2021 43rd Annual International Conference of the
IEEE Engineering in Medicine & Biology Society (EMBC)
Oct 31 - Nov 4, 2021. Virtual Conference

Analysis and Design of a Bypass Socket for Transradial Amputations

Brett M. Musolf, *Student Member IEEE*, Eric J. Earley, *Member,* Maria Munoz-Novoa, and
Max Ortiz-Catalan, *Senior Member IEEE*

Abstract— **The ability to measure functional performance of a prosthesis is hindered by the lack of an equalized mechanical platform to test from. Researchers and designers seeking to increase the pace of development have attempted novel mounts for prostheses so these can be used by able-bodied participants. Termed "bypass sockets", these can increase the sampling pool during prosthetic evaluations. Here, we present an open-source, 3D printable prosthetic bypass socket for below-elbow (transradial) amputations. Methods to quantify the effectiveness of bypass sockets are limited and therefore we propose the use of a validated and clinically relevant evaluation tool, the Assessment of Capacity for Myoelectric Control (ACMC). We performed the ACMC in six able-bodied subjects with limited experience with myoelectric prostheses and found the participants to be rated from "non-" to "somewhat capable" using the ACMC interpretation scale. In addition, we conducted a secondary evaluation consisting of a subset of tasks of the Cybathlon competition aimed at eliciting fatigue in the participants. All participants completed said tasks, suggesting that the bypass socket is suitable for extended use during prosthesis development.**

Clinical Relevance— **The design and validation of the bypass socket presented here can facilitate the development of upper limb prosthetic systems.**

I. Introduction

Development of upper limb prostheses has accelerated with access to rapid prototyping, and therefore means to measure the performance of these devices has become increasingly important. Prosthetic system should be evaluated by their target users, but these are not always available for rapid iterative testing. In such cases, a potential substitute would be the construction of a mount for abled-bodied individuals (hereto after referred to as a "bypass socket"). While these bypass sockets will always differ from the target population, they can still provide valuable information in the early design of prostheses and their control system.

Until recently, bypass socket designs were unique to the design group who created them and often unreproducible by others. This has changed with a series of 3D printed bypass sockets proposed over the last few years, with one being officially open-source [1], [2]. The validations of these bypass sockets have been conducted using the Box and Block Test and the Nine-hole Peg Test [1]–[3], which are relevant tests for repetition and fine motor skills, with the caveat of assessing a narrow spectrum of functionality.

In this article, we introduce an open source, 3D printed bypass socket design [4] based on previous work by the University of Utah [1]. We validated the usability of our design using a clinically relevant test for upper limb prosthesis control, namely the Assessment of Capacity for Myoelectric Control (ACMC), as this is a less abstract test of functionality of the prosthesis and its control scheme. The bypass socket design files are freely available in the Open Science Framework platform [4].

II. Methods

Six volunteers with varying levels of experience with prosthetics participated in this study: a seventh volunteer was unable to successfully control the prosthesis and was therefore excluded. We gauged their experience via a brief survey that also asked questions related to factors that could impact electromyographic (EMG) recordings (e.g., soreness from work or sport). All participants were inexperienced in both the bypass socket and the prosthetic control scheme. All participants provided informed consent for their de-identified data to be used in this study.

We recorded EMG data from four bipolar differential surface electrodes placed in an equidistance ring around the proximal part of the forearm. The bypass socket was used with a conventional myoelectric hand and wrist rotator (VariPlus Speed and 10S17 Electric Wrist Rotator, both by Ottobock, Germany).

The control scheme utilized a conventional feedforward Multi-Layer Perceptron (MLP) trained to recognize intuitive hand open and close, and wrist pronation and supination.

A. Evaluation

1) Assessment of Capacity for Myoelectric Control

The ACMC (3.1) is a clinically validated method to evaluate the functional ability of upper limb myoelectric prosthetic users [5]. While bypass sockets were not in mind in the

---

Research supported by the Promobilia Foundation, the IngaBritt and Arne Lundbergs Foundation, the Swedish Innovation Agency (VINNOVA), and the Swedish Research Council (Vetenskapsrådet).

