Evaluation of Activities of Daily Living Tesbeds for Assessing Prosthetic Device Usability

Junho Park
Dept. of Industrial and Systems Engineering
Texas A&M University
Texas, U.S.A.
junho.park@tamu.edu

Maryam Zahabi
Dept. of Industrial and Systems Engineering
Texas A&M University
Texas, U.S.A.
mzahabi@tamu.edu

David Kaber
Dept. of Industrial and Systems Engineering
University of Florida
Florida, U.S.A.
dkaber@ise.ufl.edu

Jaime Ruiz
Dept. of Computer & Information Science & Engineering
University of Florida
Florida, U.S.A.
jaime.ruiz@ufl.edu

He (Helen) Huang
Joint dept. of Biomedical Engineering
North Carolina State University and University of North Carolina at Chapel Hill, North Carolina, U.S.A.
hhuang11@ncsu.edu

***Abstract*—Individuals with upper limb amputations rely on prosthetic devices to perform activities of daily living. However, these technologies are often reported as being difficult to use. Prior studies have used a variety of testbeds to assess the usability of prosthetic devices. However, there is no defined strategy for selecting the most effective batteries. This study developed a task selection strategy and a test battery to assess usability of upper-limb prosthetic devices. A combination of methods was applied, including a constrained literature review, sensitivity analysis, and review of fundamental upper-limb movements. Findings suggest that the clothespin relocation task (CRT) and Southampton hand assessment protocol (SHAP) are the most sensitive testbeds for usability assessment of upper-limb prosthetic devices and these tasks require similar limb movements to high frequency ADLs.**

Keywords—Amputee, activity of daily living, prosthetic, testbed

I. Introduction

Limb amputation can cause severe functional disability for performance of activities of daily living (ADLs). There are more than 2.1 million persons with limb loss in the United States [1]. About 35% of these cases were upper limb amputations. Upper limb amputee patients use prosthetic devices on a regular basis to perform ADLs. Without these devices, ADLs may not be possible or may require additional effort and time [2]. However, existing devices are often reported to be challenging to use, leading to poor utilization and rejection [3]. In a study assessing the usability of different prosthetic devices, it was found that 53% of passive hand users, 50% of body-powered hook users, and 39% of myoelectric hand users rejected prosthetic hands [4].

A. Upper-limb prosthesis control methods

Upper-limb prostheses can be categorized in three main groups, including passive, body powered, and externally powered (myoelectric) devices [5]. A passive prosthesis has no movable parts and its configuration cannot be adjusted. Body powered devices, or cable-operated limbs, work with a harness and a cable around the opposite shoulder of the injured arm. The patient can pull the cable to open the prosthetic hand (hook) by shoulder movements. Myoelectric devices, use two main types of configurations based on electromyography (EMG; muscle activation signals), including: (1) *direct control* (DC); and (2) *pattern recognition* (PR) control schemes [6]. In the DC, the magnitude of an EMG signal captured from one agonist-antagonist muscle pair proportionally controls the speed of a servo-motor [7]. Most DC systems use two independent EMG sites to control one degree-of-freedom (DOF) of prosthesis movement, such as hand open/close. A great deal of intentional effort is required for a DC configuration when more than two DOFs needs to be controlled. In addition, the DC-based prosthesis control generally produces slow movements. Due to these limitations, only 25% of upper-limb amputees use prostheses with DC mode control for performing ADLs [8]. The PR approach involves EMG pattern classification that identifies user intent based on activation patterns of residual muscle when transradial amputees imagine "executing" a motion of the missing limb. Based on user intent, the controller selects a corresponding servo-motor and controls the motor speed proportionally to the sum of the EMG intensity across all monitored muscle signals. PR algorithms have been widely investigated in prior studies as an advanced EMG control method [9]. The main disadvantage of the PR approach is that the controller must be trained for learning patterns of individual muscle activation and to make association of patterns with desired motions. In addition, the PR controller only allows users to move one joint at a time, while natural limb motions are usually multi-joint movements coordinated with high precision and versatility.

B. Activities of daily living

ADLs include most fundamental and essential functions to sustain one's life such as self-feeding, work, homemaking, cleaning, bathing, dressing, grooming and leisure. Modern prosthetic devices can help amputees perform ADLs with a mechanical wrist consisting of an active or passive rotator that enables the pronation/supination of a hand [10]. To assess their performance, researchers have used measures such as task completion time and average number of transported items. However, previous studies on usability evaluation of upper-limb prosthetic devices have not identified the logic behind their selection of ADL testbeds except that they are standardized tests for upper-limb extremity use or rehabilitation [11]. There have been no studies on the relationship between human limb movements and the selected test tasks.

