Myoelectric Prosthesis Users and Non-Disabled Individuals Wearing A Simulated Prosthesis Exhibit Similar Compensatory Movement Strategies

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Abstract

Background: Research studies on upper limb prosthesis function often rely on the use of simulated myoelectric prostheses (attached to and operated by individuals with intact limbs), primarily to increase participant sample size. However, it is not known if these devices elicit the same movement strategies as myoelectric prostheses (operated by individuals with amputation). The objective of this study was to compare compensatory movement strategies, measured by hand and upper body kinematics, of twelve non-disabled individuals wearing a simulated prosthesis to those of three individuals with transradial amputation using their custom-fitted myoelectric devices.

Methods: Motion capture was used to obtain kinematic data as participants performed a standardized functional task. Performance metrics, end effector movements and angular kinematics were analyzed.

Results: Results show that participants using a simulated or actual myoelectric prosthesis had similar differences in phase durations, hand velocities, hand trajectories, movement units, grip aperture plateaus, and trunk and shoulder motion when compared to normative behaviour.

Conclusions: This study suggests that the use of a simulated device in upper limb research offers a reasonable approximation of compensatory movement strategies employed by a novice to mid-skilled transradial myoelectric prosthesis user.

Background

Myoelectric prostheses aim to restore or improve impaired arm and hand function so that individuals with amputation can independently accomplish activities of daily living (1). However, upper limb prosthesis use requires individuals to adapt their movement strategies to successfully execute tasks that involve object manipulation (2–4). The laborious nature of prosthesis movements is one reason for device rejection (3, 5). Innovations in prosthetic design and control strategies have attempted to improve control and function of prosthetic devices; however, the ability to test such advances is limited by the small (6) and heterogenous population of individuals with amputations (6, 7).

For these reasons, researchers studying myoelectric prostheses often use simulated prosthetic devices to assess new control methods. Simulated devices have been used to study control system alternatives (8–11), hand-eye coordination (12), feedback systems (13–15), and compensatory movements (16–18). A simulated device allows a non-disabled research participant to control a myoelectric prosthetic hand by activating their forearm muscles, in a similar manner to an individual with a transradial amputation. Simulated prostheses generally consist of a brace that attaches to the wearer's forearm, with a prosthetic terminal device (hand or hook) extending distally or offset to the dorsal, palmar, or radial side of their hand (19, 20). The benefit of using simulated devices is that they allow recruitment of a larger number of participants, with a controllable level of training experience, compared to the relatively low incidence and high heterogeneity of individuals with transradial upper limb amputation. Acquiring data from a larger number of research participants improves the statistical power of research findings.

It is assumed that non-disabled individuals fitted with simulated myoelectric prostheses will mimic the movement strategies of those who use actual myoelectric prostheses, but this has yet to be confirmed. While previous studies have included both non-disabled participants wearing simulated prostheses and myoelectric prosthesis users, they did not aim to provide a detailed comparison of hand and upper body kinematics between such groups or compared to normal non-disabled limb function. Amsuess et al. included both types of participants when comparing different device control algorithms, but only examined duration and error measures (21). Brown et al. used both such participant groups to investigate the effect of sensory feedback, but only analyzed grasping slip measures (22). Sobuh et al. included both types of participants to study visuomotor behaviour, but only analyzed gaze behaviour and task duration measures (23). Hence, despite the use of simulated prostheses in research, the inherent assumption that non-disabled individuals will exhibit similar movement compensations as actual prosthesis users remains untested.

The goal of this study was to compare compensatory movement strategies, measured by hand and upper body kinematics, of individuals wearing a simulated prosthesis to those of three myoelectric prosthesis users with transradial amputation. The study aimed to validate the research practice of using non-disabled individuals with simulated prostheses as a proxy for actual prosthesis users by examining how their movement strategies differ from expected non-disabled performance of the same tasks. A validated, standardized object transfer task (24–27) was used for kinematic data collection in both the simulated and prosthesis participant groups, from which performance metrics, end effector movements, and angular kinematics were derived and compared to known normative values.

Methods

Simulated Prosthesis Design

In this study, the simulated sensory motor prosthesis developed by Kuus et al. (20) was used. It was designed 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 rigid brace to immobilize the wearer's wrist and hand; two electrodes (electrode model: 13E200 = 60; Otto Bock Healthcare Products; Duderstadt, Germany) to read electromyography signals from the user's forearm muscles; and a myoelectric hand (MyoHand VariPlus Speed model: 8e38 = 9-R7 1/4; Otto Bock Healthcare Products) mounted underneath the brace in the approximate location of the participant's real hand, with a slight radial offset to ensure line of sight to the terminal device. The simulated prosthesis wearer controls the device by activating their wrist extensor muscles to open the hand, and the wrist flexor muscles to close the hand. Although this simulated sensory-motor prosthesis was originally designed to investigate the impact of sensory feedback (20), it was used in this study to solely examine motor control.

Participants

A group of 12 non-disabled individuals were recruited to perform a functional task while wearing the simulated prosthesis (hereafter referred to as ‘SP participants’). These individuals had no upper-body pathology or history of neurological or musculoskeletal injuries within the past two years. All SP participants were right-handed, 11 were male, with an average age of 23.8 ± 3.4 years (mean $\pm$ standard deviation) and an average height of 176.2 ± 6.2 cm.

Three individuals with transradial amputations were recruited to perform the same functional task while wearing their usual, custom-fitted myoelectric prosthesis (hereafter referred to as ‘MP participants’ – ‘P1’, ‘P2’, and ‘P3’). A pre-task assessment of the Assessment of Capacity for Myoelectric Control (ACMC) (28) was administered by a trained occupational therapist. This assessment was chosen since it is a well-validated assessment of skill level for myoelectric prosthesis users. The attributes and assessment scores of the MP participants are shown in Table 1. According to the ascending ACMC scores of the MP participants, P1 was considered to be the least-skilled, P2 mid-skilled, and P3 the most-skilled.

Table 1
Attributes of the MP participants.