B. M. Musolf and E. J. Earley are with the Center for Bionics and Pain Research, Mölndal, Sweden, and with the Department of Electrical Engineering, Chalmers University of Technology, Gothenburg, Sweden. (e-mail: musolf@student.chalmers.se & earley@chalmers.se).

M. Munoz-Novoa is with the Center for Bionics and Pain Research, Mölndal, Sweden, and with the Centre for Advanced Reconstruction of Extremities, Institute of Clinical Sciences, Sahlgrenska University Hospital, Mölndal, Sweden, and with the Institute of Neuroscience and Physiology, Department of Clinical Neuroscience, Rehabilitation Medicine, Sahlgrenska Academy, University of Gothenburg, Gothenburg, Sweden (e-mail: maria.munoz.novoa@vgregion.se).

M. Ortiz-Catalan is with the Center for Bionics and Pain Research, Mölndal, Sweden, with the Department of Electrical Engineering, Chalmers University of Technology, Gothenburg, Sweden, with the Operational Area 3, Sahlgrenska University Hospital, Mölndal, Sweden, and with the Department of Orthopaedics, Institute of Clinical Sciences, Sahlgrenska Academy, University of Gothenburg, Sweden (e-mail: maxo@chalmers.se).

978-1-7281-1178-0/21/$31.00 ©2021 IEEE

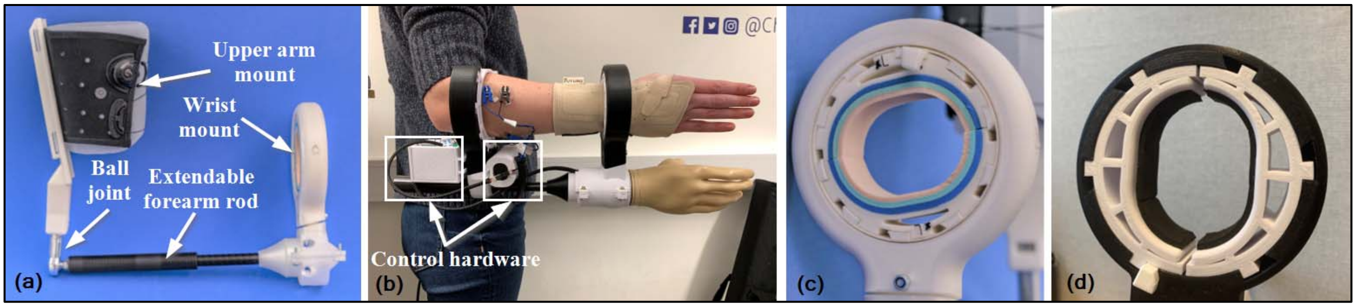

Figure 1. (a) The previous University of Utah Design [8]. (b) The proposed design. Note: the control hardware is custom to this control scheme. (c) The previous design's free/band-restricted wrist ring design [8]. (d) The proposed design's fixed wrist ring design.

evaluated population, the only requirement for the test is that the participant is able to operate an upper limb myoelectric prosthesis. Additionally, capacity for myoelectric control is defined by the ACMC as both functionality of the prosthesis (or in this case bypass and prosthesis) components and how the user uses the hand. Therefore, an effective bypass should be one that is unimpeding (if not enhancing) to prosthesis control by the user which is reflected by a higher score.

The participant performed an activity that demonstrates six functionality aspects: arm support, appropriate grip force, different positions, re-adjusting the grip, coordination, and visual feedback. The raters grade these facets on a scale of zero to three throughout the activity either in person or via recording. The rater instructs the participant throughout the test, offering guidance on order of tasks and giving encouragement to use their prosthesis.

We chose a single Activity of Daily Live (ADL) task for all the participants to perform: the luggage packing task. We tasked participants with packing a suitcase with common everyday items stored in various containers and locations. To mitigate inter-rater bias, two raters scored the ACMC separately before discussing to decide the final scores.