C. Problem statement

Although amputee patients are able to perform ADLs with prostheses, there are several usability issues with these technologies. In order to effectively assess the usability of prosthetic devices, there is a need to define appropriate test batteries. The selected tasks should not only represent ADLs and different limb motions but should be sensitive enough to reveal device usability issues or differences among multiple devices. Therefore, the objective of the present

Funding for this research was provided by the National Science Foundation (No. IIS-1856676/1856441/1900044)
978-1-7281-5871-6/20/$31.00 ©2020 IEEE

study was to identify a test battery for assessing usability of upper-limb prosthetic devices. The identified tasks and the proposed approach may be useful for future usability assessments of technologies aimed at reducing rejection rates. The proposed test approach can be incorporated during device design and development processes.

II. Method

A. Available ADL test beds

Four standard ADL test beds have been used in prior research, including (1) Box and blocks test (B&B), (2) Jebsen-Taylor test of hand function (JHFT), (3) Clothespin relocation task (CRT), and (4) Southampton hand assessment protocol (SHAP). These tasks have been chosen to assess hand, wrist and elbow functions and replicate activities that could be reasonably completed with physical prosthetic devices. In this study, we conducted an analysis on these four testbeds in order to identify the task battery that is most sensitive to reveal usability differences among prosthetic devices and that best represents human limb movements in ADLs.

B. Constrained literature review

A literature review was conducted using the protocol for preferred reporting items for systematic reviews and meta-analysis with extension for scoping reviews (PRISMA-ScR) [13]. The initial search was conducted in November, 2019. Two databases including the Web of Science (WoS) and Compendex were systematically searched to find relevant research published since 2005 (the year in which DARPA initiated the "Revolutionizing Prosthetics" program [14]). Search terminology submitted to these databases included: ("prosthesis" or "prosthetic") and ("box and block" or "jebsen" or "clothepin" or "southampton"). Inclusion criteria for the literature review were: (1) peer-reviewed journal publications or conference proceedings, (2) English language papers, and (3) studies that presented comparisons of prosthetic devices (e.g., DC vs. PR controllers) or usability evaluations of devices.

Initially, 71 studies were identified based on researcher review of paper titles resulting from the database searches. These papers were further evaluated for relevance through abstract review. Finally, the full text of articles considered to be relevant (based on both title and abstract) was reviewed by at least two researchers from our team. Among the initial search results, 17 studies were found to meet the inclusion criteria. Each study was classified in terms of the four ADL test beds (i.e., B&B, JHFT, CRT, and SHAP).

III. Results

A. Comparison of ADL testbeds used in prosthetic device usability assessments

The Four ADL testbeds (i.e., B&B, CRT, JHFT, and SHAP) are compared in Table in terms of their characteristics, task description, and performance index. While B&B and CRT only include transporting tasks, JHFT and SHAP involve several ADL activities. Quantitative performance indices include the number of transported items or the time to complete a task. Results revealed that while the B&B, CRT, and JHFT are simple and easy to perform, the SHAP is a very detailed testbed including several tasks that can be elaborate and time-consuming.

B. Sensitivity analysis of ADL test beds for assessing usability of prosthetic devices

An analysis was conducted in order to identify the testbeds that were most sensitive in usability assessment of prosthetic devices. Findings from this analysis are shown in Table . The studies were categorized based on the testbed used, prosthetic device configuration, dependent measures, and whether findings were significant ($p < 0.05$). From the studies that used statistical analysis, 4 used B&B, one used JHFT, 6 used CRT, and 8 were focused on the SHAP. It was found that the CRT and SHAP were the most sensitive testbeds (i.e., resulted in more significant findings: CRT: 83% and SHAP: 87.5%) used in prior studies to compare the usability of different prosthetic devices.

C. Overlap between fundamental movements and ADLs

To identify the testbeds that are closely related to human upper-limb movements, we compared required movements of the CRT and SHAP tasks with fundamental upper-limb movements. For this comparison, seven upper-limb movements were selected including (a) Shoulder abduction-adduction; (b) Shoulder flexion-extension; (c) Shoulder internal-external rotation; (d) Flexion-extension of the elbow; (e) Pronation-supination of the forearm; (f) Flexion-Extension of the wrist; and (g) Radial-Ulnar deviation [15]. For example, to perform the CRT, the following upper-limb movements are required: (a), (b), (c), (d), (f), and (g). To further assess the testbeds in terms of matching ADLs, we considered the example of a driving task (Table III). Driving was selected as the task poses high psychomotor demands. Furthermore, the combination of advanced (vehicle) automation technologies and EMG- based human-machine interfaces (HMIs), such as prosthetic devices, may make ADLs, like moving within a community (or driving), more accessible for special populations. Driving includes the four basic tasks of: (1) steering, (2) turn signal activation, (3) emergency light activation, and (4) changing gears (manual shifting), which requires upper-limb movements [16]. For

