BeBionic, and HANDi Hand	Target met; expand modularity with new components
User input sensor integration	6 sites; compatible with commercially-available electrodes	10 sites; compatible with FSRs, MyoBock (Ottobock Inc.), and Bagnoli (Delsys, Inc.) electrodes
Context detection & sensory feedback	Accommodate 2 sensory-feedback modalities & IMU	Compatible with mechanotactile & vibrotactile feedback and IMU
Cost	\$500	< \$200
Fitting time	< 15 minutes	10 min initial fitting; 2-4 min re-donning
Socket weight	500 g	450 g
Shear/ axial load	2 kg	5 kg
Comfort	Comfortable over the course of an experiment (3 hrs)	Comfortable for 3 hrs (user-reported)
Sanitation	Non-porous, cleanable interface surface with limb	All contact surfaces lined with closed-cell neoprene

MATERIALS AND METHODS

Socket Design Requirements

Critical features were identified through consultation with prosthetists from the Glenrose Rehabilitation Hospital. Table 1 summarizes the design requirements and specifications for the developed socket. Unless otherwise stated, all components were 3D-printed using Ultimaker 2+ (Ultimaker BV) and Makerbot Replicator 2 (MakerBot Industries, LLC). Rigid components were printed using PLA and flexible components using Ninjaflex Cheetah filament (Ninjatek, Inc.). Figure 1 shows the design of the MAPP platform as a prosthetic socket for a person with transradial amputation. The developed socket consists of rigid panels supported by stainless steel M4 threaded rods with flexible cushions attached via Velcro® (Velcro BVBA). All panels are connected to a ring at the distal end of the socket.

Suspension

Suspension is achieved through radial compression generated by tightening the circumferential straps threaded through each rigid panel. Alternating regions of soft tissue compression and release are created by the cushions and spaces between them, distributed both radially and axially along the limb. This design choice improves translation of motion between bone and socket as described in [16].

Adaptability

To accommodate different limb lengths, the spacing between each 3D-printed panel can be adjusted and fixed by adjusting the position of the nuts embedded in each panel along the rods attached to the adjacent panel. A panel can also be removed entirely by unscrewing the rods which anchor it to the adjacent panel. This combination of modularity and adjustability enables the socket to accommodate residual limbs extending beyond 5 cm (the length of one panel) from the cubital fossa and up to 5 cm proximal to the wrist. Different limb thicknesses are accommodated by interchangeable inner rings with different diameters. As forearms are not cylindrical in nature, the channels in each panel through which the rod substructure passes are purposely made loose-fitting such that the slope between each panel can be adjusted. Furthermore, the interfacing cushions are made slightly compliant and convex such that they can match the profile of the limb surface without causing pinch points. When the circumferential straps are tightened, the socket profile is maintained due to opposing pressure exerted between each of the straps, cushion infill material, and limb surface (Figure 1). Able-bodied participants can be accommodated by replacing the connecting ring and distal support cushion with a hollow connecting ring. An optional hand mount can be screwed to that ring, thereby restraining the hand and fingers if isometric contractions are necessary. The hand mount, offset in the radial direction, directly fits with the Quick-Connect Wrist (Otto Bock, Inc.) to connect commercial end effectors. Custom 3D-printed adapters enable compatibility with other end-effectors.

Modularity and Socket Structure

The MAPP enables user input and sensory feedback devices to interface directly with a user's limb across a range of positions. Such devices can be embedded in each interior panel (Figure 2), providing a direct interface with the user's limb through which suspension loads are transferred. Rigid inserts provide a stable base for various actuators, which can be interchanged to accommodate other devices. Sensors can also be mounted in the spaces between regions with panels via the Velcro-backed circumferential straps. Velcro-backed modules prevent slip relative to the circumferential straps, and radial compression from the straps provides a stable interface with the user's limb. The interchangeable outer-panels add to the stability of this mounting method by securing the position of the circumferential straps relative to the rest of the socket structure with a Velcro-backed surface. Further, these outer panels provide an interchangeable platform for mounting devices (see Figure 1) on the socket's surface. A final method of modular device mounting is provided by the rails connecting the main panels. 3D-printed

Figure 2: *Exploded view of a) FSR and b) surface EMG electrode into panel system via removable inserts*.

mounts can be threaded onto these rods providing a rigid platform which provides direct access to the user's limb via the spaces between exterior panels.