2) *Cybathlon Tasks*

As a supplemental evaluation, the participants performed a wide variety of additional tasks to gauge further performance. These tasks were selected from the Cybathlon 2020 Global Edition Powered Arm Prosthesis Race [6], which offers a number of ADLs that are well codified. These tasks represented a challenge to the participants to gauge their capacity for ADLs. Secondarily, we used these tasks to assess fatigue over time, as the participants did these tasks after the ACMC, and with little rest between each task. Hereafter, these tasks are referred to as "Cybathlon tasks". The Cybathlon tasks and each participant's performance are available in Supplementary Tables III-VI [4].

After each Cybathlon task, we asked each participant to indicate their perceived exertion regarding fatigue and overall difficulty along a standard physical Visual Analog Scale (VAS). This method was chosen as it has been validated for fatigue measurement [7]. These tested tasks were all done under a time limit of three minutes (ten minutes for the tactile task) to function as a tertiary measure of performance.

B. *Bypass socker design*

To assess the framework to evaluate prosthesis bypasses, we updated a bypass designed at the University of Utah to address challenges encountered during its recreation [1], [8]. The biggest issue was the weight bearing capability of the bypass socket. While freeing up the forearm for more surface electrodes, the original design mountings caused the prosthesis to be generally unsteady when carrying or holding higher weight objects. Another issue was due to the nearly free wrist motion. This was unideal for EMG motion artifacts and it allowed for more isotonic rather than isometric contractions [9]. This also increased the complexity of the design. The last issue we addressed was the requirements for manufacture; the original design required hardware that would have to be custom ordered and most likely must be locally re-sourced for international use.

The intention of the design modifications was thus to reduce the load on the wrist, improve stability of the bypass socket, increase range of motion, and maximize EMG quality. The ball and joint required by the Utah design limited the former three issues (see Fig. 1a). While this mounting scheme allowed more access to the forearm, the ball and joint limited the range of motion and gave limited prosthesis carrying support. Replacing the upper arm mounting piece of the original design with a forearm ring piece like that of the wrist mount rectified all these issues (see Fig. 1b). This change had the added benefit of removing the custom-made region-specific hardware in the upper arm segment.

The last goal involved the complete removal of the constructed ball bearing system of the wrist piece, in favor of a stiff ring (see **Error! Reference source not found.**c & 1d). While the original design cited concerns that the change in the palmar radial position would hinder the user, this did not appear to cause a serious issue with our participants. Particular to our test of our bypass socket design, a wrist brace was used to minimize motion artifacts from wrist movements. Additionally, the weight of the prosthesis offered an inherent minimizer of motion, as the extra weight made rotation more difficult.

III. RESULTS

A. *Performance Evaluation with ACMC*

Reviewing the average score among all participants per item (Fig. 2 and Supplementary Table I [4]), we observed wide variation between and within individual items. This is most notable with the worst item scoring 0 while the best being over 2.5.