Attributes	MP Participants		
	P1	P2	P3
Age (years)	41	52	37
Gender	F	M	M
Height (cm)	170	184	167
Hand dominance before amputation	Right	Left	N/A (congenital)
Amputation side	Right	Left	Left
Time between amputation and data collection	11 months	18 years	37 years
Hours of prosthesis use per day	10	13	10
Prosthetic Hand	i-Limb	i-Limb	MyoHand VariPlus Speed
ACMC score	44.6	59.1	62.0

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). Each participant provided written informed consent.

Functional Task

The Pasta Box Task, developed by Valevicius et al. (24), validated by Williams et al. (30), and used in prior prosthesis user studies (2, 29), mimics the actions of reaching for a kitchen item and moving it to shelves of different heights – thereby including common prosthesis assessment requirements. In this task, the participant is required to perform three movements: *Movement 1* – moving a 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 task. Each movement, as well as the location of ‘home’, are depicted in Fig. 1. 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 (24). Note that Fig. 1 shows the Pasta Box Task setup arranged for SP participants (who used the right-side simulated device) and the MP participant with a right-side prosthesis; however, the setup was mirrored for the two MP participants with a left-side prosthesis.

Prosthetic Device Training

Each of the SP participants took part in a two-hour device usage training session. During the session, these participants donned the device, were taught how to control the myoelectric hand using their muscle activity, and were given an opportunity to practice 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 the control of their device. The participants were allowed to take breaks throughout their training session, as required.

Given that the MP participants were to perform the functional testing with their usual prostheses, they did not require a device usage training session, but were allowed to practice the Pasta Box Task until they felt comfortable executing it.

SP Participant Experimental Setup

A 12-camera Vicon Bonita motion capture system (Vicon Motion Systems Ltd, Oxford, UK) was used to capture the three-dimensional trajectories of motion capture markers affixed to the SP participants at a sampling frequency of 120 Hz. Three individual motion capture markers were affixed to a rigid surface of the simulated prosthesis, along with additional markers on the index finger (middle phalange) and thumb (distal phalange), as shown in Fig. 2a. In accordance with Boser et al.’s *Clusters Only* model, rigid plates, each holding four markers, were placed on the participants’ upper arm, trunk, and pelvis (31). Additional individual markers were placed on the pasta box, shelving unit, and side table, as outlined in the supplementary materials of Valevicius et al. (24).

MP Participant Experimental Setup

An 8-camera Optitrack Flex 13 motion capture system (Natural Point, OR, USA) was used to capture the three-dimensional trajectories of motion capture markers affixed to the MP participants at a sampling frequency of 120 Hz. It should be noted that the reproducibility of the protocol and kinematic results across different motion capture technologies have been previously confirmed (30). A rigid plate holding four motion capture markers was affixed to the back of each MP participant’s myoelectric hand, along with individual markers on their index finger and thumb as shown in Fig. 2b. As with the SP participants, rigid plates holding four markers were placed on the upper arm, trunk, and pelvis. Additional individual

markers were placed on the pasta box, shelving unit, and side table, as outlined in the supplementary materials of Valevicius et al. (24).

Experimental Data Acquisition and Processing

Before each participant performed the functional task, a motion capture calibration using the anatomical pose was performed, as outlined by Boser et al. (31). Then, trial data were collected as follows.

SP Participants

Each of the twelve SP participants performed a total of five task trials. If they made an error during a trial, the error was flagged, and that trial's data were discarded. All data from one SP participant were discarded due to poor data quality. Data from a total of 46 trials (from eleven participants) were used in this study.

MP Participants: The goal was to obtain 20 completed trials for each MP participant. However, if multiple error trials were noted in sequence, or fatigue or frustration were noted due to inability to complete the task, the trial collection was stopped. This resulted in a different number of completed trials for each MP participant: P1 performed 8 trials, with 4 error-free; P2 performed 10 trials, with 4 error-free; and P3 performed 20 trials, with 19 error-free. All error-free trials were used in this study (total of 27 trials across MP participants).

The motion capture data were filtered and segmented into Reach, Grasp, Transport, and Release phases, as outlined by Valevicius et al. (24). The duration of each phase and relative duration of each phase were calculated. For the simulated and myoelectric prosthetic hands, a rigid body was created using the respective hand markers (the three markers on the side of the simulated prosthesis, shown in Fig. 2a, or the four markers on the back of the myoelectric prostheses, shown in Fig. 2b). Then, a virtual rectangular prism was created to represent the hand object, relative to the rigid body but with an offset so its position would be representative of the simulated or myoelectric hand's position. Hand movement measures were calculated using the centre of the virtual hand object's three-dimensional position and its velocity. Time-normalized plots of hand velocity were generated, as described by Valevicius et al. (24). Hand movement measures of peak hand velocity, percent-to-peak hand velocity, hand distance travelled, hand trajectory variability (maximum of three-dimensional standard deviation at each point in time), 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. (24). Grip aperture was measured as the distance between the index and thumb markers, and time-normalized plots of grip aperture were generated, as described by Valevicius et al. (24). Angular kinematics of the shoulder and trunk degrees of freedom (DOFs) were calculated, as outlined by Boser et al. (31). For each task movement (Movements 1, 2, and 3), ranges of motion (ROMs) were calculated for shoulder and trunk DOFs.

Data Analysis

The three MP participants were represented as individual case studies and mean values across trials for each measure were calculated separately for P1, P2, and P3. For the population of SP participants, an overall mean value was calculated for each measure by averaging across trials and participants.

To show that the SP participants exhibited movement strategies that were different from normative movement patterns, they were compared to the mean values of non-disabled individuals, collected by Valevicius et al. (24, 25). Both datasets followed a normal distribution for each measure, as determined through the use of the Kolmogorov-Smirnov test. To investigate differences between these two groups, a series of mixed analyses of variance (ANOVAs) and pairwise comparisons were conducted for each measure and task. Mixed ANOVA group effects or interactions involving group were followed up with either an additional mixed ANOVA or pairwise comparisons between groups if the Greenhouse-Geisser corrected p value was less than 0.05. Pairwise comparisons were considered to be significant if the Bonferroni corrected p value was less than 0.05.

The MP participants were individually compared to the normative baseline. Based on the commonly used convention of defining the normative reference range as two standard deviations above and below the mean (32), the individual P1, P2, and P3 mean values were judged, for each measure, as different from that of the normative baseline if they fell outside of 2 standard deviations (between-participant) of the corresponding normative mean. The aim was to observe the differences in the SP participants compared to the normative baseline, and the differences in the MP participants compared to the normative baseline, to identify similar compensatory strategies.