The interchangeable in-cushion sensor modules were designed to fit FSRs as described in [17]. Myobock 13E200 Electrodes (Ottobock Inc.) and Bagnoli Electrodes (Delsys, Inc.) were also made compatible with the initial prototype, enabling a mixed method of user-input detection. C2 and C3 vibrotactors (Engineering Acoustics Inc.) were similarly embedded into the interior cushion via interchangeable inserts, providing vibrotactile feedback in any cushion. 3D-printed mechanotactile tactor modules, the design of which is described in [8], were integrated into both the removable panels and substructure. The modularity of this socket system enables the integration of Inertial Measurement Units (IMU) (BNO055, Adafruit Industries) that could be used to detect forearm orientation and acceleration with respect to an inertial reference frame.

The structural rod segments were selected to support a 2 kg end effector load in both the transverse (ie. weight of 2 kg end load with residual limb parallel to ground) and axial (ie. 2 kg end load with residual limb perpendicular to ground). Using ASME Elliptic Failure Criteria and a life of at least 10,000 cycles of fully reversed loading, M4 rods were selected, leading to a minimum factor of safety of 2.5. The 3D-printed exterior panels were tested using both SolidWorks FEA (Dassault Systems, Inc.) and mechanical loading in the aforementioned configurations. These tests demonstrated that the overall minimum factor of safety was still limited by fatigue or bending of the rods; therefore, the socket system was capable of safely supporting up to a 2 kg end-effector or payload.

Figure 3: *A participant wearing a) the Modular-Adaptable Prosthetic Platform as a simulated prosthesis and b) the orthotic splint.*

Socket Interface Validation Study

Participants: Eight able-bodied, right-handed, male participants (mean and standard deviation of age: 28.8 ± 8.2 years) volunteered to participate in this study. Written informed consent according to the University of Alberta Research Ethics Board (Pro00077893) and the German Aerospace Center's internal committee for personal data protection (DLR authorization 3.7.2017) was obtained.

Experimental setup: Participants conducted the experiment while wearing the developed MAPP (Figure 3a) and while using a version of an orthotic splint commonly used to simulate a prosthesis (Figure 3b). Participants were randomly assigned to start with one condition or the other. For each simulated prosthesis, a band of five evenly-spaced Myobock electrodes and a concentric band of five FSRs as described in [17] were placed on the participant's right forearm [18]. Signals from both bands were processed using the same hardware as [17], with a 3rd-order low-pass Butterworth filter and cut-off frequency of 1 Hz to remove high-frequency disturbances. Mean absolute value for each channel was extracted and used to train a linear-discriminant analysis (LDA) classifier, representative of commercially available classifier-based controllers [3]. An i-LIMB Ultra prosthetic hand was attached to simulate the effects of normal prosthesis loading on each socket (Figure 3). Participants were asked to match seven gestures (rest, index point, power grip, wrist flexion, wrist extension, forearm pronation, forearm supination) shown on a computer screen for two-second intervals, three times each.

