To appear: 2019 IEEE-RAS-EMBS International Conference on Rehabilitation Robotics (ICORR), 24-28 June, 2019, Toronto, Canada, 6 pages.

Hand Function Kinematics when using a Simulated Myoelectric Prosthesis

Heather E. Williams*, Quinn A. Boser, Patrick M. Pilarski, Craig S. Chapman, Albert H. Vette,
Jacqueline S. Hebert

***Abstract*— Studies that investigate myoelectric prosthesis control commonly use non-disabled participants fitted with a simulated prosthetic device. This approach improves participant recruitment numbers but assumes that simulated movements represent those of actual prosthesis users. If this assumption is valid, then movement performance differences between simulated prosthesis users and normative populations should be similar to differences between actual prosthesis users and normative populations. As a first step in testing this assumption, the objective of this study was to quantify movement performance differences between simulated transradial myoelectric prosthesis hand function and normative hand function. Motion capture technology was used to obtain hand kinematics for 12 non-disabled simulated prosthesis participants who performed a functional object-manipulation task. Performance metrics, end effector movement, and grip aperture results were compared to 20 non-disabled participants who used their own hand during task execution. Simulated prosthesis users were expected to perform the functional task more slowly, with multiple peaks in end effector velocity profiles, and a plateau in grip aperture when reaching to pick up objects, when compared to non-disabled participants. This study confirmed these expectations and recommends that subsequent research be undertaken to quantify differences in actual myoelectric prosthesis hand function versus normative hand function.**

I. INTRODUCTION

Upper extremity amputation can be a result of traumatic injury, disease, or congenital limb loss. In 2005, over 40,000 adults in the United States were reportedly living with an upper extremity amputation [1]. Prosthetic technology continues to be developed to help individuals adapt to the functional challenges of upper limb loss. However, adult rejection rates for these devices are estimated to be 38 to 58% [2], and surveys of users point to a number of areas where improvement is desired [3].

It is important that research and development of upper limb prosthetic technology continues, in order to increase the usability of these devices. Testing new devices in a real-world setting may help to confirm their efficacy with users. However, it can be difficult to recruit a large enough sample of prosthesis users to overcome the inherent heterogeneity of a clinical group, and, as a result, small sample sizes are a common limitation in such studies [4]–[7]. To solve this limitation, many upper limb researchers opt to fit a simulated prosthesis to non-disabled participants; such devices have been used to investigate different control systems [8]–[11], hand-eye coordination [12], and feedback control systems [13]–[15].

Simulated prostheses generally consist of a brace that attaches to the forearm of a non-disabled individual, with a prosthetic terminal device extending distally or offset to the dorsal, palmar, or radial side of the user's hand. The benefit of this simulated prosthesis research approach is that it allows recruitment of participants from a greater population, thereby improving the potential for statistical validity of research findings. Although researchers have compared the function of non-disabled individuals using a simulated prosthesis to that of actual myoelectric prosthesis users, the functional tests used in these studies simply provide performance scores and/or task completion durations, with no precise details about the quality of end effector movements [7], [10], [16].

Studies of prosthesis users reveal that they perform experimental tasks slower than non-disabled individuals, with multiple peaks in end effector velocity profiles, and a plateau in grip aperture when reaching to pick up objects [5], [17]. When simulated prostheses are worn by non-disabled individuals in movement behaviour research, there is an inherent assumption that their performance will mimic that of actual prosthesis users. If this assumption holds true, then a similar variance in movement performance measurements can be expected between: (1) normative populations and individuals using simulated prostheses, and (2) normative populations and individuals using actual prostheses. This paper investigates the first of such comparisons; the identification of movement performance differences between simulated prosthesis hand function and normative hand function.

The objectives of this study were to quantify the effects of using a simulated transradial myoelectric prosthesis on movement behaviour, and to compare these effects to normative movement performance. To accomplish this

---

This work was sponsored by the Defense Advanced Research Projects Agency (DARPA) BTO under the auspices of Dr. Doug Weber and Dr. Al Emondi through the DARPA Contracts Management Office; Grant/Contract No. N66001-15-C-4015 (JSH). Partial funding support was also received through the Natural Sciences and Engineering Research Council (NSERC), as well as Alberta Innovates and Alberta Advanced Education.

