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EMG Pattern Recognition Control of the DEKA Arm: Impact on User Ratings of Satisfaction and Usability

LINDA RESNIK[1,2], FRANTZY ACLUCHE[1], MATT BORGIA[1], GAIL LATLIEF[3], AND SAM PHILLIPS[4]
[1]Research Department, Providence VA Medical Center, Providence, RI 02908, USA
[2]Health Services, Policy and Practice, Brown University, Providence, RI 02903, USA
[3]Department of PM&R, James A. Haley Veterans' Hospital, Tampa, FL 33612, USA
[4]Department of Rehabilitation and Engineering Laboratories, James A. Haley Veterans' Hospital, Tampa, FL 33612, USA
CORRESPONDING AUTHOR: L. RESNIK (linda.resnik@va.gov)

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ABSTRACT The DEKA Arm has multiple degrees of freedom which historically have been operated primarily by inertial measurement units (IMUs). However, the IMUs are not appropriate for all potential users; new control methods are needed. The purposes of this study were: 1) to describe usability and satisfaction of two controls methods—IMU and myoelectric pattern recognition (EMG-PR) controls—and 2) to compare ratings by control and amputation level. A total of 36 subjects with transradial (TR) or transhumeral (TH) amputation participated in the study. The subjects included 11 EMG-PR users (82% TR) and 25 IMU users (68% TR). The study consisted of in-laboratory training (Part A) and home use (Part B). The subjects were administered the Trinity Amputation and Prosthesis Experience satisfaction scale and other usability and satisfaction measures. Wilcoxon rank-sum tests compared the differences by control type. The differences were compared for those who did and did not want a DEKA Arm. The preferences for features of the DEKA Arm were compared by control type. The comparisons revealed poorer ratings of skill, comfort, and weight among EMG-PR users. The TR amputees using IMUs rated usability more favorably. TH amputees rated usability similarly. The TR amputees using EMG-PR were less satisfied with weight, pinch grip, and wrist display, whereas the TH amputees were less satisfied with the full system, wires/cables, and battery. Usability and satisfaction declined after Part B for EMG-PR users. Overall, we found that the IMU users rated the DEKA Arm and the controls more favorably than the EMG-PR users. The findings indicate that the EMG-PR system we tested was less well accepted than the IMUs for control of the DEKA Arm.

INDEX TERMS Patient satisfaction, pattern recognition, prosthesis, usability.

I. INTRODUCTION

Although there have been numerous technological advances in upper limb prosthetic hardware and controls in the past decade, the rates of reported prosthetic abandonment remain high. The U.S. government has made major investments in the development of new upper limb prostheses and controls. One example is the DEKA Arm, an advanced multi-degree of freedom (DOF) upper limb prosthesis [1]. During the development phase, the Department of Veterans Affairs conducted an optimization study which evaluated end-users' perspectives on the device and made recommendation for improvements [2]. The resulting Generation 3 prototype utilized inertial measurement units (IMU) worn on the feet to control the multiple degrees of freedom and functions of the device [1], [3].

The usability of the IMU controlled Gen 3 DEKA Arm was recently evaluated in a home study [4]. Usability is the usefulness of a device, and its perceived value for the purpose for which it is intended [5]. Data published from home study showed that subjects rated usability of the overall DEKA Arm and IMU controls as "easy", and indicated that they were "happy" with the Arm's overall function Arm, and IMU controls.

A qualitative evaluation of user experiences with IMU controls showed that most, but not all, were satisfied with them [3]. Although IMUs enable control of many more degrees of freedom than dual site myoelectric (EMG) control, they have disadvantages. Because IMUs are operated by tilting the foot, they cannot be used when lower limb control is severely compromised. To maximize safety and prevent unintended prosthesis movement, they go into standby and cannot be activated when the user is walking or moves their ankle suddenly [3]. Alternatives to IMU control of the DEKA Arm would overcome these limitations.

One promising alternative is EMG pattern recognition (EMG-PR) [6]–[12]. Unlike direct EMG control, EMG-PR does not utilize independent muscle contractions. Instead, EMG-PR uses the myoelectric activity from groups or patterns of muscles that are mapped to prosthesis movements. Supplementary funding was received to extend the Home Study to evaluate EMG-PR control of the DEKA Arm. This manuscript reports on the usability and satisfaction evaluation of EMG-PR controlled DEKA Arm and compares ratings by control type and amputation level.