TABLE I. A Comparison of ADL Test Beds

Point of Comparison	B&B	JHFT	CRT	SHAP
Characteristics	- Simple & Commonly used - 2-5 mins to complete	- 15-45 mins to complete - No specific training is required	- Several degrees of freedom (DOFs) - A rehabilitation tool - Four clothespins of different resistances (1, 2, 4, and 8 lbs)	- One of the most elaborate hand impairment evaluation test - Very detailed - Can be lengthy and tiring
Task description	- Transporting (one by one) - Number of tasks: 1	- Example of tasks: writing a short sentence, simulated feeding, picking up cans - Number of tasks: 7	- Transporting pins from a horizontal to a vertical bar - Number of tasks: 1	- Transporting - ADL - Number of tasks: 20
Quantitative performance index	The number of blocks that are successfully moved in a fix time interval	Time to complete a task	The time execution from the starting neutral position to the final neutral position	Time score (0-100): 0 corresponds to absence of hand function and 100 to a healthy hand function

example, for the task of vehicle steering, at a minimum, the upper-limb movements of (b), (c), (d), and (e) are required. The CRT, SHAP-Task 19 (rotate a screw), and SHAP-Task 20 (door handle) also require movements (b), (c), (d) and (e) and would be appropriate for testing prosthetic user capability for steering. Similar to that, for the task of controlling a turn signal, the CRT, SHAP-Task 8 (button board), and SHAP-Task 16 (lifting a tray) all require similar upper-limb movements (i.e., f and g) and could be useful for testing special population capability to use an indicator.

IV. Discussion

Previous studies on usability evaluation of prosthetic devices used a variety of testbeds, such as B&B, CRT, JHFT, and SHAP. However, no structured approach has been developed for selecting the most effective test batteries. This study identified a task selection strategy and test batteries for effectively assessing usability of prosthetic devices in terms of specific ADLs. The findings of the literature review and sensitivity analysis revealed that the CRT and SHAP are the most sensitive ADL testbeds for usability analysis of upper-limb prosthetic devices. Furthermore, in order to ensure that a testbed accurately represents a target ADL (e.g., driving), it is recommended that comparison be made of the fundamental limb movements of the ADL and those required by the testbed. For example, our study suggested that in order to evaluate the usability of upper-limb prosthetic devices for the task of vehicle steering, the CRT and SHAP (Tasks 19 and 20) can be appropriate tests due to similar upper-limb movements.

Conducting lab experiments with special populations (e.g., individuals with upper limb amputations) can be difficult, time-consuming, and costly. The approach introduced in this study can be useful to select the most relevant test batteries and can increase the efficiency of usability testing in this domain. With this approach, an experimenter can focus on specific test tasks that are directly related to a target ADL. Thus, there may be a savings of time and cost that might otherwise be committed to unnecessary tests. Another major finding of this study was that relying on only one test might not be sufficient to model an ADL. For example, even though the SHAP is a frequently used test battery, it provides very little information on compensatory movements, and it is a time-based metric that does not provide other types of performance measures, such as the number of transported items. Thus, a combination of test tasks should be adopted, based on the degree of overlap of required movements with target ADL movements with the objective of minimizing the number of tasks while still supporting a comprehensive device usability assessment [26]. In addition, some prior studies have modified test tasks to fit their specific research needs (e.g., targeted B&B, refined CRT, and Southampton adaptive manipulation scheme), which can be another approach to achieve an improved testbed [27].

This study had some limitations. First, the approach and the identified testbed were based on a constrained literature review focusing on previous studies. The findings of this study need to be further validated using laboratory experiments and user testing. Second, although the selected