H. E. Williams and A. H. Vette are with the Department of Mechanical Engineering, Faculty of Engineering, University of Alberta, Edmonton, AB T6G 1H9, Canada.

Q. A. Boser is with the Department of Biomedical Engineering, Faculty of Engineering, University of Alberta, Edmonton, AB T6G 2V2, Canada.

P. M. Pilarski and J. S. Hebert are with the Division of Physical Medicine and Rehabilitation, Department of Medicine, University of Alberta, Edmonton, AB T6G 2R3, Canada.

C. S. Chapman is with the Faculty of Kinesiology, Sport, and Recreation, University of Alberta, Edmonton, AB T6G 2R3, Canada.

*Corresponding author - email: heather.williams@ualberta.ca

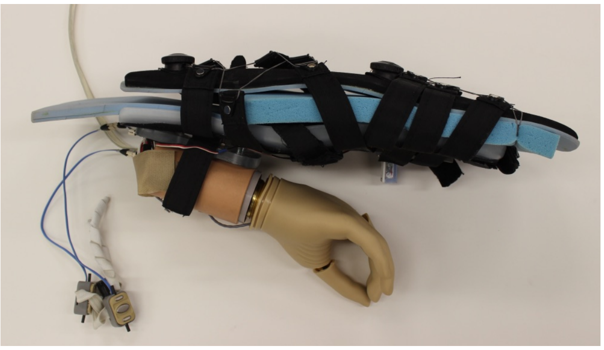

Figure 1. Simulated prosthesis, including the hand brace, myoelectric hand mounted below the brace, and surface muscle electrodes.

comparison, a functional object transfer task was used for movement data collection, from which performance metrics, end effector movement, and grip aperture measurements were derived.

II. METHODS

A. *Simulated Prosthesis Design*

The simulated sensory motor prosthesis, developed by Kuus et al. [18], was fabricated for the purpose of this study. It was intended to be worn by non-disabled individuals to simulate the function of a myoelectric prosthesis worn by an individual with a right-arm transradial amputation. The simulated prosthesis consists of: a brace to immobilize the user's wrist and hand; electrodes to read electromyography (EMG) signals from the user's forearm muscles (placed over the wrist extensor and wrist flexor muscle groups); and a myoelectric prosthetic hand mounted underneath the brace, with a slight radial offset to ensure line of sight to the terminal device. Wrist extension by the user controls the opening of the myoelectric hand, whereas wrist flexion controls the closing of the hand. Although this device was designed to also study the impact of prosthesis sensory feedback, it was used in this study to solely investigate motor control. Figure 1 provides an image of the simulated prosthesis that was used.

B. *Participants*

A group of 12 non-disabled individuals were recruited to perform a functional task while wearing the simulated prosthesis (hereafter referred to as 'simulated prosthesis participants'). These individuals had no upper-body pathology or history of neurological or musculoskeletal injuries within the past two years. Of these 12 participants, all were right-handed and 11 were male, with an average age of 23.8 ± 3.4 years (mean ± standard deviation). The data collected from the simulated prosthesis participants were compared to those of an established normative dataset from non-disabled participants [19]. The study was approved by the University of Alberta Health Research Ethics Board (Pro00054011), the Department of the Navy Human Research Protection Program (DON-HRPP), and the SSC-Pacific Human Research Protection Office (SSCPAC HRPO).