II. METHODS AND PROCEDURES

A. THE DEKA ARM OVERVIEW

The DEKA Arm, now called the LUKE Arm (Mobius Bionics, Manchester, NH) is available in three configuration levels: radial configuration (RC) for persons with a transradial (TR) amputation; humeral configuration (HC) for most persons with transhumeral (TH) amputation; and shoulder configuration (SC) for persons with a shoulder disarticulation, forequarter or very short TH amputation. A full description of the device has been reported [1]. The sub-analyses reported in this manuscript pertain to subjects using the RC and HC devices.

The RC and HC have six powered grip patterns, powered wrist flexion/extension (combined with ulnar and radial deviation) and powered wrist pronation/supination. The HC also has powered elbow flexion/extension and humeral internal/external rotation movements. The RC operates only in hand mode to control grip open/close and wrist movements. The HC operates in hand mode and arm mode, which is used to control humeral rotation and elbow movements. Both configurations have a standby mode that deactivates device functions, and have wrist displays which indicate the grip pattern, mode of operation and power status [1], [4], [13].

B. CONTROL SCHEMES: IMU CONTROL AND EMG-PR CONTROL

The DEKA Arm can be controlled through IMUs worn on the top of the shoes [3], which can be supplemented or partially replaced with pneumatic bladders, manual switches and direct myoelectric (EMG) controls. IMUs, utilize gyroscopes and micro electromechanical systems accelerometers to sense small movements of the foot/ankle in relation to a ‘‘zero’’ position. In this study, the DEKA Arm was controlled by IMUs, sometimes in combination with other controls, or by a newly developed EMG-PR system.

To operate the IMUs, users move their feet/ankle in preprogrammed directions; each movement is assigned to a device function. IMUs have a walk detect feature that places the device into and out of standby mode, reducing the likelihood of unintentionally activating an arm function when ambulating. IMU control schemes cannot be used by persons missing both lower limbs or those who have severely impaired lower limb function.

EMG-PR controls used in this study were newly developed by Coapt LLC in collaboration with DEKA Integrated Solutions (DISC, Manchester, NH) as an experimental prototype. Research staff were trained to utilize the experimental EMG-PR systems. Two research prototypes were used; both employed 8 dome electrode pairs to register patterns of muscle contractions and one reference electrode. A calibration process mapped each distinct pattern of muscle contraction to a DEKA function [14].

EMG-PR Prototype 1 could detect up to eight distinct patterns of muscle contractions and had an external ‘‘mode switching’’ function which enabled the user to control up to 4 functions: 4 powered DOFs, or 3 DOFs and the DEKA grip selection function. Prototype 1’s electrodes and system were connected to the DEKA Arm through a Coapt control system processor, a multi-connection interface cable (i.e. mating cable), and an Arm Control Unit (ACI). All wires and components were mounted on the prosthesis socket. Pressure transducers connected to the ACI were used to operate mode switching and grip selection functions as needed.

EMG-PR Prototype 2 could detect up to twelve distinct patterns of muscle contractions which could be programmed to operate up to 6 functions of the DEKA Arm. Thus, Prototype 2 did not need to utilize mode switching to switch between arm and hand modes. Prototype 2 electrodes were connected directly to the DEKA Arm though a CAN Bus connection cable. ACIs were used to connect pressure transducers as needed. Research staff was provided with additional training when Prototype 2 was introduced.

EMG signal quality of each channel could be observed using the control software. The EMG-PR software was utilized when setting up and troubleshooting issues around control and electrode function.

C. STUDY DESIGN

The data analyzed were collected as part of the VA Home Study of an Advanced Upper Limb Prosthesis (Home Study), a quasi-experimental, multi-site study with repeated measures. The Home Study was approved by the Institutional Review Boards of the Providence VA Medical Center, Center for the Intrepid at Brooke Army Medical Center, VA NYHHS, and James A Haley VA. All provided voluntary consent to participate. Subjects were fit and trained with a DEKA Arm controlled either by IMUs or by EMG-PR. The Home Study included in-laboratory prosthetic training (Part A) and up to 3 months of DEKA home usage (Part B). Data was collected at repeated testing intervals: baseline, end of in-laboratory training (EOA), and at end of home use (EOB).

D. PARTICIPANTS

Subjects were eligible to enroll in Part A if they: were $\geq$18 years old, had an upper limb amputation at the TR, TH, shoulder disarticulation or scapulothoracic level, could undergo socket fitting for the DEKA Arm, and had no health conditions inhibiting full study participation. The sub-analysis presented in this manuscript includes only subjects with TR or TH amputation. A subset who completed Part A was eligible to enroll in Part B if they demonstrated: at least fair functional performance, consistent safety awareness during usage, and independent problem solving of minor technical problems.

