UNIVERSAL, LOW-COST TRANSRADIAL CHECK SOCKET FOR RAPIDLY VALIDATING MYOELECTRIC CONTROL

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ABSTRACT

The validation of myoelectric prosthetic control strategies for individuals experiencing upper-limb loss is hindered by the time and cost affiliated with traditional custom-fabricated sockets. Consequently, researchers often rely on virtual reality or robotic arms to validate novel control strategies, limiting end-user involvement. Here we present a multi-user, low-cost, 3D-printed transradial socket for short-term use that can be custom-fit and donned rapidly, used in conjunction with various electromyography configurations, and adapted for use with various residual limbs and terminal devices. The check socket was fabricated prior to participants' arrival, fitted by the researchers within ten minutes, and donned in under one minute. It accommodated multiple individuals and terminal devices, and its total cost of materials was under $10 USD. Across all participants, the socket did not significantly impede functional task performance or reduce the electromyography signal-to-noise ratio. The socket was comfortable enough for at least two hours of use. The development of this universal transradial check socket constitutes an important step towards increased end-user participation in advanced myoelectric prosthetic research.

INTRODUCTION

Up to 50% of individuals with upper-limb loss abandon their myoelectric prostheses [1], often citing unreliable control as a critical factor [2]. More dexterous myoelectric control could improve prosthesis acceptance. However, validation of new control strategies with end users is limited by the time, cost, and expertise needed to fabricate a custom-fit socket with several embedded electrodes. Traditional transradial sockets include only two electrodes and require three to four visits with a prosthetist over three to six weeks for $800 to $3,000 before affiliated labor costs [3,4]. Due to these constraints, research is often limited to just one or a few individuals with upper-limb loss, often working in virtual reality environments or with a robotic arm mounted apart from the user. Other studies rely on intact participants or offline analyses with no active human involvement.

One approach to increasing end-user participation is to reduce cost by using an adjustable socket. Recent work in this area has focused on photogrammetry and expandable foams [5, 6]. Though these sockets reduce cost, they still require a lengthy fabrication process that must be repeated for each individual. While sockets that are both customizable and affordable have been explored, they have yet to be adapted for myoelectric prosthesis use.

To address these needs, we developed a multi-user, 3D-printed transradial check socket for functional validation of new myoelectric control strategies in research settings. The socket can be fabricated by the researchers prior to the participants' arrival, and rapidly fit, donned, and used. We explored its comfort and functionality with a high-count surface-electromyography (sEMG) control system. The development of this socket constitutes an important step towards expanding the involvement of individuals with upper-limb loss in myoelectric control research.

MATERIALS AND METHODS

Device Development

The multi-user check socket is designed to: i) optimize accessibility and cost; ii) accommodate a wide range of data acquisition (DAQ) methods, residual limbs, and prostheses; and iii) ensure durability, functionality, and comfort. The 3D-printed socket consists of four customizable struts that attach to a collet, which in turn connects to a custom terminal-device attachment that varies for each unique terminal device (Figure 1). A layer of self-adhesive wrap between the skin and the socket provides grip, and a second layer of self-adhesive wrap around the socket secures the fit. The socket design is available at https://github.com/utahneurorobotics/u-of-u-functional-test-socket.