Results

Phase Duration

The SP participants had an average overall task duration of 24.5 ± 2.8 seconds, which was significantly longer than the normative duration of 8.8 ± 1.2 seconds (24) ($p < 0.01$). The three MP participants (P1, P2, and P3) had average overall task durations of 32.7 ± 2.8 seconds, 25.5 ± 4.1 seconds, and 18.8 ± 0.7 seconds, respectively, which were all more than two standard deviations larger than the normative mean. As shown in Fig. 3, the SP participants had similar phase durations to P2. P1 typically took more time to complete each phase versus the SP participants, whereas P3 took less time (although they still took more time than normative participants). As shown in Table 2, the SP participants had significantly longer durations than the normative baseline for all phases. The MP participants also had durations that were more than two standard deviations longer than the normative mean for all phases.

Table 2
Duration and hand movement measures.

		Duration (sec)					Relative Duration (%)				
		ND	SP	P1	P2	P3	ND	SP	P1	P2	P3
M 1	R	0.66 ± 0.08	↑ 1.39 ± 0.28**	↑ 1.61 ± 0.21	↑ 1.39 ± 0.09	↑ 1.21 ± 0.11	29.0 ± 2.0	↓ 22.6 ± 4.4**	↓ 22.0 ± 1.9	↓ 22.0 ± 3.3	↓ 24.3 ± 2.5
	G	0.27 ± 0.08	↑ 1.63 ± 0.53**	↑ 1.80 ± 0.21	↑ 2.21 ± 0.47	↑ 1.10 ± 0.37	11.5 ± 2.5	↑ 25.5 ± 5.9**	↑ 24.6 ± 1.7	↑ 34.4 ± 4.2	↑ 21.6 ± 6.0
	T	1.08 ± 0.12	↑ 2.15 ± 0.50**	↑ 3.06 ± 0.62	↑ 1.83 ± 0.21	↑ 2.17 ± 0.19	47.1 ± 2.2	↓ 34.0 ± 4.0**	↓ 42.3 ± 9.8	↓ 28.7 ± 1.5	43.4 ± 5.0
	RL	0.28 ± 0.07	↑ 1.16 ± 0.43**	↑ 0.82 ± 0.55	↑ 0.94 ± 0.16	↑ 0.54 ± 0.15	12.4 ± 2.3	↑ 17.9 ± 3.3**	11.1 ± 6.8	14.9 ± 2.6	10.8 ± 3.1
M 2	R	0.52 ± 0.06	↑ 1.07 ± 0.17**	↑ 2.12 ± 0.70	↑ 0.96 ± 0.08	↑ 0.97 ± 0.09	24.4 ± 2.0	↓ 17.2 ± 2.6**	↓ 25.0 ± 7.4	↓ 17.0 ± 1.1	24.2 ± 2.8
	G	0.18 ± 0.05	↑ 1.84 ± 0.43**	↑ 1.00 ± 0.40	↑ 1.63 ± 0.22	↑ 0.67 ± 0.15	8.3 ± 1.7	↑ 28.6 ± 5.7**	11.5 ± 2.8	↑ 29.1 ± 5.2	↑ 16.4 ± 2.7
	T	1.12 ± 0.13	↑ 2.05 ± 0.45**	↑ 3.71 ± 1.45	↑ 1.86 ± 0.23	↑ 1.84 ± 0.16	53.0 ± 2.9	↓ 32.8 ± 4.9**	↓ 43.0 ± 11.2	↓ 32.8 ± 2.0	↓ 45.8 ± 2.6
	RL	0.30 ± 0.08	↑ 1.40 ± 0.61**	↑ 1.78 ± 0.94	↑ 1.21 ± 0.50	↑ 0.55 ± 0.08	14.2 ± 2.7	↑ 21.4 ± 6.6**	↑ 20.6 ± 10.2	↑ 21.1 ± 7.7	13.5 ± 1.4
M 3	R	0.65 ± 0.10	↑ 1.49 ± 0.35**	↑ 1.75 ± 0.52	↑ 1.64 ± 0.57	↑ 1.31 ± 0.10	26.2 ± 1.8	↓ 21.3 ± 3.8*	↓ 17.9 ± 4.8	↓ 22.0 ± 3.5	28.5 ± 1.5
	G	0.19 ± 0.06	↑ 2.32 ± 0.61**	↑ 1.81 ± 0.28	↑ 2.84 ± 2.45	↑ 0.46 ± 0.10	7.4 ± 1.8	↑ 32.5 ± 5.3**	↑ 18.6 ± 2.7	↑ 32.9 ± 13.7	10.1 ± 1.7
	T	1.31 ±	↑ 2.10	↑ 2.74	↑ 2.30	↑ 2.36 ± 0.31	52.9 ± 2.1	↓ 30.5	↓ 28.3	↓ 32.3	51.4 ± 6.1