E. PROSTHETIC TRAINING

Subjects participated in virtual reality environment (VRE) training with the prosthesis deactivated, and active prosthesis training with the prosthesis activated. Training sessions were led by occupational therapists (OTs). Subjects using IMUs were acclimated to functions of the controls and features of the prosthesis while performing foot movements mapped onto an avatar in the VRE environment [1], [15]. Subjects using EMG-PR used the VRE within the EMG-PR software to familiarize themselves with the controls. Once subjects demonstrated adequate control of the avatar and familiarity with the prostheses, they progressed to active training.

Subjects participated in a minimum of 5 active prosthesis training sessions, which were typically 2 hours each (10 hours of training). Training time for IMU users was capped at 20 sessions (40 hours). Additional training hours were allowed for EMG-PR users, as needed. Training sessions progressed from repeated activation of controls and grasp and release activities using each of the DEKA grip patterns, to more functional activities and bilateral activities. Active training also included several supervised community outings.

F. DATA COLLECTION

At the end of Parts A and B, all subjects were administered survey items and completed the Trinity Amputation and Prosthesis Experience (TAPES) satisfaction scale [16]. The survey items asked subjects to rate their skill level using the DEKA Arm on a scale of 0-4 (0 = ‘Very poor’ 1 = ‘Poor’ 2 = ’‘Fair’ 3 = ‘Good’ 4 = ‘Excellent’), comfort of the socket (1 = ‘Could not tolerate’ 2 = ‘Uncomfortable’ 3 = ‘Tolerable’ 4 = ‘Comfortable’ 5 = ‘Very comfortable’), perception of the DEKA Arm weight (1 = ‘Very light’ 2 = ‘Light’ 3 = ‘A little heavy’ 4 = ‘Heavy’ 5 = ‘Very heavy’), and to indicate if they wanted to receive a DEKA Arm in the future. The TAPES Satisfaction subscale is a 10-item measure of prosthesis satisfaction that uses a 5 point Likert scale (1 = Dissatisfied to 5 = Very Satisfied) to rate aspects of the prosthesis such as reliability, comfort, fit, and cosmesis [16].

At EOA the DEKA Ease of Use Measure (Usability) and DEKA Satisfaction Measure (Satisfaction) were administered [4]. Usability items employed a 6-point Likert scale (1 = ‘unable’ 2 = ‘very difficult’ 3 = ‘difficult’ 4 = ‘neither easy nor difficult’ 5 = ‘easy’ 6 = ‘very easy’). Satisfaction items utilized a 7-point scale (1 = ‘very unhappy’ 2 = ‘unhappy’ 3 = ‘mostly dissatisfied’ 4 = ‘mixed’ 5 = ‘mostly satisfied’ 6 = ‘happy’ 7 = ‘very happy’). Six usability subscales were used: Overall Usability, Batteries, Cosmetic Covering, Suspension, Tactor, and Other Controls. Additionally, there were 6 usability items that were not part of any usability subscale. We utilized 8 satisfaction subscales: Overall Satisfaction, Batteries, Cosmetic Covering, EMGs, Overall Cosmesis, Suspension, Tactor, and Other Controls, plus 3 additional satisfaction items.

We developed additional items to evaluate aspects of the EMG-PR controls (EMG-PR Usability and Satisfaction). All new items were administered at the EOA and 12 items were administered at EOB. These items were grouped into potential subscales related to calibration or general EMG-PR control use, and item-test correlations and Cronbach’s alphas were used to establish reliability of the proposed subscales. Items with low item-test correlations ($r < 0.50$) were removed from subscales, resulting in 2 new usability subscales with 1 additional item that did not fit and 2 satisfaction subscales with 4 separate items that did not fit. The final 4 subscales were: Calibration Usability (5 items; $\alpha = 0.80$), EMG-PR Usability (4 items; $\alpha = 0.64$), Calibration Satisfaction (3 items; $\alpha = 0.92$), and EMG-PR Satisfaction (3 items; $\alpha = 0.82$). Test statistics for the new metrics are shown in Table 8.

At the EOB, subjects who were prosthesis users were asked 10 survey questions about their preferences for the features of the DEKA Arm or their own prosthesis. These items pertained to hand function, controls, prosthesis weight, wrist function, hand cosmesis, overall cosmesis, socket comfort, prosthesis usage experience, elbow function (TH only); and overall function.