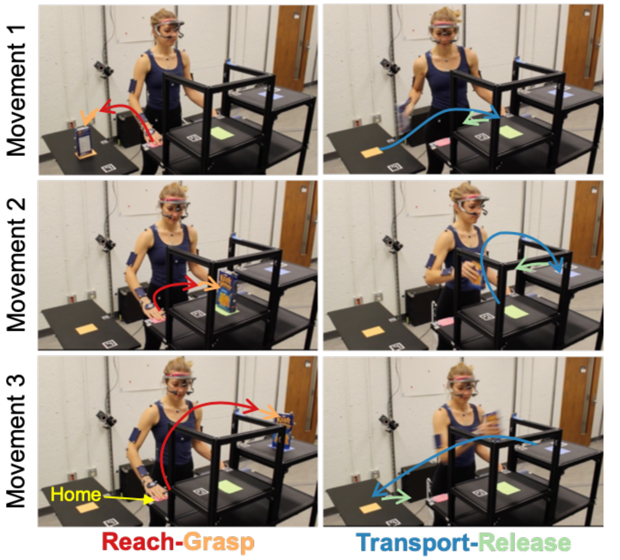

Figure 2. Sequence of the Pasta Box Task movements (Movements 1, 2, and 3) with the starting "home position" for the hand position labelled. Reach-Grasp and Transport-Release movement segments are colour-coded and illustrated with arrows to show direction of hand movements. Adapted with permission.

C. *Functional Task*

The Pasta Box Task, developed by Valevicius et al. [19], mimics the actions of reaching for a kitchen item and moving it to shelves of different heights. In this task, the participant is required to perform the following three movements: *Movement 1* – moving the pasta box from a lower side table immediately to their right (height: 30 inches) to a shelf in front of them (height: 43 inches); *Movement 2* – moving the pasta box to a second shelf at a higher height across the body (height: 48 inches); and *Movement 3* – moving the pasta box back to the starting position on the side table. The participant is required to start each movement with their hand at a "home" position, and then return their hand to this position at the completion of the movement. Each movement, as well as the "home position", is depicted in Figure 2. Following data collection, each movement can be divided into the phases of "Reach", "Grasp", Transport", and "Release", so that discrete characteristics of hand movement can be examined [19].

D. *Simulated Prosthesis Training*

Each of the simulated prosthesis participants took part in a two-hour device usage training session. During this session, the participants donned the device, were taught how to control the myoelectric hand using their muscle signals, and were given an opportunity to perform four functional tasks (including the Pasta Box Task). As the participants carried out these tasks, they were provided with verbal instructions regarding how to improve their control of the device. The participants were then given a short (5 to 10 minutes) 'free play period', wherein they grasped and transported various objects of different sizes and shapes using the simulated prosthesis. Then, in the remaining time, they were encouraged to practice performing the functional tasks independently. The participants were allowed to take breaks throughout their training session, as required.

E. *Experimental Setup*

The same 12-camera Vicon Bonita motion capture system (Vicon Motion Systems Ltd, Oxford, UK) used by Valevicius et al. [19] was used to capture the hand movements of the simulated prosthesis participants at 120 Hz. Three motion capture markers were affixed to a rigid surface on the simulated prosthesis and on the simulated hand's index finger (middle phalange) and thumb (distal phalange). Additional motion capture markers were placed on the pasta box, shelving unit, and side table, as outlined in the supplementary materials of Valevicius et al. [19].

F. *Experimental Data Acquisition and Processing*

With motion capture markers affixed and the motion capture equipment recording, each simulated prosthesis participant performed five trials of the Pasta Box Task. If they had an error during the trial, the error was flagged, and that trial was not analyzed. The data of one participant were discarded due to poor data quality. Data from a total of 46 trials (from 11 participants) were used.

The motion capture data were filtered and segmented into Reach, Grasp, Transport, and Release phases as outlined by Valevicius et al. [19]. Hand movement measures (for both the normative and simulated prosthetic hand) were calculated using the centre of the hand's three-dimensional position and its velocity. Grip aperture was measured as the distance between the index and thumb markers. Time-normalized plots of the hand trajectory, hand velocity, and grip aperture results were generated as described by Valevicius et al. [19]. Hand movement measures of peak hand velocity, percent to peak hand velocity, hand distance travelled, hand trajectory variability, and number of movement units (number of velocity peaks) were calculated for each Reach-Grasp and Transport-Release movement segment, as per Valevicius et al. [19]. In addition to these hand movement measures, the duration of each phase and the relative duration of each phase (the percent of time of the Reach-Grasp-Transport-Release sequence spent in each individual phase) were calculated.