		0.16	± 0.38**	± 0.24	± 0.31		± 4.5**	± 3.1	± 7.5		
	RL	0.34 ± 0.07	↑ 1.13 ± 0.55**	↑ 3.40 ± 0.18	↑ 0.87 ± 0.28	↑ 0.46 ± 0.28	13.6 ± 2.2	15.7 ± 5.9	↑ 35.2 ± 2.7	12.8 ± 5.9	10.0 ± 5.9
		Peak Hand Velocity (mm/s)					Percent-to-Peak Hand Velocity (%)				
		ND	SP	P1	P2	P3	ND	SP	P1	P2	P3
M 1	RG	1164 ± 163	↓ 812 ± 107**	873 ± 117	1038 ± 132	↓ 714 ± 61	41.2 ± 4.5	↓ 25.8 ± 4.6**	↓ 17.7 ± 2.4	↓ 16.3 ± 1.7	↓ 27.3 ± 5.7
	TRL	1447 ± 136	↓ 1057 ± 188**	↓ 682 ± 33	↓ 1053 ± 179	↓ 860 ± 47	29.3 ± 3.1	↓ 22.1 ± 5.5**	28.4 ± 3.8	↓ 22.2 ± 4.4	↑ 37.2 ± 5.1
M 2	RG	1352 ± 191	↓ 927 ± 195**	↓ 663 ± 32	1018 ± 96	↓ 702 ± 62	36.8 ± 4.4	↓ 11.9 ± 2.0**	↓ 14.1 ± 3.8	↓ 9.9 ± 0.7	↓ 17.0 ± 3.1
	TRL	1069 ± 112	↓ 779 ± 172**	↓ 463 ± 64	971 ± 99	↓ 661 ± 49	44.8 ± 8.6	↓ 32.5 ± 8.4**	36.2 ± 10.2	32.8 ± 7.5	48.5 ± 5.4
M 3	RG	1666 ± 261	↓ 1267 ± 277**	↓ 1030 ± 199	1389 ± 125	↓ 1104 ± 98	35.5 ± 4.0	↓ 11.7 ± 2.4**	↓ 16.1 ± 2.1	↓ 11.4 ± 5.7	↓ 18.1 ± 2.0
	TRL	1598 ± 180	↓ 1343 ± 267*	↓ 931 ± 47	1432 ± 160	↓ 1210 ± 87	36.2 ± 3.8	35.4 ± 8.6**	↓ 24.4 ± 1.4	37.8 ± 4.9	↑ 44.1 ± 2.7
		Hand Distance Travelled (mm)					Hand Trajectory Variability (mm)				
		ND	SP	P1	P2	P3	ND	SP	P1	P2	P3
M 1	RG	492 ± 26	↑ 747 ± 58**	↑ 745 ± 51	↑ 957 ± 31	↑ 595 ± 30	19 ± 5	↑ 49 ± 18**	↑ 32	↑ 46	↑ 44
	TRL	935 ± 27	↑ 1003 ± 42**	↑ 1043 ± 10	↑ 1097 ± 28	912 ± 24	22 ± 4	↑ 72 ± 40**	↑ 54	↑ 44	↑ 52
M 2	RG	505 ± 23	↑ 545 ± 31**	↑ 627 ± 138	↑ 615 ± 21	↓ 428 ± 12	15 ± 5	↑ 38 ± 19**	↑ 48	18	16
	TRL	802	↑ 957	↑	↑ 977 ±	832	20 ±	↑ 58	↑ 83	↑	15

		± 61	± 70**	969 ± 150	61	± 30	4	± 48**	121	
M 3	RG	746 ± 24	↑ 953 ± 77**	↑ 1075 ± 12	↑ 1110 ± 252	748 ± 25	19 ± 4	↑ 68 ± 29**	↑ 40 153	23
	TRL	1186 ± 31	↑ 1407 ± 63**	↑ 1723 ± 105	↑ 1462 ± 22	↑ 1324 ± 23	35 ± 8	↑ 106 ± 55**	↑ 79 101	↑ 52
Number of Movement Units										
		ND	SP	P1	P2	P3				
M 1	RG	1.3 ± 0.3	↑ 9.8 ± 3.4**	↑ 8.8 ± 2.4	↑ 10.3 ± 3.9	↑ 4.7 ± 1.6				
	TRL	1.2 ± 0.2	↑ 8.4 ± 3.1**	↑ 6.0 ± 1.4	↑ 5.3 ± 1.0	↑ 3.8 ± 1.3				
M 2	RG	1.0 ± 0.1	↑ 11.0 ± 3.7**	↑ 9.0 ± 1.8	↑ 6.8 ± 1.9	↑ 3.3 ± 1.0				
	TRL	2.3 ± 0.4	↑ 11.1 ± 3.6**	↑ 11.3 ± 6.1	↑ 7.5 ± 3.1	↑ 4.3 ± 1.2				
M 3	RG	1.1 ± 0.1	↑ 15.7 ± 4.9**	↑ 9.3 ± 1.5	↑ 15.5 ± 12.2	↑ 3.4 ± 1.2				
	TRL	1.7 ± 0.4	↑ 8.2 ± 3.6**	↑ 13.0 ± 2.4	↑ 5.8 ± 1.3	↑ 4.1 ± 0.7				

Non-disabled ('ND') baseline and SP group duration and hand movement means and across-participant standard deviations, and MP participant (P1, P2, P3) means and standard deviations for each movement (M) and phase (Reach: R, Grasp: G, Transport: T, Release: RL) or movement segment (RG or TRL). For SP values, pairwise comparison results are indicated with asterisks (* for $p < 0.05$, ** for $p < 0.005$). Arrows indicate that a given SP mean was significantly different from the normative mean, or that an MP mean was outside of two standard deviations of the non-disabled mean (↑ indicating higher and ↓ indicating smaller).

As shown in Table 2, most deviations from normative values trended in the same direction for the SP and MP participants. The SP participants had significantly longer relative phase durations than the normative baseline for all grasp and most release phases, and, consequently, significantly shorter relative phase

durations for all reach and transport phases. P1 and P2 exhibited this trend throughout most of the task, although P3 only exhibited this trend in four phases, with the majority of their relative phase durations within two standard deviations of the normative baseline).

Hand Velocity

Table 2 identifies that the SP participants exhibited significantly smaller hand velocity peaks than the normative baseline throughout the task, since they performed the task slower. P3 exhibited this trend throughout the task, as did P1 during most movement segments, although P2 generally had peak hand velocity means that were closer to those of the normative baseline. The deviation of the SP and MP participants' peak hand velocities from normative means is also shown in Fig. 4a, with all such values below the normative means.

The SP participants exhibited significantly earlier hand velocity peaks than the normative baseline in all reach-grasp movement segments, and the MP participants all exhibited this trend throughout the task (Fig. 4b, Table 2). For transport-release movement segments, most SP and MP data points for percent-to-peak hand velocity were within or close to two standard deviations of the normative means (Fig. 4b, Table 2).

Hand Trajectory

The SP participants had significantly greater hand distances travelled than the normative baseline throughout the task. P1 and P2 also had hand distances travelled that were more than two standard deviations greater than the normative means (Table 2, Fig. 4c). P3, however, only exhibited this trend in two movement segments.

SP participants had significantly greater hand trajectory variability than the normative baseline throughout the task. P1 also exhibited this trend throughout the task, and P2 exhibited this trend for most of the task. However, P3 only followed this trend in half of the movement segments.

Finally, the SP participants had a significantly larger number of movement units than the normative baseline in all movement segments. All three MP participants also had more than two standard deviations more movement units than the normative means throughout the task (Fig. 4d).