G. DATA ANALYSES

Subject demographics were examined using descriptive statistics. Wilcoxon rank-sum tests were used to compare differences between EMG-PR and IMU users. Self-reported skill, socket comfort, perception of weight, TAPES, and desire to receive a DEKA Arm ratings were compared for the full sample at the end of Parts A and B. Comparisons by control type of the DEKA Usability and Satisfaction measures (at EOA) were stratified by amputation level.

Descriptive statistics for all EMG-PR subscales and items at EOA and EOB were examined. Wilcoxon signed-ranks tests were used to compare EOA and EOB ratings among EMG-PR users (N = 11) for the EMG-PR Related subscales and any items with paired data. Mean subscale scores at EOA and EOB were compared graphically.

Preliminary estimates of concurrent and discriminant validity were evaluated by calculating Spearman correlations between the EMG-PR Related Usability and Satisfaction subscales and the skill, socket comfort, and weight

TABLE 1. Characteristics of participants by amputation level.

	EMG-PR (N=11)			IMU (N=25)		
	TR (N=9)	**TH (N=2)**	**Total**	**TR (N=17)**	**TH (N=8)**	**Total**
	Mn (sd)	**Mn (sd)**	**Mn (sd)**	**Mn (sd)**	**Mn (sd)**	**Mn (sd)**
Age	46.5 (18.3)	32.5 (6.0)	44.9 (17.4)	38.7 (15.0)	52.1 (10.9)	43.0 (15.0)
Training visits	22.0 (8.9)	12.5 (3.5)	22.5 (8.3)	6.9 (2.8)	10.0 (2.9)	7.9 (3.1)
	N (%)	**N (%)**	**N (%)**	**N (%)**	**N (%)**	**N (%)**
Sex						
Male	7 (77.9)	2 (100.0)	9 (81.8)	14 (82.4)	8 (100.0)	22 (88.0)
Female	2 (22.2)	0 (0.0)	2 (18.2)	3 (17.7)	0 (0.0)	3 (12.0)
Prosthesis user at baseline						
No	0 (0.0)	1 (50.0)	1 (9.1)	4 (23.5)	0 (0.0)	4 (16.0)
Yes	19 (100.0)	1 (50.0)	10 (90.0)	13 (76.5)	8 (100.0)	21 (84.0)
Baseline testing with prosthesis						
No	2 (22.2)	1 (50.0)	3 (27.3)	5 (29.4)	1 (12.5)	6 (24.0)
Yes	7 (77.9)	1 (50.0)	8 (72.7)	12 (70.6)	7 (87.5)	19 (76.0)

TABLE 2. Responses to survey items administered at End of A (EOA) and End of B (EOB) by control type.

	EOA				EOB			
	All (N=36)	**EMG-PR (N=11)**	**IMU (N=24)**	**WRS / chisq**	**All (N=24)**	**EMG-PR (N=7)**	**IMU (N=17)**	**WRS / chisq**
	Mn (sd)	**Mn (sd)**	**Mn (sd)**	**p**	**Mn (sd)**	**Mn (sd)**	**Mn (sd)**	**p**
Self-rated skill level	2.9 (0.8)	2.5 (0.7)	3.0 (0.8)	**0.071**	3.1 (0.9)	2.4 (1.0)	3.4 (0.6)	**0.016**
Socket comfort	3.6 (1.0)	3.1 (0.7)	3.8 (1.0)	**0.011**	3.6 (1.0)	2.9 (0.7)	3.9 (0.9)	**0.018**
Weight of DEKA Arm	3.4 (1.1)	4.2 (0.8)	3.1 (1.0)	**0.004**	3.3 (1.0)	4.1 (0.7)	2.9 (0.9)	**0.006**
TAPES	3.4 (0.8)	3.0 (0.6)	3.6 (0.8)	0.250	3.5 (1.1)	2.7 (1.1)	3.8 (1.0)	0.177
	N (%)	**N (%)**	**N (%)**	**p**	**N (%)**	**N (%)**	**N (%)**	**p**
Want to receive a DEKA Arm?				0.122				0.365
No	5 (13.9)	1 (9.1)	4 (16.0)		6 (25.0)	3 (42.9)	3 (17.7)	
Maybe	8 (22.2)	5 (45.5)	3 (12.0)		6 (25.0)	2 (28.6)	4 (23.5)	
Yes	23 (63.9)	5 (45.5)	18 (72.0)		12 (50.0)	2 (28.6)	10 (58.8)	

ratings and the TAPES Satisfaction scale. We hypothesized that these scales would be distinct, but that TAPES Satisfaction would be correlated with EMG-PR Satisfaction. Differences in EMG-PR usability and satisfaction subscale scores were examined by users' desire to receive a DEKA Arm (yes or maybe/vs. no) using Kruskal Wallis tests. Lastly, preferences for features of the DEKA Arm over current prosthesis (prosthesis users only) at the EOB were graphically compared by control type and amputation level.