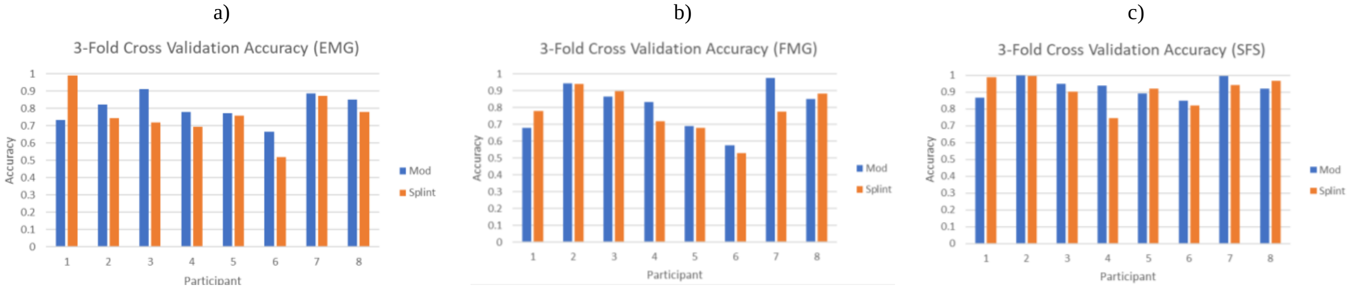
a) b) c)

Figure 4. *Offline performance was assessed for each participant using a three-fold cross validation using a) EMG only, b) FMG only, and c) mixed-modality based on a sequential forward search (SFS)*

Data Acquisition: Offline performance was assessed for each participant using a three-fold cross validation (one for each repetition of a gesture). Assessment was performed using data from a) EMG only, b) FMG only, and c) mixed-modality based on a sequential forward search (SFS) to select the best-performance from 5 channels for each participant.

Results: Figure 4 shows that collecting data when using the MAPP enabled similar accuracy results as when using the orthotic splint across all sensor modalities.

DISCUSSION AND FUTURE WORK

Here, we developed a low-cost modular transradial socket system, which can accommodate multiple geometries of the forearm, along with multiple configurations of user-input, context detection, and sensory feedback devices. We tested the developed system with sEMG and FMG and a pattern recognition control strategy for seven gestures. Offline performance of participants using MAPP was similar to their performance when using the orthotic splint.

Future work will include comparison of online performance between the MAPP, orthotic splint, and socket systems. Using machine learning strategies to map input to action may reveal whether functional performance using a splint, or the MAPP provides a better prediction of clinical performance when deployed within a prosthetic socket. The effects of variables like end-effector loading, limb position, and acceleration are not well-characterized in control strategies. Therefore, paired assessment of the MAPP with a suction socket incorporating identical control strategies in different contexts may demonstrate the extent to which each platform captures these contextual changes. In conclusion, the cost time- and resource-savings, and flexibility to test a variety of novel prosthetic control strategies in a common platform, such as the one developed here, may accelerate the throughput of prosthetic control strategy validation.

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REFERENCES

[1] L. Resnik, S. L. Klinger, and K. Etter, “The DEKA Arm: Its features, functionality, and evolution during the Veterans Affairs Study to optimize the DEKA Arm.,” *Prosthet. Orthot. Int.*, 2013.

[2] D. J. A. Brenneis, M. R. Dawson, and P. M. Pilarski, “Development of the Handi Hand: An Inexpensive, Multi-Articulating, Sensorized Hand for Machine Learning Reseearch in Myoelectric Control.”

[3] C. Castellini *et al.*, “Proceedings of the first workshop on peripheral machine interfaces: Going beyond traditional surface electromyography,” *Frontiers in Neurorobotics*, vol. 8, no. AUG. Frontiers Research Foundation, 2014.

[4] M. F. Lucas, A. Gaufriau, S. Pascual, C. Doncarli, and D. Farina, “Multi-channel surface EMG classification using support vector machines and signal-based wavelet optimization,” *Biomed. Signal Process. Control*, vol. 3, no. 2, pp. 169–174, Apr. 2008.

[5] A. L. Edwards, M. R. Dawson, J. S. Hebert, and C. Sherstan, “Application of real-time machine learning to myoelectric prosthesis control: A case series in adaptive switching Lower Extremity Prosthetics View project Reinforcement Learning Models View project.”