Grip Aperture

The grip aperture profiles of the SP and MP participants (Fig. 5a) were all visually different from that expected with normative reach and grasp (Fig. 5b), demonstrating a plateau during the early to mid-reach phase. P2's grip aperture profile was most comparable to that of the SP participants, with the exception of the grip aperture magnitudes during Transport phases. This finding is explained by the observation that P2 could only successfully complete the task by grasping the 7-inch × 3.5-inch × 1.5-inch pasta box by its 3.5-inch side to perform the task, rather than its 1.5-inch side, in order to complete the task successfully. P1's grip aperture profile was also made up of plateaus at hand open or hand closed, although that participant demonstrated early hand opening before the end of the Transport phase; P1

placed the pasta box *close to* the desired targets and then pushed the box to these locations. Finally, P3's grip aperture profile also contained plateaus, although they closed the hand while moving it back to the home location, similar to the normative individuals.

Angular Kinematics

Figure 6 illustrates the ROM values for the SP participant group and three MP participants, for trunk and shoulder DOFs, as well as the normative baseline. As shown in Table 3, the SP participants exhibited significantly greater ROMs in trunk flexion/extension and lateral bending throughout the task when compared to the normative baseline, and significantly smaller ROMs in shoulder flexion/extension throughout the task and trunk axial rotation in movement 3. As shown in Table 3 and in Fig. 6, P1 exhibited these same differences, as their mean ROMs in these DOFs and movements were outside of 2 standard deviations from the corresponding normative means. P3 exhibited these ROM trends in trunk axial rotation and shoulder flexion/extension, as well as for trunk flexion/extension in Movement 3 and in trunk lateral bending in Movements 1 and 3. P2 also exhibited the same ROM trend in trunk flexion/extension, trunk lateral bending in Movements 1 and 3, and in shoulder flexion/extension Movements 2 and 3. However, P2 exhibited greater ROMs in trunk axial rotation in Movement 2 and in shoulder abduction/adduction in Movements 1 and 3. It should also be noted that the SP participants generally exhibited large variability in their ROMs (e.g. in shoulder flexion/extension in all movements, and in trunk flexion/extension in Movements 1 and 3), indicating that the participants employed different compensatory strategies from each other.

Table 3
Angular kinematic ranges of motion.

		Range of Motion (degrees)				
		ND	SP	P1	P2	P3
Trunk Flexion/Extension	Movement 1	4.9 ± 1.6	↑ 22.8 ± 11.7**	↑ 9.9 ± 0.7	↑ 27.1 ± 2.6	6.8 ± 1.1
	Movement 2	3.6 ± 1.0	↑ 8.0 ± 2.0**	↑ 9.9 ± 1.8	↑ 8.4 ± 2.0	5.1 ± 0.8
	Movement 3	4.9 ± 1.4	↑ 30.4 ± 15.4**	↑ 12.6 ± 1.6	↑ 33.5 ± 4.0	↑ 17.6 ± 4.4
Trunk Lateral Bending	Movement 1	8.7 ± 2.8	↑ 27.9 ± 10.1**	↑ 23.4 ± 1.2	↑ 18.8 ± 1.4	↑ 20.8 ± 2.4
	Movement 2	5.6 ± 2.0	↑ 10.6 ± 5.1**	↑ 10.4 ± 2.1	9.4 ± 1.3	4.3 ± 0.6
	Movement 3	11.8 ± 2.8	↑ 26.6 ± 7.7**	↑ 32.3 ± 1.4	↑ 18.1 ± 2.6	↑ 27.0 ± 2.9
Trunk Axial Rotation	Movement 1	17.8 ± 2.4	20.6 ± 4.4	16.4 ± 1.1	20.3 ± 5.5	15.8 ± 1.1
	Movement 2	15.1 ± 3.0	14.6 ± 2.5	15.3 ± 1.0	↑ 21.1 ± 1.2	13.9 ± 1.1
	Movement 3	25.5 ± 3.0	↓ 19.9 ± 3.9**	↓ 18.2 ± 2.0	27.1 ± 2.5	↓ 17.5 ± 1.6
Shoulder Flexion/Extension	Movement 1	69.3 ± 7.6	↓ 49.1 ± 13.8**	↓ 39.8 ± 3.5	58.2 ± 8.2	↓ 51.5 ± 4.2
	Movement 2	72.1 ± 9.7	↓ 48.9 ± 15.8**	↓ 45.9 ± 2.9	↓ 43.8 ± 1.9	↓ 51.2 ± 2.4
	Movement 3	86.0 ± 9.9	↓ 54.1 ± 17.2**	↓ 45.7 ± 1.5	↓ 60.8 ± 5.6	↓ 52.9 ± 2.7
Shoulder Abduction/Adduction	Movement 1	19.3 ± 6.5	22.4 ± 8.8	20.7 ± 2.6	↑ 39.1 ± 2.3	28.8 ± 3.8
	Movement 2	25.6 ± 8.8	23.4 ± 12.9	21.6 ± 3.7	26.8 ± 1.6	31.2 ± 2.0
	Movement 3	28.9 ± 9.1	29.4 ± 10.6	28.1 ± 3.3	↑ 55.6 ± 3.5	43.4 ± 2.6
Shoulder Internal/ External Rotation	Movement 1	44.0 ± 7.9	38.5 ± 14.7	45.4 ± 5.5	37.2 ± 2.9	36.4 ± 3.7
	Movement 2	32.6 ± 6.7	35.0 ± 12.4	23.4 ± 5.4	26.4 ± 3.4	33.5 ± 2.5
	Movement 3	54.2 ±	46.7 ±	51.7 ±	42.5 ±	42.0 ±

	3	6.8	13.8	3.0	3.3	3.3
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Non-disabled ('ND') baseline and SP group range of motion means and across-participant standard deviations, and MP participant (P1, P2, P3) means and standard deviations for each movement. Ranges of motion were calculated for the following degrees of freedom: trunk flexion/extension, lateral bending, and axial rotation; shoulder flexion/extension, abduction/adduction, and internal/external rotation. For SP values, pairwise comparison results are indicated with asterisks (** for $p < 0.005$). Arrows indicate that a given SP mean was significantly different from the normative mean, or that an MP mean was outside of two standard deviations of the non-disabled mean ($\uparrow$ indicating higher and $\downarrow$ indicating smaller).