III. RESULTS

Subject characteristics by control type group and amputation level are shown in Table 1. The sample consisted of 11 EMG-PR users (mn age 45, 82% TR, 82% male, 90% prosthesis users), 3 who used only Prototype 1 EMG-PR controls, and 25 IMU users (mn age 43, 68% TR, 88% male, 84% prosthesis users). Three participants (all TR) used only Prototype 1 of EMG-PR and DEKA integration, 2 participants utilized both prototypes (1TR, 1 TH). Seven participants (6 TR, 1TH) used only Prototype 2.

Wilcoxon rank-sum comparisons of skill level, comfort, and weight ratings, TAPES score, and desire for DEKA Arm by control type revealed significantly poorer ratings of skill level, comfort, and weight among EMG-PR users at both EOA and EOB (Table 2). The mean TAPES score and proportion of participants who wanted to receive a DEKA Arm did not differ by control type.

TABLE 3. Comparison of usability at EOA for EMG-PR and IMU controlled DEKA Arm stratified by amputation level.

	TR					**TH**				
	EMG PR (N=10)		**IMU (N=17)**		**W R-S**	**EMG PR (N=2)**		**IMU (N=8)**		**W R-S**
	N	**Mn (sd)**	**N**	**Mn (sd)**	**P**	**N**	**Mn (sd)**	**N**	**Mn (sd)**	**P**
Overall Usability Score	9	4.6 (0.4)	16	5.2 (0.6)	**0.003**	2	5.0 (0.8)	8	5.2 (0.7)	0.711
DEKA arm function	9	4.0 (1.0)	16	5.1 (0.7)	**0.001**	2	5.0 (0.0)	8	4.6 (1.1)	0.956
Full arm system	9	3.3 (0.9)	16	4.5 (1.2)	**0.012**	2	2.5 (0.7)	7	4.4 (1.1)	0.167
Pinch grip	9	5.1 (0.6)	16	5.4 (0.6)	0.335	2	5.5 (0.7)	8	5.4 (0.7)	1.000
Chuck grip	9	5.2 (0.7)	16	5.2 (0.7)	0.953	2	5.5 (0.7)	8	5.3 (0.9)	1.000
Tool grip	8	4.5 (0.9)	16	4.9 (0.8)	0.242	2	5.5 (0.7)	8	5.3 (0.9)	1.000
Power grip	9	5.2 (0.7)	16	5.4 (0.5)	0.515	2	5.5 (0.7)	8	5.6 (0.5)	1.000
Switching between grips	9	4.4 (1.2)	16	5.1 (0.8)	0.187	2	4.5 (2.1)	8	5.0 (0.5)	0.667
Wrist movements	9	4.3 (1.1)	16	4.9 (0.9)	0.164	2	5.5 (0.7)	8	5.5 (0.5)	1.000
Rotation of forearm	9	3.9 (1.1)	13	5.3 (0.5)	**0.000**	2	5.5 (0.7)	8	5.5 (0.8)	1.000
Elbow movements	1	1.0 (.)	0	. (.)	NA	2	5.5 (0.7)	8	5.5 (0.5)	1.000
Wires, cables	8	3.9 (0.6)	16	4.5 (1.3)	0.083	2	3.5 (0.7)	7	4.7 (1.1)	0.333
Wrist display - grip indicator	9	5.0 (1.0)	16	5.6 (0.9)	0.078	2	5.0 (1.4)	8	5.1 (1.1)	1.000
Wrist display - error indicator	9	5.1 (0.9)	16	5.6 (0.8)	0.178	2	5.5 (0.7)	8	5.1 (1.0)	1.000
Wrist display - battery indicator	8	5.5 (0.8)	16	5.6 (0.8)	0.563	2	5.0 (1.4)	8	5.1 (1.0)	1.000
Standby feature	9	5.3 (0.9)	16	5.5 (0.6)	0.834	2	5.5 (0.7)	8	5.5 (0.5)	1.000