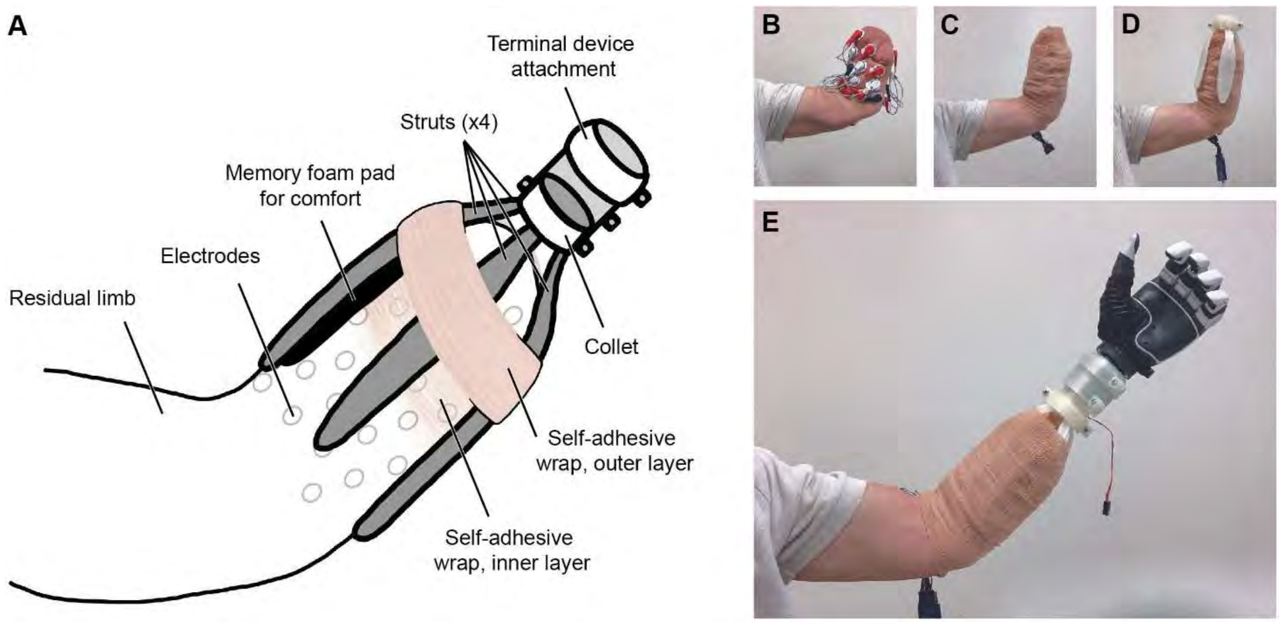

Figure 1: (**A**) Socket overview. (**B**) The residual limb is outfitted with sEMG electrodes and (**C**) wrapped securely in a disposable adhesive bandage. (**D**) After being heated, molded, and cut to the desired length, the custom-fit struts are attached to the collet, and the socket is donned. (**E**) A second layer of adhesive bandage is wrapped around the limb and socket system, and the socket is fit with a myoelectric prosthesis, pictured above with a TASKA hand. The 3D-printed components can be removed, reshaped, and reused with subsequent individuals without reprinting.

i) Accessibility

The 3D-printable design of the socket improves accessibility, enabling researchers without prosthetist expertise to complete both the fabrication and fitting processes. The socket is 3D-printed prior to the participant's arrival. Upon arrival, the custom-fitting process can be completed within ten minutes, and the socket can be donned in under one minute (Table 1), not including electrode placement, as this time will vary depending on the DAQ system. The total cost of materials of one socket is approximately \$8.00 (Table 2), excluding other 3D-printer costs such as maintenance. This contrasts with recent low-cost sockets ranging from \$100 to \$200 [5, 6]. All components are widely available materials. The accessibility of this design is conducive to greater participant involvement, allowing those with transradial amputations to rapidly use and validate advanced myoelectric prostheses.

Table 1: Time Approximation, by Process

Fabrication (3D printing)	6 hours, 30 minutes
Fitting (molding struts)	10 minutes
Donning	< 1 minute
Doffing	< 1 minute