Discussion

Users of simulated prostheses and actual myoelectric prosthesis users must employ movement compensations to achieve tasks in comparison to non-disabled individuals (24, 25). Prior work that compared the hand function metrics of individuals wearing a simulated prosthesis to those of non-disabled participants (33) demonstrated that those using the simulated device performed the Pasta Box Task slower, with prolonged grasp and release phases, smaller and earlier hand velocity peaks, larger hand distances travelled, increased hand trajectory variability, and more movement units (33). We have extended this work to identify that the compensatory movement strategies exhibited by SP users trend in the same direction as the compensations of actual myoelectric prosthesis users, acknowledging that such strategies might be associated with device skill proficiency.

Results of this study reveal that both SP and MP participants took longer to perform the task than non-disabled individuals, with the SP phase durations most closely resembling those of the mid-skilled MP participant. This is in keeping with Sobuh et al.'s observation that individuals wearing simulated prostheses have functional task performance durations that are similar to the average durations of myoelectric prosthesis users (23). The relative phase durations of the SP participants and least- and mid-skilled MP participants indicated they specifically took longer to grasp and release objects, with less relative time spent reaching and transporting the object. Given that skill level is associated with movement time duration (34), grasp and release phases were presumably prolonged because object manipulation (grasping and releasing) is more difficult to master than object transfer. The MP participant that was rated the most skilled by the ACMC expectedly demonstrated more assured object manipulation with less relative prolongation of grasp and release (only 2 grasp phases prolonged).

The SP participants and least- and mid-skilled MP participants had larger hand distances travelled than the non-disabled individuals. The most-skilled MP user, however, had values that were closer to those of the non-disabled individuals, which may reflect a more efficient reach and transport path. The SP participants and least- and mid-skilled MP participants also had larger hand trajectory variability than the normative baseline, whereas the most-skilled MP user only exhibited this trend in half of the movement segments, which may have been indicative of confidence when performing the task. However, all the SP and MP participants had larger number of movement units than the non-disabled baseline, indicating a common experience of device movement challenges. Additionally all SP and MP participants had earlier

reach-grasp hand velocity peaks, indicating a common conservative control strategy (35) and perceived difficulty in grasping an object.

The SP participants had comparable grip aperture profiles to the least- and mid-skilled MP participants, all of which showed a series of plateaus. Additionally, all of these participants displayed an uncoupling of reach and grasp, consistent with observations reported by other studies of myoelectric prosthesis use (36). The grip aperture profile of the most-skilled MP participant was more similar to that of non-disabled participants (37). This most-skilled participant closed their hand while moving it back to home (rather than keeping it open) and did not exhibit an uncoupling of reach and grasp. However, this participant still exhibited small plateaus when their hand was fully open, which is in keeping with Bouwsema et al.'s observation that myoelectric prosthesis users with higher skill levels exhibit shorter hand open plateaus (34).

The trunk and shoulder kinematic results reveal that SP and MP participants exhibited similar body movement compensations, with larger trunk flexion/extension and lateral bending movements in comparison to non-disabled individuals. These findings are consistent with prior studies of myoelectric prosthesis users performing different functional tasks (3, 16, 38). The SP and MP participants also exhibited smaller shoulder flexion/extension ROMs than non-disabled individuals, in keeping with previous observations of myoelectric (16) and other upper limb prostheses users (2). Carey et al. noted that the constraint due to a wrist-immobilizing brace while using the intact hand did not produce the same magnitudes of compensatory movements as those introduced by myoelectric prosthesis use (16). This finding suggests that wrist immobilization alone does not adequately simulate myoelectric prosthesis use, but rather, myoelectric hand grasp function also affects the compensatory movements observed. Finally, the simulated prosthesis users exhibited large variability in their ROMs, which is in keeping with Major et al.'s observation that myoelectric prosthesis users tend to exhibit varied kinematic movement strategies between each other (38).

This study was not without limitations. The three MP users recruited for this study may not have been a true representation of the population, although they did present a range of skill levels. Group statistical analyses could not be performed for the MP participants, so additional MP user data could further support the inferences presented, notwithstanding the large heterogeneity of prosthesis users, which may dilute group comparisons. Another influence on the study was the amount of training that the SP participants received, since presumably more practice would result in more efficient movement strategies (39), and may have changed certain results closer to the more skilled prosthesis user. The type of training provided might also explain the large between-participant standard deviation for the ROMs of the SP participants. As the training session involved primarily instruction regarding prosthetic hand grasp control (rather than training on movement strategies), SP participants adopted various trunk and shoulder movements to accomplish the task. The impact of additional training on kinematic strategies would be an important area of future study, as well as determining the optimal amount of practice needed for SP participants to accurately represent the varied skill levels exhibited by prosthesis users. Finally, since only one simulated prosthesis design was investigated in this study with one complex functional task, the

findings cannot be directly applied to other simulated devices if the designs are substantially different (e.g., if placement of the terminal device is distal to the arm (23), rather on the palmar side).

Conclusions

Overall, this study suggests that participants using a simulated prosthesis reach for and transport objects using comparable compensatory movement strategies to those of a novice to mid-skilled transradial myoelectric user, with respect to grasp strategy, hand movements, and angular kinematics. The influence of training and task practice on simulated prosthesis performance requires further investigation to formulate additional profiles of more highly skilled myoelectric prosthesis users. Broadly, this study provides reassurance for kinematic research that employs simulated devices to study transradial myoelectric prostheses operation, and presents recommendations towards further assessments of the validity of this research practice.

List Of Abbreviations

ACMC

Assessment of Capacity for Myoelectric Control; ANOVA:analysis of variance; DOF:degree of freedom; MP:myoelectric prosthesis; ROM:range of motion; SP:simulated prosthesis

Declarations

Ethics approval and consent to participate

Ethical approval for these procedures was obtained by the University of Alberta Health Research Ethics Board (Pro00054011), the Department of the Navy Human Research Protection Program, and the SSC-Pacific Human Research Protection Office.

Consent for publication

All participating subjects signed informed consent for this study and subsequent publications, and all identifying features were removed.