Batteries Subscale Score	9	5.1 (0.8)	16	5.5 (0.5)	0.193	2	5.4 (0.9)	8	5.5 (0.5)	0.644
Battery charger	8	5.3 (0.9)	16	5.6 (0.7)	0.397	2	5.0 (1.4)	8	5.8 (0.5)	0.689
External battery life	8	5.1 (0.6)	16	5.5 (0.6)	0.176	2	5.5 (0.7)	8	5.3 (0.7)	1.000
Internal battery life	2	5.5 (0.7)	2	6.0 (0.0)	1.000	2	5.5 (0.7)	8	5.4 (0.7)	1.000
Internal battery charging	0	. (.)	2	6.0 (0.0)	NA	2	5.5 (0.7)	8	5.5 (0.5)	1.000
Cosmetic Covering Subscale Score	8	4.4 (0.7)	16	4.8 (0.8)	0.121	2	4.5 (2.1)	8	4.8 (0.7)	1.000
Hand covering	7	4.7 (0.8)	13	4.8 (0.6)	0.875	2	4.5 (2.1)	7	5.0 (1.0)	0.667
Material of hand cover	6	3.8 (0.4)	16	4.9 (1.1)	**0.014**	2	4.5 (2.1)	6	5.0 (0.6)	0.786
Finger nails	7	4.3 (0.5)	16	4.9 (0.9)	0.166	2	4.5 (2.1)	7	4.7 (0.8)	1.000
Suspension Subscale Score	9	4.1 (1.2)	16	5.0 (0.7)	**0.047**	2	5.5 (0.7)	7	5.1 (0.8)	0.667
Putting on socket and harness	9	4.0 (1.3)	16	5.0 (0.5)	**0.041**	2	5.5 (0.7)	7	4.7 (1.1)	0.500
Taking off socket and harness	9	4.4 (1.5)	16	5.2 (1.1)	0.230	2	6.0 (0.0)	7	5.4 (0.5)	0.444
Harnessing system	3	3.7 (0.6)	2	4.0 (0.0)	1.000	2	5.0 (1.4)	6	5.0 (1.3)	1.000
Tactor Subscale Score	3	4.1 (1.0)	13	5.4 (0.9)	0.064	2	5.5 (0.7)	7	5.8 (0.4)	0.833
Vibration sensors pressure	2	4.0 (1.4)	11	5.4 (1.2)	0.115	0	. (.)	3	5.7 (0.6)	NA
Vibration sensors mode change	1	4.0 (.)	9	5.3 (1.0)	0.200	2	5.5 (0.7)	7	5.9 (0.4)	0.417
Vibration sensors grip change	3	4.0 (1.0)	12	5.3 (0.9)	0.086	2	5.5 (0.7)	7	5.9 (0.4)	0.417
Other Controls Subscale Score	5	4.3 (0.8)	10	4.5 (1.1)	0.655	1	5.0 (.)	5	5.4 (0.5)	1.000
Other controls	5	4.2 (0.8)	5	4.0 (1.9)	1.000	0	. (.)	3	5.7 (0.6)	NA
Inflatable bladders –	3	4.3 (1.2)	8	4.9 (0.6)	0.612	1	5.0 (.)	4	5.3 (0.5)	1.000
Individual items										
Myoelectric controls	6	4.3 (1.0)	13	5.6 (0.5)	0.009	1	5.0 (.)	7	5.6 (0.5)	1.000
VRE software	9	5.1 (0.9)	15	5.0 (1.0)	0.834	2	5.5 (0.7)	7	5.0 (1.0)	0.917
Lateral pinch grip	9	5.1 (0.6)	16	5.3 (0.8)	0.335	2	5.5 (0.7)	8	5.5 (0.5)	1.000
Rotation of upper arm	0	NA	0	NA	NA	2	5.5 (0.7)	1	6.0 (.)	1.000

Table 3 shows descriptive statistics of usability subscales by control type, stratified by amputation level at EOA. EMG-PR users with TR amputation had significantly worse ratings compared to IMU users with TR amputation on the Overall Usability subscale, and 3 of its items (DEKA Arm function, full arm system and rotation of forearm),

TABLE 4. Comparison of satisfaction at EOA for EMG-PR and IMU controlled DEKA arm, stratified by amputation level.