[6] F. Clemente, S. Dosen, L. Lonini, M. Markovic, D. Farina, and C. Cipriani, “Humans Can Integrate Augmented Reality Feedback in Their Sensorimotor Control of a Robotic Hand,” *IEEE Trans. HUMAN-MACHINE Syst. Tech.*, pp. 1–7, 2016.

[7] L. F. Engels, A. W. Shehata, E. J. Scheme, J. W. Sensinger, and C. Cipriani, “When Less Is More – Discrete Tactile Feedback Dominates Continuous Audio Biofeedback in the Integrated Percept While Controlling a Myoelectric Prosthetic Hand,” *Front. Neurosci.*, vol. 13, p. 578, 2019.

[8] K. R. Schoepp, M. R. Dawson, J. S. Schofield, J. P. Carey, and J. S. Hebert, “Design and Integration of an Inexpensive Wearable Mechanotactile Feedback System for Myoelectric Prostheses,” *IEEE J. Transl. Eng. Heal. Med.*, vol. 6, 2018.

[9] B. W. Hallworth, J. A. Austin, H. E. Williams, M. Rehani, A. W. Shehata, and J. S. Hebert, “A Modular Adaptable Transhumeral Prosthetic Socket for Evaluating Myoelectric Control,” *Under Rev. IEEE Transl. Eng. Heal. Med.*, 2020.

[10] I. Vujaklija *et al.*, “Translating research on myoelectric control into clinics-are the performance assessment methods adequate?,” *Front. Neurorobot.*, vol. 11, no. FEB, pp. 1–7, 2017.

[11] A. Belyea, K. Englehart, and E. Scheme, “FMG Versus EMG: A Comparison of Usability for Real-Time Pattern Recognition Based Control,” *IEEE Trans. Biomed. Eng.*, vol. 66, no. 11, pp. 3098–3104, 2019.

[12] P. J. Kyberd, “The influence of control format and hand design in single axis myoelectric hands: assessment of functionality of prosthetic hands using the Southampton Hand Assessment Procedure,” *Prosthet. Orthot. Int.*, vol. 35, pp. 285–293, 2011.

[13] D. Johansen, C. Cipriani, D. B. Popovic, and L. N. S. A. Struijk, “Control of a Robotic Hand Using a Tongue Control System-A Prosthesis Application,” *IEEE Trans. Biomed. Eng.*, vol. 63, no. 7, pp. 1368–1376, 2016.

[14] A. W. Shehata, L. F. Engels, M. Controzzi, C. Cipriani, E. J. Scheme, and J. W. Sensinger, “Improving Internal Model Strength and Performance of Prosthetic Hands Using Augmented Feedback,” *J. Neuroeng. Rehabil.*, vol. 15, no. 70, 2018.

[15] H. E. Williams, Q. A. Boser, P. M. Pilarski, C. S. Chapman, A. H. Vette, and J. S. Hebert, “Hand Function Kinematics when using a Simulated Myoelectric Prosthesis.,” *IEEE Int. Conf. Rehabil. Robot.*, vol. 2019, pp. 169–174, Jun. 2019.

[16] R. D. Alley, T. Walley Williams III, M. J. Albuquerque, and D. E. Altobelli, “Prosthetic sockets stabilized by alternating areas of tissue compression and release,” vol. 48, no. 6, pp. 679–696, 2011.

[17] M. Connan, E. Ruiz Ramírez, B. Vodermayer, and C. Castellini, “Assessment of a Wearable Force- and Electromyography Device and Comparison of the Related Signals for Myocontrol,” *Front. Neurorobot.*, vol. 10, Nov. 2016.

[18] M. Nowak, T. Eiband, and C. Castellini, “Multi-modal myocontrol: testing combined force-and electromyography,” in *IEEE International Conference on Rehabilitation Robotics*, 2017.