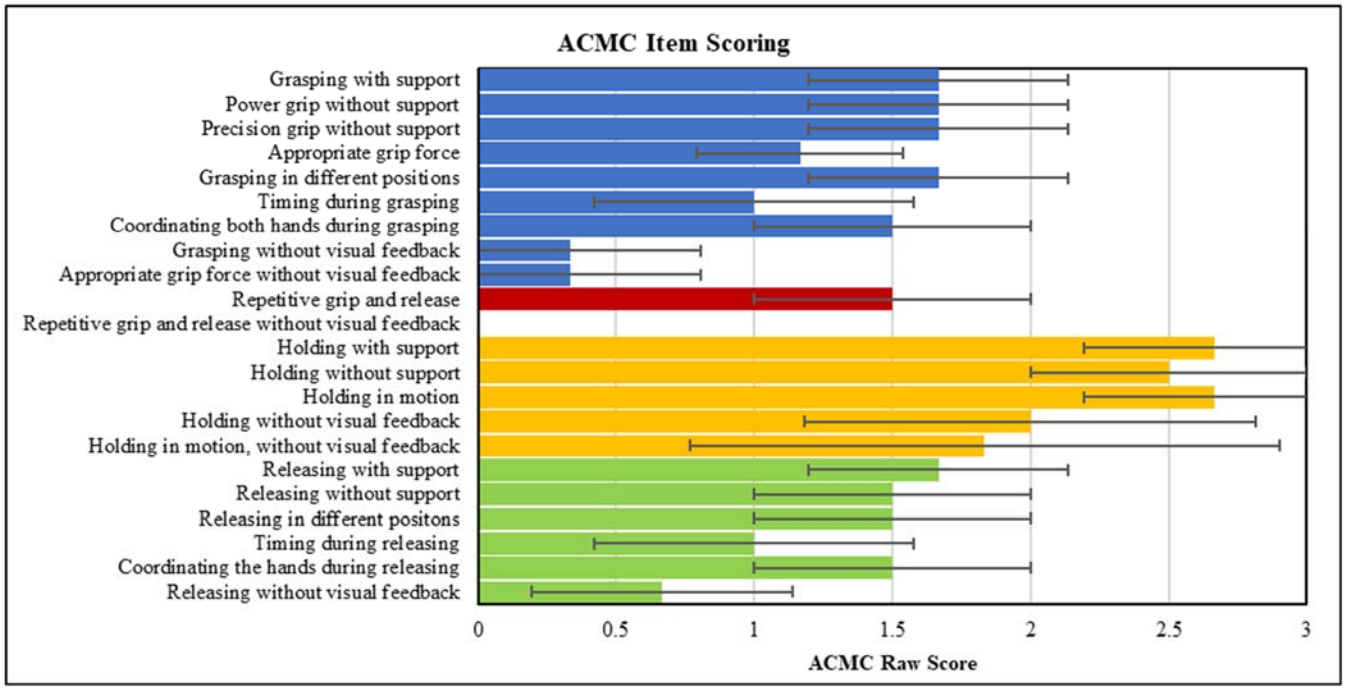

Figure 2. Average score of each task in ACMC. Blue tasks are related to grasping; red to repetitive use; yellow to holding; and green to releasing.

The ACMC classifies participants based off their cumulative ACMC scores (see Table I). The overall scores of each participant were as expected from a relatively inexperienced group. Two participants were classified as “somewhat capable” and the rest were “non-capable”. This was expected given the naivete of all the participants.

The abilities rated on the ACMC were grouped into four major areas: grasping, repetitive use, holding, and releasing. As depicted in Fig. 3, the participants showed the largest difference in holding and repetitive use, however, we found no statistical significance (Wilcoxon signed-rank test with Holm-Bonferroni Correction, p = 0.1875).

B. Performance Evaluation with Cybathlon Tasks

We did not observe a strong correlation in fatigue throughout the Cybathlon tasks (Fatigue $R^2 = 0.30$, see OSF Fig. I [4]). No participant reached fatigue to such a point they either had to stop because of general fatigue or because the prosthesis would not respond to their actions. No participants were able to perform the two tasks replicating a full cup and the paper cutting task. Interestingly, the participant with the longest total time reported in the survey to have played a sport that require hand use. We observed no other factors related to the survey as relevant.