	TR					**TH**				
	EMG PR (N=10)		**IMU (N=17)**		**W R-S**	**EMG PR (N=2)**		**IMU (N=8)**		**W R-S**
	N	**Mn (sd)**	**N**	**Mn (sd)**	**P**	**N**	**Mn (sd)**	**N**	**Mn (sd)**	**P**
Overall Satisfaction Score	9	4.7 (0.7)	16	5.4 (1.0)	0.076	2	4.2 (1.9)	8	5.5 (1.1)	0.400
DEKA arm function	9	4.4 (1.0)	15	5.3 (1.5)	0.110	2	3.5 (3.5)	8	5.4 (1.3)	0.600
Full arm system	9	2.8 (1.4)	16	4.3 (2.1)	0.070	2	2.0 (0.0)	8	4.9 (1.1)	**0.022**
Hardware reliability	9	3.4 (1.1)	16	5.0 (1.7)	**0.015**	2	4.5 (2.1)	8	5.3 (1.4)	0.622
Speed of hand open/close	9	5.0 (1.9)	16	6.1 (1.0)	0.136	2	5.0 (1.4)	7	6.1 (1.1)	0.333
Pinch grip	9	5.4 (1.0)	16	6.3 (0.9)	**0.046**	2	5.0 (1.4)	8	5.9 (0.8)	0.422
Chuck grip	9	5.7 (0.9)	16	5.8 (1.0)	0.814	2	5.0 (1.4)	8	5.6 (1.3)	0.511
Lateral pinch grip	9	5.7 (0.7)	16	5.8 (1.4)	0.474	2	5.0 (1.4)	8	6.1 (0.8)	0.222
Tool grip	8	4.6 (1.2)	16	5.1 (1.6)	0.324	2	5.0 (1.4)	8	5.8 (1.0)	0.511
Power grip	8	6.1 (0.6)	16	6.0 (1.0)	0.943	2	5.0 (1.4)	8	6.0 (0.8)	0.422
Switching between grips	9	4.8 (1.3)	16	5.3 (1.3)	0.402	2	3.5 (3.5)	8	5.5 (1.1)	0.600
Wrist movements	9	4.7 (1.6)	16	5.4 (1.1)	0.315	2	5.0 (2.8)	8	5.8 (1.3)	0.800
Rotation of forearm	9	4.3 (1.6)	13	5.4 (1.1)	0.159	2	4.0 (4.2)	8	5.9 (1.1)	0.711
Elbow movements	0	. (.)	0	. (.)	NA	2	5.0 (2.8)	8	5.6 (1.3)	0.778
Rotation of upper arm	0	. (.)	0	. (.)	NA	2	5.0 (2.8)	1	6.0 (.)	1.000
Weight of arm	9	1.9 (1.4)	16	4.4 (1.7)	**0.001**	2	1.5 (0.7)	8	3.9 (1.6)	0.244
Wires, cables	8	2.6 (1.5)	16	3.8 (1.9)	0.180	2	1.5 (0.7)	8	5.1 (1.4)	**0.022**
Wrist display - grip indicator	9	5.0 (0.9)	16	5.9 (1.1)	**0.025**	2	4.0 (2.8)	8	5.6 (1.8)	0.311
Wrist display - error indicator	8	5.6 (0.9)	16	5.9 (1.1)	0.348	2	4.0 (2.8)	8	5.5 (1.7)	0.511
Wrist display - battery indicator	8	6.0 (1.1)	16	5.8 (1.0)	0.672	2	4.5 (2.1)	8	5.5 (1.7)	0.511
Standby feature	9	5.3 (1.8)	16	5.8 (1.0)	0.687	2	5.0 (1.4)	8	5.9 (1.0)	0.467
Batteries Subscale Score	9	5.5 (0.9)	16	5.5 (1.1)	1.000	2	3.8 (1.1)	8	6.0 (0.9)	**0.044**
External battery charger	8	4.9 (1.7)	16	5.3 (1.8)	0.487	2	4.0 (2.8)	8	6.1 (1.0)	0.311
External battery life	9	6.0 (1.1)	16	5.6 (1.4)	0.411	2	5.0 (1.4)	8	5.8 (1.0)	0.489
Internal battery life	0	NA	0	NA	NA	2	2.0 (0.0)	8	5.9 (1.1)	**0.022**
Internal battery charging	0	NA	0	NA	NA	2	4.0 (2.8)	7	6.1 (0.9)	0.230
Cosmetic Covering Subscale Score	9	5.1 (0.9)	16	5.5 (1.3)	0.122	2	4.1 (2.7)	8	5.2 (1.0)	0.600
Hand covering	9	5.2 (1.1)	15	5.7 (0.9)	0.235	2	4.5 (2.1)	8	5.5 (1.6)	0.533
Hand cover durability	9	4.6 (1.7)	16	5.4 (1.5)	0.157	2	4.0 (2.8)	8	5.4 (0.9)	0.622
Material of hand cover	9	5.3 (1.2)	16	5.5 (1.5)	0.545	2	4.0 (2.8)	8	5.1 (1.2)	0.756
Finger nails	7	5.1 (1.1)	15	5.9 (0.8)	0.109	2	4.0 (2.8)	8	4.9 (1.2)	0.756
EMGs Subscale Score	6	4.4 (1.2)	13	6.1 (1.1)	**0.008**	0	. (.)	7	5.7 (1.1)	NA
Myoelectric controls	6	4.5 (1.0)	13	6.1 (1.1)	**0.008**	0	. (.)	7	5.4 (1.3)	NA
EMG speed	5	4.2 (1.8)	13	6.2 (1.1)	**0.019**	0	. (.)	7	6.0 (1.2)	NA
Overall Cosmesis Subscale Score	9	4.4 (1.2)	16	5.3 (1.5)	0.109	2	4.5 (2.1)	8	5.6 (1.2)	0.400
DEKA arm appearance	9	3.7 (1.7)	15	4.5 (2.0)	0.295	2	3.5 (3.5)	8	5.3 (1.3)	0.556
DEKA hand shape	9	5.3 (1.2)	16	5.7 (1.4)	0.448	2	5.0 (1.4)	8	5.9 (1.2)	0.667
DEKA hand size	9	4.3 (1.8)	16	5.5 (1.7)	0.088	2	5.0 (1.4)	8	5.8 (1.5)	0.667
Overall Cosmesis Subscale Score	9	4.4 (1.2)	16	5.3 (1.5)	0.109	2	4.5 (2.1)	8	5.6 (1.2)	0.400
DEKA arm appearance	9	3.7 (1.7)	15	4.5 (2.0)	0.295	2	3.5 (3.5)	8	5.3 (1.3)	0.556