Availability of data and materials

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

The study design was conceived by J.H., A.H., C.C, and P.P, and H.W. carried out data collection and analysis, with input from all authors. The manuscript was written by H.W., edited by J.H., and reviewed by all authors.

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References

1. Cordella F, Ciancio AL, Sacchetti R, Davalli A, Cutti AG, Guglielmelli E, et al. Literature review on needs of upper limb prosthesis users. *Front Neurosci.* 2016;10:209.
2. Hebert JS, Boser QA, Pilarski PM, Valevicius AM, Vette AH, Tanikawa H, et al. Quantitative Eye Gaze and Movement Differences in Visuomotor Adaptations to Varying Task Demands Among Upper-Extremity Prosthesis Users. *JAMA Netw Open.* 2019;2(9):e1911197.
3. Metzger AJ, Dromerick AW, Holley RJ, Lum PS. Characterization of compensatory trunk movements during prosthetic upper limb reaching tasks. *Arch Phys Med Rehabil.* 2012;93(11):2029–34.
4. Hussaini A, Zinck A, Kyberd P. Categorization of compensatory motions in transradial myoelectric prosthesis users. *Prosthet Orthot Int.* 2017;41(3):286–93.
5. Biddiss E, Chau T. Upper-limb prosthetics: Critical factors in device abandonment. *Am J Phys Med Rehabil.* 2007;86(12):977–87.
6. Ziegler-Graham K, MacKenzie EJ, Ephraim PL, Travison TG, Brookmeyer R. Estimating the Prevalence of Limb Loss in the United States: 2005 to 2050. *Arch Phys Med Rehabil.* 2008;89(3):422–9.

7. Krueger CA, Wenke JC, Ficke JR. Ten years at war: Comprehensive analysis of amputation trends. *J Trauma Acute Care Surg*. 2012;73(6):438-44.
8. White MM, Zhang W, Winslow AT, Zahabi M, Zhang F, Huang H, et al. Usability Comparison of Conventional Direct Control Versus Pattern Recognition Control of Transradial Prostheses. *IEEE Trans Human-Machine Syst*. 2017;47(6):1146–57.
9. Johansen D, Cipriani C, Popovic DB, Struijk LNSA. Control of a Robotic Hand Using a Tongue Control System-A Prosthesis Application. *IEEE Trans Biomed Eng*. 2016;63(7):1368–76.
10. Amsuess S, Vujaklija I, Goebel P, Roche AD, Graimann B, Aszmann OC, et al. Context-dependent upper limb prosthesis control for natural and robust use. *IEEE Trans Neural Syst Rehabil Eng*. 2016;24(7):744–53.
11. Amsuess S, Goebel P, Graimann B, Farina D. Extending mode switching to multiple degrees of freedom in hand prosthesis control is not efficient. In: *Proceedings of the 36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*. 2014. p. 658–61.
12. Parr JVV, Vine SJ, Harrison NR, Wood G. Examining the Spatiotemporal Disruption to Gaze When Using a Myoelectric Prosthetic Hand. *J Mot Behav*. 2018;50(4):416–25.
13. Godfrey SB, Bianchi M, Bicchi A, Santello M. Influence of force feedback on grasp force modulation in prosthetic applications: A preliminary study. In: *Proceedings of the 38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. Orlando, USA; 2016. p. 5439–42.
14. Panarese A, Edin BB, Vecchi F, Carrozza MC, Johansson RS. Humans can integrate force feedback to toes in their sensorimotor control of a robotic hand. *IEEE Trans Neural Syst Rehabil Eng*. 2009;17(6):560–7.
15. Clemente F, Dosen S, Lonini L, Markovic M, Farina D, Cipriani C. Humans Can Integrate Augmented Reality Feedback in Their Sensorimotor Control of a Robotic Hand. *IEEE Trans Human-Machine Syst*. 2017;47(4):583–9.
16. Carey SL, Jason Highsmith M, Maitland ME, Dubey RV. Compensatory movements of transradial prosthesis users during common tasks. *Clin Biomech*. 2008;23(9):1128–35.
17. Wang SL, Bloomer C, Kontson K. Comparing Methods of Upper-Limb Prosthesis Simulation in Able-Bodied: Bracing vs. Body-Powered Bypass Prosthesis. *Arch Phys Med Rehabil*. 2018;99(10):e49.
18. Bloomer C, Wang S, Kontson K. Kinematic analysis of motor learning in upper limb body-powered bypass prosthesis training. *PLoS One* [Internet]. 2020;15(1):e0226563. Available from: <http://dx.doi.org/10.1371/journal.pone.0226563>.
19. Wilson AW, Blustein DH, Sensinger JW. A third arm - Design of a bypass prosthesis enabling incorporation. In: *Proceedings of the 2017 International Conference on Rehabilitation Robotics (ICORR)*. 2017. p. 1381–6.
20. Kuus TG, Dawson MR, Schoepp K, Carey JP, Hebert JS. Development of a simulated sensory motor prosthesis: a device to research prosthetic sensory feedback using able-bodied individuals. In: *Proceedings of MEC17 - A Sense of What's to Come*. 2017.