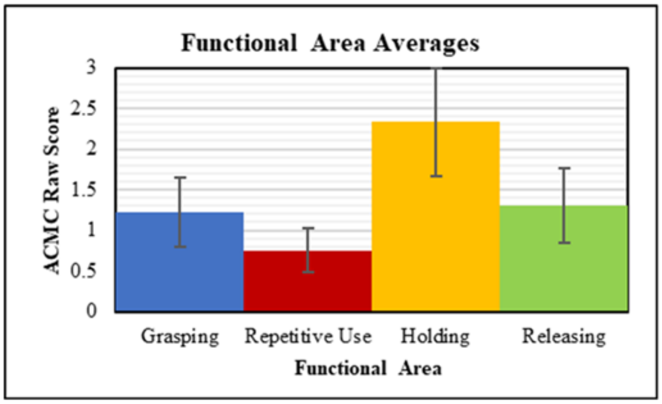

Figure 3. Averages of the four ACMC functional areas

IV. DISCUSSION

Participants consistently found it difficult to perform wrist rotation throughout the entire study. Typically, one rotational direction would be easier to actuate than the other. This resulted in an inadvertent “fidgeting” in the easier direction. While the ACMC did not directly measure these motions, they played an essential role in doing many of these tasks. This also may have lowered the scoring on average, because even the tasks that would not require rotation, required the participant to actively manage the rotational “fidgeting” by repositioning the hand angle. The grasping functional area, which had the second lowest average area score, best demonstrates this.

We found the best ACMC performance was in the holding functional area (Fig. 3 and Supplementary Table II [4]). This can reflect both the stability of the bypass socket as well as of the control scheme; as at a minimum, the prosthesis must receive either no classified action or a continuous “close” classified action. This confirms that the stability goal was met either from the original bypass design or may have been improved by the updated design.

TABLE I. OVERALL SCORE OF EACH PARTICIPANT

Subject	Average Score	Cumulative Score	Interpretation
Subject 1	1.6 ± 0.9	35	Non-capable
Subject 2	1.8 ± 0.8	40	Somewhat capable
Subject 3	0.9 ± 0.6	20	Non-capable
Subject 4	1.5 ± 0.9	34	Non-capable
Subject 5	2.0 ± 0.7	44	Somewhat capable
Subject 6	0.9 ± 0.6	19	Non-capable
Total	1.5 ± 0.8	32	Non-capable

Releasing was the second highest scoring ACMC functional area. This is intuitively consistent because releasing an item did not require lining up the hand to targets, as grasping would (i.e., the participant could drop the item at any wrist angle). However, the difference between both releasing and grasping proved statistically insignificant.

The worst scoring ACMC items were all without visual feedback. This is to be expected given the inexperience of the participants; they would not have developed a compensation ability to make assumptions on where the hand was as when grasping. However, this poor scoring did not necessarily correlate with in the Cybathalon blind shape identification task (referred to as the "haptic box" in supplemental). For example, subject 2 was able to identify all the shapes by aggressively knocking the box and shapes with their prosthesis. While their score among nonvisual ACMC items remains unremarkable (subject 6 received the same scoring), it is noteworthy that they had the highest familiarity with prosthetics according to the survey.

The holding area scoring better even without visual feedback can be related to the continual aspect of the function. That is, once the participant initiated the hand position, the hand will stay in that position until another hand position contradicts the first.

Comparing results of the Cybathlon tasks to the ACMC, there seemed to be little relation between the best or worst performing individuals. Of note, however, is that the highest VAS fatigue rating and longest total time was by participant 2, who also had the second highest ACMC score and fell into the "somewhat capable" range. Unfortunately, the intention to elicit fatigue such that the myoelectric prosthesis was unusable was not achieved. To better achieve this, it may be necessary to assess with a fatigue-specific motion not necessarily considered to be an ADL. Regardless, almost all tasks proved to be achievable across different participants. No participants were able to achieve the full cup carry Cybathlon tasks as the rotation control issue caused them to spill the contents. We also observed the participants lacked enough control over hand close and open to align the fingers into the scissor grips for the paper cutting Cybathlon task. This task is a particularly interesting evaluator to observe because it was a *unimanual* task for the prosthesis requiring high precision. Such a task in the ACMC would likely be relegated to bimanual control as the ACMC only expects tasks to be done as the most "natural" or "efficient".

Overall, it appears that the bypass socket may have had less impact as other variables on the participants' performance. From the participants' comments, the biggest contributors to use-fatigue were repetitive failure attempts and overall weight of the prosthesis. The former issue is multifaceted, including bypass socket obstruction, electrode positioning and reading, and correct motion classification. The bypass socket may have contributed to the deficit in wrist rotation as it utilized an arm mounting ring over the area where muscles responsible for this movement are more superficial [10]. Ideally to follow up this study, a test of electrodes embedded in the cuff is warranted to consider the effect of the cuff (similar to [2]).