III. RESULTS

A. *Phase Durations*

The simulated prosthesis participants had an overall task duration that was significantly longer than that of the normative participants, at 24.5 ± 2.8 seconds versus 8.8 ± 1.2 seconds, respectively ($p < 0.0001$). As shown in Table I, all phase durations were longer for simulated prosthesis participants (greater than two standard deviations) as compared to those of normative participants. Although all phases were prolonged, simulated prosthesis users consistently spent proportionally more time in Grasp and Release compared to Reach and Transport phases, as demonstrated by the relative phase durations. Specifically, Reach and Transport relative phase durations were smaller by at least two standard deviations, whereas Grasp and Release relative phase durations were larger by at least two standard deviations, except for the Movement 3 Release phase.

TABLE I. NORMATIVE AND SIMULATED PROSTHESIS ('SIMULATED') PARTICIPANT GROUP MEANS AND ACROSS-PARTICIPANT STANDARD DEVIATIONS FOR EACH MOVEMENT (MVMT) AND PHASE (REACH: R, GRASP: G, TRANSPORT: T, RELEASE: RL) OR SEGMENT (RG, TRL). TABLE CELLS THAT ARE HIGHLIGHTED INDICATE THAT THE GROUP MEAN OF THE SIMULATED PROSTHESIS PARTICIPANTS IS OUTSIDE OF TWO STANDARD DEVIATIONS OF THE NORMATIVE PARTICIPANT GROUP MEAN (RED = HIGHER AND BLUE = LOWER THAN THE NORMATIVE GROUP).

		Phase Duration (sec)		Relative Phase Duration (%)	
		Normative	Simulated	Normative	Simulated
Mvmt 1	R	0.66 ± 0.08	1.39 ± 0.28	29.0 ± 2.0	22.6 ± 4.4
	G	0.27 ± 0.08	1.63 ± 0.53	11.5 ± 2.5	25.5 ± 5.9
	T	1.08 ± 0.12	2.15 ± 0.50	47.1 ± 2.2	34.0 ± 4.0
	Rl	0.28 ± 0.07	1.16 ± 0.43	12.4 ± 2.3	17.9 ± 3.3
Mvmt 2	R	0.52 ± 0.06	1.07 ± 0.17	24.4 ± 2.0	17.2 ± 2.6
	G	0.18 ± 0.05	1.84 ± 0.43	8.3 ± 1.7	28.6 ± 5.7
	T	1.12 ± 0.13	2.05 ± 0.45	53.0 ± 2.9	32.8 ± 4.9
	Rl	0.30 ± 0.08	1.40 ± 0.61	14.2 ± 2.7	21.4 ± 6.6
Mvmt 3	R	0.65 ± 0.10	1.49 ± 0.35	26.2 ± 1.8	21.3 ± 3.8
	G	0.19 ± 0.06	2.32 ± 0.61	7.4 ± 1.8	32.5 ± 5.3
	T	1.31 ± 0.16	2.10 ± 0.38	52.9 ± 2.1	30.5 ± 4.5
	Rl	0.34 ± 0.07	1.13 ± 0.55	13.6 ± 2.2	15.7 ± 5.9
		Peak Hand Velocity (mm/s)		Percent to Peak Hand Velocity (%)	
		Normative	Simulated	Normative	Simulated
Mvmt 1	RG	1164 ± 163	812 ± 107	41.2 ± 4.5	25.8 ± 4.6
	TRl	1447 ± 136	1057 ± 188	29.3 ± 3.1	22.1 ± 5.5
Mvmt 2	RG	1352 ± 191	927 ± 195	36.8 ± 4.4	11.9 ± 2.0
	TRl	1069 ± 112	779 ± 172	44.8 ± 8.6	32.5 ± 8.4
Mvmt 3	RG	1666 ± 261	1267 ± 277	35.5 ± 4.0	11.7 ± 2.4
	TRl	1598 ± 180	1343 ± 267	36.2 ± 3.8	35.4 ± 8.6
		Hand Distance Travelled (mm)		Hand Trajectory Variability (mm)	
		Normative	Simulated	Normative	Simulated
Mvmt 1	RG	492 ± 26	747 ± 58	19 ± 5	49 ± 18
	TRl	935 ± 27	1003 ± 42	22 ± 4	72 ± 40
Mvmt 2	RG	505 ± 23	545 ± 31	15 ± 5	38 ± 19
	TRl	802 ± 61	957 ± 70	20 ± 4	58 ± 48
Mvmt 3	RG	746 ± 24	953 ± 77	19 ± 4	68 ± 29
	TRl	1186 ± 31	1407 ± 63	35 ± 8	106 ± 55
		Number of Movement Units			
		Normative	Simulated		
Mvmt 1	RG	1.3 ± 0.3	9.8 ± 3.4		
	TRl	1.2 ± 0.2	8.4 ± 3.1		
Mvmt 2	RG	1.0 ± 0.1	11.0 ± 3.7		
	TRl	2.3 ± 0.4	11.1 ± 3.6		
Mvmt 3	RG	1.1 ± 0.1	15.7 ± 4.9		
	TRl	1.7 ± 0.4	8.2 ± 3.6		