TABLE II. Sensitivity Analysis

ADL test bed	Ref.	Prosthetic device configuration	Dependent variable	Results
B&B	**[17]**	PR, DC	Transporting performance (The number of items moved)	NS
	[18]	PR, DC	Transporting performance (The number of items moved)	$p<0.05$
	[19]	CSP-PE (Common Spatial Patterns - Proportional Estimator), CDE (Context Dependent Estimator)	The number of blocks moved	$p<0.001$
	[20]	Prosthetic hand for able bodied subjects with differenct levels of delay	Average blocks moved	$p<0.05$
JHFT	**[21]**	PR, DC	Time to Complete Task (TCT)	NS
CRT	**[17]**	PR, DC	Transporting performance (The number of items moved)	$p=0.02$
	[18]	PR, DC	Transporting performance (The number of items moved)	NS
	[22]	PR, DC	CRT Successful Pins	$p<0.0001$
	[27]	PR, DC	Combination of the average time to complete a task and the average subjective grade of the compensations	$p<0.001$
	[21]	PR, DC	CRT Successful Pins	$p=0.009$
	[19]	CSP-PE and CDE	TCT	$p<0.001$
SHAP	**[17]**	PR, DC	Time score (0-100)	$p=0.041$
	[18]	PR, DC	SHAP score	$p<0.05$
	[21]	PR, DC	SHAP score	$p=0.024$
	[23]	PR, DC	SHAP score	NS
	[12]	Anatomic hand, Prosthesis simulator	Time to place coins from right to left (One of SHAP tasks)	$p<0.001$
	[7]	An experimental orthosis, unconstrained arm	TCT	$p<0.05$, $p<0.05$, $p<0.001$
	[24]	Anatomic hand vs. Prosthesis simulator	Time & performance	$p<0.001$
	[25]	IH2 Azzurra artificial hand controller	SHAP score	$p<0.05$

NOTE: NS= Not significant

databases (i.e., WOS and Compendex) are the most common databases for science and engineering, it is possible that some relevant studies were not available through these databases and, consequently, were not included in our review. Finally, the sensitivity analysis should be further analyzed using a meta-analysis approach in order to validate the findings.

ACKNOWLEDGMENT

Funding for this research was provided by the National Science Foundation (No. IIS-1856676/1856441/1900044). The views and opinions expressed are those of authors.

REFERENCES

[1] Amputee Coalition, A., *Limb loss in the U.S.A.* 2018.

[2] Lusardi, M.M., M. Jorge, and C.C. Nielsen, *Orthotics and Prosthetics in Rehabilitation-E-Book*. 2013: Elsevier Health Sciences.

[3] Engdahl, S.M., et al., *Surveying the interest of individuals with upper limb loss in novel prosthetic control techniques.* Journal of neuroengineering and rehabilitation, 2015. 12(1): p. 53.

[4] Bowker, J., *The art of prosthesis prescription.* Smith DG, Michael JW, Bowker JH. American Academy of Orthopaedic Surgeons. Atlas of Amputations and Limb Deficienciens Surgical, Prosthetic and Rehabilitation Principles. 3st ed. Rosemont IL: Bone and Joint Decade, 2004: p. 739-744.

[5] Maat, B., et al., *Passive prosthetic hands and tools: A literature review.* Prosthetics and orthotics international, 2018. 42(1): p. 66-74.

[6] Zahabi, M., et al., *Application of Cognitive Task Performance Modeling for Assessing Usability of Transradial Prostheses.* IEEE Transactions on Human-Machine Systems, 2019. 49(4): p. 381-387.

[7] Parker, P.A. and R.N. Scott, *Myoelectric control of prostheses.* Critical reviews in biomedical engineering, 1986. 13(4): p. 283-310.

[8] Davidson, J., *A survey of the satisfaction of upper limb amputees with their prostheses, their lifestyles, and their abilities.* Journal of Hand Therapy, 2002. 15(1): p. 62-70.

[9] Huang, H., T.A. Kuiken, and R.D. Lipschutz, *A strategy for identifying locomotion modes using surface electromyography.* IEEE Transactions on Biomedical Engineering, 2008. 56(1): p. 65-73.

[10] Kanitz, G., et al., *Compliant Prosthetic Wrists Entail More Natural Use Than Stiff Wrists During Reaching, Not (Necessarily) During Manipulation.* Ieee Transactions on Neural Systems and Rehabilitation Engineering, 2018. 26(7): p. 1407-1413.

[11] Huinink, L.H.B., et al., *Learning to use a body-powered prosthesis: changes in functionality and kinematics.* Journal of Neuroengineering and Rehabilitation, 2016. 13.

[12] Parr, J.V.V., et al., *Examining the Spatiotemporal Disruption to Gaze When Using a Myoelectric Prosthetic Hand.* Journal of Motor Behavior, 2018. 50(4): p. 416-425.

[13] Tricco, A.C., et al., *PRISMA extension for scoping reviews (PRISMA-ScR): checklist and explanation.* Annals of internal medicine, 2018. 169(7): p. 467-473.

[14] Adee, S., *The revolution will be prosthetized.* IEEE spectrum, 2008. 46(1): p. 44-48.

[15] Leal-Naranjo, J., et al., *An experimental characterization of human arm motion.* Proceedings of MESROB2016, Medical and Service Robotics, 2016.