Table 2: Cost Analysis, in USD

3D-printed Components (i.e., filament)	\$3.50
Hardware (i.e., nuts and bolts)	\$1.00
Self-adhesive Wrap	\$3.00
Memory Foam	\$0.50
Total	**\$8.00**

ii) Adaptability

Our socket is designed to be versatile and is compatible with a broad range of control methods, residual limbs, and terminal devices. The socket grants access to the skin for various means of control, and the 3D-printed struts can be molded around a range of DAQ methods (electromyography, magnetomyography, sonomyography, etc.) without affecting fit or comfort. The polylactic acid (PLA) filament allows the struts to be heated in a hot water bath or with a heat gun and quickly molded to the unique presentation of the participant's limb. The adaptability of the socket improves the overall participant experience by accommodating limb-volume fluctuations and avoiding any painful sites (e.g., bone protrusions, neuromas, wounds). The design is adaptable to other open-source connectors that can be printed along with the socket to accommodate a variety of commercially available prostheses. Such adaptability is also conducive to improved hand orientation, as the default position of the prosthesis can be adjusted by rotating the terminal device attachment within the collet (Figure 1A).

iii) Durability

The struts are printed flat to ensure structural stability [7] and take their contoured shape only in the custom fitting process. PLA offers greater toughness and higher break elongation, break load, and break strength when compared to other thermoplastic filaments [8]. The struts are designed to minimize deflection and slipping; a reinforcing layer along the top of each strut distributes weight and maintains structural integrity, and surface texture along the bottom creates grip. The surface area of the widened struts also helps distribute pressure evenly throughout the socket. Such weight distribution is key to supporting loads beyond that of the terminal devices. The weight of the socket is approximately 150 g, which is at the low end of the 100- to 420-g range for traditional sockets and low-cost alternatives [5, 9]. Incorporating memory foam beneath the greatest load-bearing strut further increases comfort. Altogether, these design considerations ensure comfort while promoting greater maximum load and durability.

Testing

Before participant recruitment, we tested the mechanical capabilities of the socket. Using a plaster limb replica, two modes of extreme-use load suspension were evaluated: vertical and horizontal. Vertical load suspension is most prone to slippage, so masses up to 8 kg (approximately twice that of a gallon of water [10]) were incrementally and statically hung. The amount, if any, by which the socket had slipped was recorded. The socket was also moved rapidly to simulate a dynamic load condition such as going down a flight of stairs. Horizontal load suspension is most likely to induce fracture; the same mass was added, and the degree, if any, of downward deflection was measured.

Three participants with transradial amputations were recruited for functional testing. The participants reported their perceived comfort at three time points in the experimental session using a 0-10 Likert scale [11, 12]. We utilized high-count sEMG (Ripple Neuro LLC, Salt Lake City, UT) and recorded data while participants mimicked movements of a virtual prostheses to train a modified Kalman filter [13] in order to provide myoelectric control. Signal-to-noise ratio (SNR) was measured with and without the socket during three movement sets [14]. Performance was evaluated via a target-touching task in a virtual environment [15] and the modified box and blocks test (BBT), in which participants were instructed to transfer 16 blocks arranged in a grid from one compartment of the box to the other [16].

Across all metrics, we tested within-participant performance and group-mean performance to interpret our results in the context of the larger patient population. All data were screened for normality prior to analyses. We performed paired t-tests to compare the socket- and no-socket cases and to compare with reported literature values.

RESULTS

Mechanical testing demonstrated socket reliability. Vertical load suspension up to 8 kg yielded no measurable slipping in static or dynamic conditions. In horizontal load suspension, less than 1º of vertical deflection was noted in the connection between the dorsal-most strut and the collet. This minimal deflection was elastic, as the socket quickly reverted to its original orientation once the load was removed. No perceptible fractures resulted from loading.

Three participants with transradial amputation were recruited for this study. Our socket encountered no difficulties accommodating the variance in arm length or circumference across these three individuals (residual limb length, 15 cm to 20 cm; circumference, 26 cm to 27 cm).

Comfort remained adequate throughout experimental sessions, but our socket was rated lower than participants' traditional clinically-prescribed socket. Immediately after donning, our socket scored 6.7 ± 1.2 on a 0-10 Likert scale (mean ± standard deviation). In comparison, traditional socket scores were reported to be 8.8 ± 1.3. There was an imperceptible degradation of comfort over time, with comfort scores of 6.5 ± 1.5 partway through and 5.7 ± 2.1 at the end of the experiment. The mean difference of 1.0 in comfort falls within the 2.7-point minimum detectable change [12]. Notably, the participant with the lowest reported comfort score remarked that it was still tolerable for multiple hours of use.