B. *Hand Velocities*

Figure 3 shows the average hand velocity profiles of both the normative and simulated prosthesis participant groups over the course of the Pasta Box Task. Simulated prosthesis participants had smaller hand velocity peaks. As shown in Table I, all velocity peaks were smaller by at least two standard deviations, except for the movement segments in

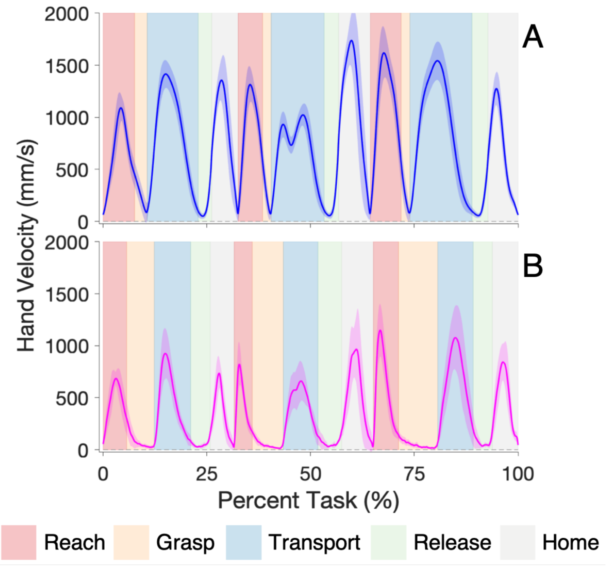

Figure 3. Hand velocity profile of the non-disabled participants (A; blue); and of the simulated prosthesis participants (B; pink). The solid lines represent participant group averages, and the shading represents the standard deviation of the participant group means. Relative duration of each phase (Reach, Grasp, Transport, Release) can be inferred from the width of the corresponding shaded bars.

Movement 3. As Movement 3 consisted of the longest Reach phase and longest Transport phase in the Pasta Box Task, simulated prosthesis participants had a greater opportunity to approach the peak velocity values of normative participants. Table I also shows that the simulated prosthesis participants had earlier hand velocity peaks for each movement segment, as compared to those of normative participants. The velocity peaks were all earlier by at least two standard deviations, except for Movement 2 and 3 Transport-Release.

C. *Hand Trajectories*

The simulated prosthesis participants had an overall hand distance travelled that was significantly longer than that of the normative participants, at 772 ± 31 cm versus 625 ± 16 cm, respectively ($p < 0.0001$). Figure 4 illustrates the average hand trajectories, as well as the standard deviations (between participants) of the trajectories, for both participant groups for all three Movements of the Pasta Box Task. The figure illustrates the varied hand trajectories that the simulated prosthesis participants took, versus those exhibited by the normative participants for all movement segments – particularly for the Movement 3 Transport-Release segment.

As shown in Table I, the hand distances travelled for each movement segment were longer for simulated prosthesis participants, as compared to those of normative participants. Specifically, all hand distances were larger by at least two standard deviations, except for the Movement 2 Reach-Grasp movement segment. Table I also shows that, for each movement segment, both the hand trajectory variabilities and the number of movement units were greater for simulated prosthesis participants (each greater than two standard deviations), as compared to those of normative participants.