[16] Texas Department of Public Safety, *Texas Driver Handbook*. 2017.

[17] Hargrove, L.J., et al., Myoelectric Pattern Recognition Outperforms Direct Control for Transhumeral Amputees with Targeted Muscle Reinnervation: A Randomized Clinical Trial. Scientific Reports, 2017. 7.

[18] Hargrove, L., et al., Control within a virtual environment is correlated to functional outcomes when using a physical prosthesis. Journal of Neuroengineering and Rehabilitation, 2018. 15.

[19] Amsuess, S., et al., Context-Dependent Upper Limb Prosthesis Control for Natural and Robust Use. Ieee Transactions on Neural Systems and Rehabilitation Engineering, 2016. 24(7): p. 744-753.

[20] Farrell, T.R. and R.F. Weir, The optimal controller delay for myoelectric prostheses. Ieee Transactions on Neural Systems and Rehabilitation Engineering, 2007. 15(1): p. 111-118.

[21] Kuiken, T., L. Miller, and K. Turner. A comparison of direct control and pattern recognition control in Transhumeral TMR subjects. in ISPO World Congress. 2015.

[22] White, M.M., et al., Usability comparison of conventional direct control versus pattern recognition control of transradial prostheses. IEEE Transactions on Human-Machine Systems, 2017. 47(6): p. 1146-1157.

[23] Light, C.M., P.H. Chappell, and P.J. Kyberd, Establishing a standardized clinical assessment tool of pathologic and prosthetic hand function: normative data, reliability, and validity. Archives of physical medicine and rehabilitation, 2002. 83(6): p. 776-783.

[24] Sobuh, M.M.D., et al., Visuomotor behaviours when using a myoelectric prosthesis. Journal of Neuroengineering and Rehabilitation, 2014. 11.

[25] Segil, J.L., et al., Comparative study of state-of-the-art myoelectric controllers for multigrasp prosthetic hands. Journal of Rehabilitation Research and Development, 2014. 51(9): p. 1439-1454.

[26] Fougner, A.L., Ø. Stavdahl, and P.J. Kyberd, *System training and assessment in simultaneous proportional myoelectric prosthesis control.* Journal of neuroengineering and rehabilitation, 2014. 11(1): p. 75.

[27] Hussaini, A., W. Hill, and P. Kyberd, *Clinical evaluation of the refined clothespin relocation test: A pilot study.* Prosthetics and orthotics international, 2019: p. 0309364619843779.

TABLE III. OVERLAP BETWEEN FUNDAMENTAL MOVEMENTS OF DRIVING AND ADL TEST BEDS

Task	*Upper limb movement*	***Shoulder***			***Elbow***	***Forearm***	***Wrist***	***Hand***
		(a)	***(b)***	***(c)***	***(d)***	***(e)***	***(f)***	***(g)***
Driving	*Steering a wheel*	×	✔	✔	✔	✔	×	×
	Controlling a turn signal indicator	×	×	×	×	×	✔	✔
	Pressing an emergency light	✔	✔	×	✔	✔	✔	✔
	Changing a gear shift	✔	✔	✔	✔	✔	×	×
CRT	*Moving an object*	✔	✔	✔	✔	×	✔	✔
SHAP	*1~6. Moving an object*	✔	✔	×	✔	✔	×	✔
	7. Pick Up Coins	×	×	×	✔	×	×	✔
	8. Button Board	×	×	×	✔	×	✔	✔
	9. Simulated Food Cutting	✔	✔	✔	×	×	×	×
	10. Page Turning	×	✔	×	×	×	×	✔
	11. Jar Lid	×	✔	×	✔	×	×	×
	12. Glass Jug Pouring	×	✔	×	✔	×	×	×
	13. Carton Pouring	✔	✔	✔	×	×	×	×
	14. Lifting a Heavy Object	✔	✔	✔	×	×	×	×
	15. Lifting a Light Object	✔	✔	✔	×	×	×	×
	16. Lifting a Tray	×	✔	×	×	×	✔	✔
	17. Rotate Key	×	×	✔	×	×	×	✔
	18. Open/Close Zip	×	×	×	×	✔	×	✔
	19. Rotate A Screw	×	✔	✔	✔	✔	×	×
	20. Door Handle	✔	✔	✔	✔	✔	×	✔

NOTE: (a) Shoulder abduction-adduction; (b) Shoulder flexion-extension; (c) Shoulder internal-external rotation; (d) Flexion-extension of the elbow; (e) Pronation-supination of the forearm; (f) Flexion-Extension of the wrist; (g) Radial-Ulnar deviation.