Functional testing demonstrated that the socket did not impede performance. SNR was comparable between socket- and no-socket cases across all three movements (Figure 2A). Similarly, target-touching performance was not hindered by the socket, as quantified by percentage times in target (PTT) (Figure 2B) and root-mean-squared error (RMSE) (Figure 2C). Lastly, modified BBT performance with our socket was comparable to literature values, with no reduction in the average number of blocks transferred with our socket as compared to values reported for myoelectric prosthesis users [17-19] (Figure 2D). Participants ($N = 3$) transferred 19 ± 3 blocks in 60 s compared to 13 ± 0 for modified BBT ($N = 2$) and 21 ± 6 for original BBT ($N = 17$).

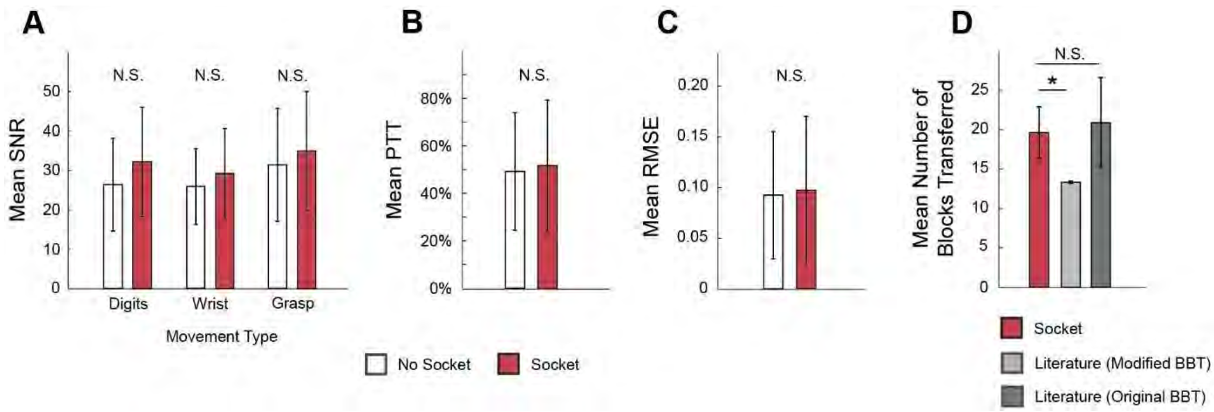

Figure 2: (**A**) Signal-to-noise ratio (SNR) was not affected by the socket for any movement type (N = 3). (**B**) For a virtual target-touching task, neither mean percent time in the target region (PTT) nor (**C**) mean root-mean-squared error (RMSE) were significantly different while using the socket (N = 3). (**D**) Modified box and blocks test (BBT) performance (N = 3) was comparable to literature values, with no statistical difference from reported values for the original BBT (N = 17). However, performance with the socket was significantly improved from reported values for the modified BBT (N = 2). *p< 0.025.

CONCLUSION

We developed a novel, multi-user check socket that can be used to quickly assess myoelectric control with individuals with transradial amputation. The socket makes custom myoelectric control more accessible; it can be printed in less than seven hours, custom fit within ten minutes, donned in under a minute, and the total cost is approximately $8.00. The socket also accommodates multiple individuals without requiring reprinting, adapts to volume fluctuations and painful sites, and works with a variety of terminal devices and DAQ methods. Importantly, the socket presented here is not intended to serve as a clinical diagnostic check socket, nor is it meant for long-term use as a definitive socket; rather, it is best utilized briefly in a research or clinical setting to explore myoelectric control with a physical prosthesis. Future work should validate this socket with additional participants and terminal devices.

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