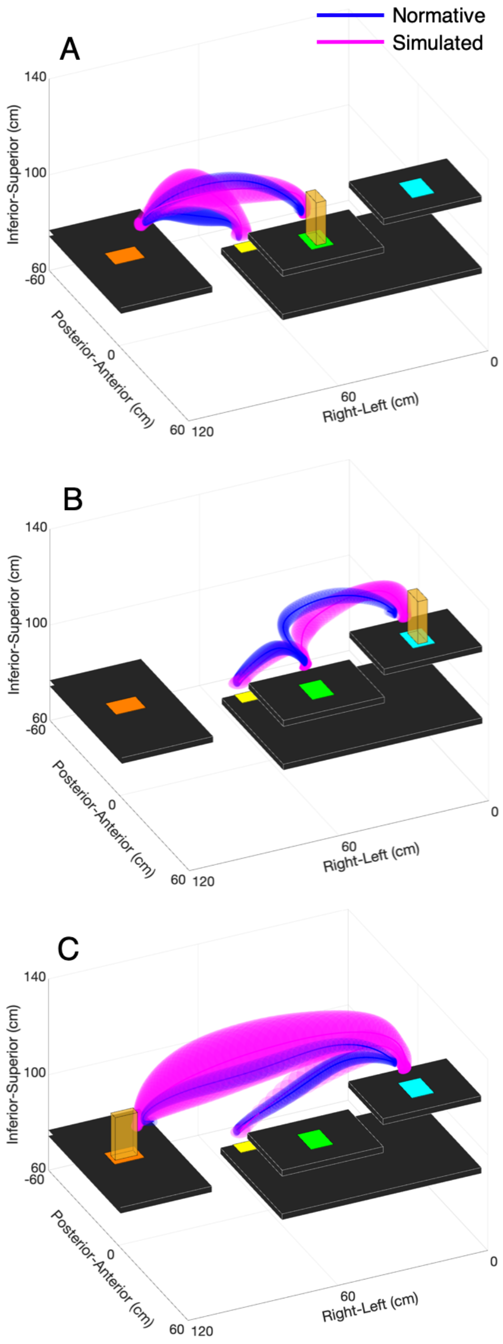

Figure 4. Hand trajectories of the non-disabled participants (blue); and of the simulated prosthesis participants (pink) for Movement 1 (A), Movement 2 (B), and Movement 3 (C). The solid lines represent participant group averages, and the three-dimensional shading represents the standard deviation of participant group means.

D. *Grip Apertures*

Figure 5 illustrates the average grip aperture profiles of the normative and simulated prosthesis participant groups over the course of the Pasta Box Task trials. The simulated prosthesis grip aperture can be seen to plateau at fully open and closed, whereas the normative grip aperture displays distinct peaks. The normative participants reached a peak grip aperture at the start of Grasp, whereas the simulated prosthesis participants had their grip aperture fully open

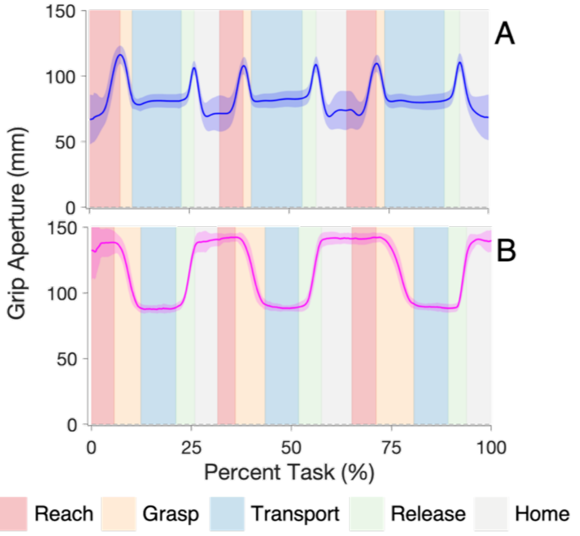

Figure 5. Grip aperture profiles of the normative participants (A; blue); and for the simulated prosthesis participants (B; pink). The solid lines represent participant group averages, and the shading represents the standard deviation of participant group means.

throughout and, in fact, prior to Reach. The simulated prosthesis participants also had delayed initiation of hand closure until after the Grasp phase had begun, whereas the normative participants began closing their hand immediately at start of Grasp. Both participant groups fully opened their grip aperture at the very end of the Release phase. However, the normative participants did not leave their hand open throughout the Home and Reach phases as did the simulated prosthesis participants.