Perceived weight is a major issue that is unlikely to be resolved in bypass sockets. The weight of the bypass socket itself was already minimal given it was semi-hollow and plastic, however, the infill of the print could be lowered if necessary. This would come at a drawback of integrity and durability. Regardless of the bypass socket design, the largest contributor to the weight would be the prosthesis and this is immutable without offering a suspension system. Said suspension system (similar to [11]) would reduce usable workspace, but may be a suitable tradeoff depending on what function is being assessed.

V. CONCLUSION

We introduced an upgraded design of an open-source bypass socket for upper limb prosthesis that proved functional on conducting ADLs based on the ACMC. To better assess the ACMC as a bypass socket evaluation tool, additional studies using other prosthetic bypass sockets are warranted. These would ideally be able to recognize the strengths and weaknesses of any design and possibly serve as a selection tool for future prosthesis designers pursuing functional prosthesis testing. The Cybathlon tasks offered a less distinct result. Nevertheless, reapplying it to future works may have merit, especially with a more comprehensive survey and a consideration for physical attributes of the subjects.

ACKNOWLEDGMENT

The authors would like to thank Jan Zbinden for providing the program for prosthesis control.

REFERENCES

[1] M. D. Paskett *et al.*, "A Modular Transradial Bypass Socket for Surface Myoelectric Prosthetic Control in Non-Amputees," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 27, no. 10, pp. 2070–2076, 2019.

[2] B. W. Hallworth *et al.*, "A Transradial Modular Adaptable Platform for Evaluating Prosthetic Feedback and Control Strategies," in *Myoelectric Controls and Upper Limb Prosthetics Symposium*, Jul. 2020, pp. 203–206.

[3] L. Haverkate, G. Smit, and Di. H. Plettenburg, "Assessment of body-powered upper limb prostheses by able-bodied subjects, using the Box and Blocks Test and the Nine-Hole Peg Test," *Prosthet. Orthot. Int.*, vol. 40, no. 1, pp. 109–116, 2016, doi: 10.1177/0309364614554030.

[4] B. Musolf and M. Ortiz-Catalan, 2021, "Design of a Bypass Socket for Transradial Amputations." OSF, doi: 10.17605/OSF.IO/W2Q5P.

[5] H. Y. N. Lindner, J. M. Linacre, L. M. Norling, and M. Sciences, "Assessment of Capacity for Myoelectric Control," pp. 13–16, 2008.

[6] ETH Zürich, "Race Task Description Cybathlon 2020," 2018. www.cybathlon.com.

[7] K. A. Lee, G. Hicks, and G. Nino-Murcia, "Validity and reliability of a scale to assess fatigue," *Psychiatry Res.*, vol. 36, no. 3, pp. 291–298, 1991, doi: 10.1016/0165-1781(91)90027-M.

[8] "GitHub - mpaskett/University-of-Utah-Bypass-Socket: Instructions and part files for creating a University of Utah Bypass Socket." https://github.com/mpaskett/University-of-Utah-Bypass-Socket (accessed Feb. 02, 2021).

[9] N. Nazmi, M. A. A. Rahman, S. I. Yamamoto, S. A. Ahmad, H. Zamzuri, and S. A. Mazlan, "A review of classification techniques of EMG signals during isotonic and isometric contractions," *Sensors (Switzerland)*, vol. 16, no. 8. MDPI AG, Aug. 17, 2016, doi: 10.3390/s16081304.

[10] L. Mitchell, Brittney;Whited, "Anatomy, Shoulder and Upper Limb, Forearm Muscles."

[11] A. W. Wilson, D. H. Blustein, and J. W. Sensinger, "A third arm - Design of a bypass prosthesis enabling incorporation," *IEEE Int. Conf. Rehabil. Robot.*, pp. 1381–1386, 2017.