21. Amsuess S, Goebel P, Graimann B, Farina D. A multi-class proportional myocontrol algorithm for upper limb prosthesis control: Validation in real-life scenarios on amputees. *IEEE Trans Neural Syst Rehabil Eng.* 2015;23(5):827–36.
22. Brown JD, Paek A, Syed M, O'Malley MK, Shewokis PA, Contreras-Vidal JL, et al. Understanding the role of haptic feedback in a teleoperated/prosthetic grasp and lift task. In: *Proceedings of the 2013 World Haptics Conference (WHC)* [Internet]. Daejeon, South Korea: IEEE; 2013 [cited 2019 Apr 9]. p. 271–6. Available from: <http://ieeexplore.ieee.org/document/6548420/>.
23. Sobuh MMD, Kenney LPJ, Galpin AJ, Thies SB, McLaughlin J, Kulkarni J, et al. Visuomotor behaviours when using a myoelectric prosthesis. *J Neuroeng Rehabil.* 2014;11:72.
24. Valevicius AM, Boser QA, Lavoie EB, Murgatroyd GS, Pilarski PM, Chapman CS, et al. Characterization of normative hand movements during two functional upper limb tasks. *PLoS One.* 2018;13(6):e0199549.
25. Valevicius AM, Boser QA, Lavoie EB, Chapman CS, Pilarski PM, Hebert JS, et al. Characterization of normative angular joint kinematics during two functional upper limb tasks. *Gait Posture.* 2019;69:176–86.
26. Lavoie EB, Valevicius AM, Boser QA, Kovic O, Vette AH, Pilarski PM, et al. Using synchronized eye and motion tracking to determine high-precision eye-movement patterns during object-interaction tasks. *J Vis.* 2018;18(6):18.
27. Williams HE, Chapman CS, Pilarski PM, Vette AH, Hebert JS. Gaze and Movement Assessment (GaMA): Inter-site validation of a visuomotor upper limb functional protocol. *bioRxiv.* 2019.
28. Hermansson LM, Fisher AG, Bernspång B, Eliasson A. Assessment of Capacity for Myoelectric Control: A new Rasch-built measure of prosthetic hand control. *J Rehabil Med.* 2005;37(3):166–71.
29. Valevicius AM, Boser QA, Chapman CS, Pilarski PM, Vette AH, Hebert JS. Compensatory strategies of body-powered prosthesis users reveal primary reliance on trunk motion and relation to skill level. *Clin Biomech.* 2020;72:122–9.
30. Williams HE, Chapman CS, Pilarski PM, Vette AH, Hebert JS. Gaze and Movement Assessment (GaMA): Inter-site validation of a visuomotor upper limb functional protocol. *PLoS One.* 2019;14(12):e0219333.
31. Boser QA, Valevicius AM, Lavoie EB, Chapman CS, Pilarski PM, Hebert JS, et al. Cluster-based upper body marker models for three-dimensional kinematic analysis: Comparison with an anatomical model and reliability analysis. *J Biomech.* 2018;72:228–34.
32. Bland JM. Normal range or reference interval. *An Introduction to Medical Statistics.* 3rd ed. Oxford: Oxford University Press; 2000.
33. Williams HE, Boser QA, Pilarski PM, Chapman CS, Vette AH, Hebert JS. Hand Function Kinematics when using a Simulated Myoelectric Prosthesis. In: *Proceedings of the 2019 IEEE 16th International Conference on Rehabilitation Robotics (ICORR).* Toronto, Canada; 2019. p. 169–74.
34. Bouwsema H, Kyberd PJ, Hill W, van der Sluis CK, Bongers RM. Determining skill level in myoelectric prosthesis use with multiple outcome measures. *J Rehabil Res Dev.* 2012;49(9):1331–48.

35. Butler EE, Ladd AL, LaMont LE, Rose J. Temporal-spatial parameters of the upper limb during a Reach & Grasp Cycle for children. *Gait Posture*. 2010;32(3):301–6.
36. Bouwsema H, van der Sluis CK, Bongers RM. Movement characteristics of upper extremity prostheses during basic goal-directed tasks. *Clin Biomech*. 2010;25(6):523–9.
37. Valevicius AM, Jun PY, Hebert JS, Vette AH. Use of optical motion capture for the analysis of normative upper body kinematics during functional upper limb tasks: A systematic review. *J Electromyogr Kinesiol*. 2018;40:1–15.
38. Major MJ, Stine RL, Heckathorne CW, Fatone S, Gard SA. Comparison of range-of-motion and variability in upper body movements between transradial prosthesis users and able-bodied controls when executing goal-oriented tasks. *J Neuroeng Rehabil*. 2014;11:132.
39. Shmuelof L, Krakauer JW, Mazzoni P. How is a motor skill learned? Change and invariance at the levels of task success and trajectory control. *J Neurophysiol*. 2012;108(2):578–94.

Figures

Figure 1

Pasta Box Task. Sequence of the Pasta Box Task movements (Movements 1, 2, and 3) with the 'home' position labelled. Reach-Grasp and Transport-Release movement segments are colour-coded and illustrated with arrows to show direction. Although this figure shows a normative participant wearing an eye tracking device, eye gaze behaviour data were not analyzed in this study. Reproduced from Valevicius et al. (24) with permission.

Figure 2

Motion capture marker placement. Placement on the simulated prosthesis (a), and a myoelectric prosthesis (b). The unlabelled marker on the simulated prosthesis in panel (a) was not used for analysis in this study.

Figure 3

Phase Durations. Average Pasta Box Task durations of normative participants ('Norm'), SP participants, and the three MP participants (P1, P2, P3). These durations are presented for each movement of the task and are divided into Reach, Grasp, Transport, and Release phases, color coded as per legend.

Figure 4

Hand movement measures. Peak hand velocity (a), percent-to-peak hand velocity (b), hand distance travelled (c), and number of movement units (d) of the SP participants (black) and the MP participants (P1: blue, P2: red, P3: green), for each task movement and movement segment (RG: reach-grasp, TRL: transport-release). Dots indicate the average value for each movement segment, and each error bar represents ± 1 standard deviation (between-participant standard deviation is presented for SP

participants). The ranges of motion of a normative baseline (25) are presented with grey lines representing the average and with shading representing ± 2 between-participant standard deviations.

Figure 5

Grip aperture profiles. Profiles of the SP participants (black) and of the MP participants (P1: blue, P2: red, P3: green) (a) and of the normative baseline (24) (grey, b) over the course of the Pasta Box Task (all 3 movements). The solid lines represent averages and the shading represents ± 1 standard deviation (between-participant standard deviation is presented for SP participants). The average (all SP and MP participants) relative durations of each phase (Reach, Grasp, Transport, Release, Home) can be inferred from the width of the corresponding colored bars. Grip aperture profiles were time normalized by phase and resampled using these average relative phase durations. Normative grip aperture plots are shown in a separate panel due to the differences between normative relative phase durations and those of the SP and MP participants.

Figure 6

Angular kinematic ranges of motion. Ranges of motion of the SP participants (black) and the MP participants (P1: blue, P2: red, P3: green), for each degree of freedom and each task movement. Dots indicate the average range of motion for each movement, and each error bar represents ± 1 standard deviation (between-participant standard deviation is presented for SP participants). The ranges of motion

of a normative baseline (25) are presented with grey lines representing the average and with shading representing ± 1 between-participant standard deviation.