IV. DISCUSSION

This study verifies that the use of a simulated prosthesis device for research purposes yields slower and more labored hand movement results when compared normative function.

Throughout the Pasta Box Task, simulated prosthesis participants moved slower than the normative participants, as indicated by longer phase durations and smaller velocity peaks in the comparative dataset. These results are in keeping with studies that compare the movement duration of actual myoelectric prosthesis users to normative populations [5], [6], [17]. The Grasp and Release phases performed by the simulated prosthesis participants were prolonged, presumably as these participants needed to mentally focus on flexing or extending their wrist to control their simulated hand, and to rely solely on visual feedback to judge the quality of their grasp and/or release. While a normative participant could feel the pasta box, a simulated prosthesis user likely used additional time to adjust their grasp repeatedly, before confidently attempting to transport it. The simulated prosthesis participants reached their peak hand velocity earlier in each movement sequence than the normative participants. As earlier velocity peaks have been said to indicate a more conservative control strategy [20], the simulated prosthesis participants may have perceived the task movements to be riskier than the normative participants, or were more cautious and less confident in their movements overall.

In all movement sequences of the Pasta Box Task, hand movements exhibited by the simulated prosthesis participants had a higher number of movement units and covered longer distances than those of the normative participants. These findings again align with results from actual prosthesis users. Researchers have noted an increased number of peaks in the hand velocity profiles of prosthesis users [17], which is indicative of less smooth movements. Researchers have also observed a greater curvature in the hand movements of myoelectric prosthesis users compared to norms [5], which results in greater hand distances travelled. Throughout the Pasta Box Task, simulated prosthesis participants had high hand trajectory variability. This indicates that these participants tried different hand movement paths in each of their five trials, and implies that they were still learning methods of device control during these trials, even after their training trials were completed. This suggests that longer training periods may be required prior to testing, in order to reduce learning effects.

The grip aperture profile of the simulated prosthesis participants followed a substantially different path than that of the normative participants; i.e., the simulated prosthesis grip aperture consisted of a series of plateaus, rather than peaks. Similar grip aperture profiles have been observed in prosthesis users [6]. Researchers have also identified an "uncoupling of reach and grasp" in prosthesis function that is characteristic of prosthesis users who begin to adjust their grip aperture only after the Grasp phase has begun [17]. This uncoupling pattern was also evident in this study's movement behavior of simulated prosthesis participants.

V. CONCLUSIONS

Overall, this study represents an important step toward the objective of confirming that users of simulated myoelectric prostheses perform functional tasks with movement strategies that are in agreement with those of actual users of transradial myoelectric prosthetic hands. As anticipated, this study demonstrated that simulated prosthesis participants perform the Pasta Box Task slower than normative populations, with multiple peaks in end effector velocity profiles, and a plateau in grip aperture when reaching to pick up objects. In future research, it will be important to determine whether results on simulated prosthesis movement reported by this study align with those of actual transradial myoelectric prosthetic device users.

ACKNOWLEDGMENT

The authors thank the volunteer participants in this study, as well as the staff and students at the Bionic Limbs for Natural Control (BLINC) lab for their help and support. We thank Tarvo Kuus, Brody Kalwajtys, and Ognjen Kovic for their contributions to data collection and processing.

REFERENCES

[1] K. Ziegler-Graham, E. J. MacKenzie, P. L. Ephraim, T. G. Travison, and R. Brookmeyer, “Estimating the Prevalence of Limb Loss in the United States: 2005 to 2050,” *Arch. Phys. Med. Rehabil.*, vol. 89, no. 3, pp. 422–9, 2008.

[2] E. Biddiss, D. Beaton, and T. Chau, “Consumer design priorities for upper limb prosthetics,” *Disabil. Rehabil. Assist. Technol.*, vol. 2, no. 6, pp. 346–57, 2007.

[3] F. Cordella *et al.*, “Literature review on needs of upper limb prosthesis users,” *Front. Neurosci.*, vol. 10, p. 209, 2016.

[4] J. S. Hebert and J. Lewicke, “Case report of modified Box and Blocks test with motion capture to measure prosthetic function,” *J. Rehabil. Res. Dev.*, vol. 49, no. 8, pp. 1163–74, 2012.

[5] J. Cowley, L. Resnik, J. Wilken, L. Smurr Walters, and D. Gates, “Movement quality of conventional prostheses and the DEKA Arm during everyday tasks,” *Prosthet. Orthot. Int.*, vol. 41, no. 1, pp. 33–40, 2017.

[6] C. Fraser and A. W. Wing, “A case study of reaching by a user of a manually-operated artificial hand,” *Prosthet. Orthot. Int.*, vol. 5, no. 3, pp. 151–6, 1981.

[7] M. M. D. Sobuh *et al.*, “Visuomotor behaviours when using a myoelectric prosthesis,” *J. Neuroeng. Rehabil.*, vol. 11, p. 72, 2014.

[8] M. M. White *et al.*, “Usability Comparison of Conventional Direct Control Versus Pattern Recognition Control of Transradial Prostheses,” *IEEE Trans. Human-Machine Syst.*, vol. 47, no. 6, pp. 1146–1157, 2017.

[9] 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. 1368–76, 2016.

[10] S. Amsuess *et al.*, “Context-dependent upper limb prosthesis control for natural and robust use,” *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 24, no. 7, pp. 744–53, 2016.

[11] S. Amsuess, P. Goebel, B. Graimann, and D. Farina, “Extending mode switching to multiple degrees of freedom in hand prosthesis control is not efficient,” in *2014 36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBC 2014*, 2014, pp. 658–61.

[12] J. V. V. Parr, S. J. Vine, N. R. Harrison, and G. Wood, “Examining the Spatiotemporal Disruption to Gaze When Using a Myoelectric Prosthetic Hand,” *J. Mot. Behav.*, vol. 50, no. 4, pp. 416–425, 2018.

[13] S. B. Godfrey, M. Bianchi, A. Bicchi, and M. Santello, “Influence of force feedback on grasp force modulation in prosthetic applications: A preliminary study,” in *International Conference of the IEEE Engineering in Medicine and Biology Society*, 2016, pp. 5439–5442.

[14] A. Panarese, B. B. Edin, F. Vecchi, M. C. Carrozza, and R. S. Johansson, “Humans can integrate force feedback to toes in their sensorimotor control of a robotic hand,” *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 17, no. 6, pp. 560–7, 2009.

[15] 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.*, vol. 47, no. 4, pp. 583–589, 2017.

[16] S. Amsuess, P. Goebel, B. Graimann, and D. Farina, “A multi-class proportional myocontrol algorithm for upper limb prosthesis control: Validation in real-life scenarios on amputees,” *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 23, no. 5, pp. 827–36, 2015.

[17] H. Bouwsema, C. K. van der Sluis, and R. M. Bongers, “Movement characteristics of upper extremity prostheses during basic goal-directed tasks,” *Clin. Biomech.*, vol. 25, no. 6, pp. 523–9, 2010.

[18] T. G. Kuus, M. R. Dawson, K. Schoepp, J. P. Carey, and S. Jacqueline, “Development of a simulated sensory motor prosthesis: a device to research prosthetic sensory feedback using able-bodied individuals,” in *MEC17 - A Sense of What’s to Come*, 2017.

[19] A. M. Valevicius *et al.*, “Characterization of normative hand movements during two functional upper limb tasks,” *PLoS One*, vol. 13, no. 6, 2018.

[20] E. E. Butler, A. L. Ladd, L. E. LaMont, and J. Rose, “Temporal-spatial parameters of the upper limb during a Reach & Grasp Cycle for children,” *Gait Posture*, vol. 32, no. 3, pp. 301–6, 2010.