TABLE 4. ***(Continued.)* Comparison of satisfaction at EOA for EMG-PR and IMU controlled DEKA arm, stratified by amputation level.**

DEKA hand shape	9	5.3 (1.2)	16	5.7 (1.4)	0.448		2	5.0 (1.4)	8	5.9 (1.2)	0.667
DEKA hand size	9	4.3 (1.8)	16	5.5 (1.7)	0.088		2	5.0 (1.4)	8	5.8 (1.5)	0.667
Suspension Subscale Score	9	4.4 (1.3)	16	5.8 (1.0)	**0.004**		2	4.8 (2.1)	8	5.3 (1.2)	0.711
Putting on socket and harness	9	3.3 (1.7)	16	5.4 (1.0)	**0.002**		2	4.5 (2.1)	7	5.1 (1.6)	0.667
Comfort of socket	8	4.6 (2.1)	15	6.2 (0.9)	0.062		2	6.0 (1.4)	8	5.6 (1.2)	0.800
Harnessing system	4	3.8 (1.3)	2	3.5 (0.7)	0.933		2	4.0 (2.8)	8	5.0 (1.2)	0.667
Stability of socket	8	5.4 (0.7)	16	6.3 (0.9)	**0.013**		2	4.5 (2.1)	8	5.6 (1.3)	0.444
Tactor Subscale Score	4	4.0 (1.9)	14	5.6 (1.9)	0.064		2	5.5 (0.7)	7	5.6 (1.0)	0.972
Vibration sensors pressure	3	3.3 (2.1)	12	5.4 (2.2)	0.070		0	. (.)	3	6.0 (1.0)	NA
Vibration sensors mode change	1	5.0 (.)	9	5.2 (2.2)	0.500		2	5.5 (0.7)	7	5.6 (1.0)	0.972
Vibration sensors grip change	4	4.0 (1.6)	12	5.5 (1.9)	0.101		2	5.5 (0.7)	7	5.7 (1.1)	0.944
Other Controls Subscale Scores	5	4.3 (0.8)	10	4.5 (1.1)	0.655		1	5.0 (.)	5	5.4 (0.5)	1.000
Other controls	5	4.2 (0.8)	5	4.0 (1.9)	1.000		0	. (.)	3	5.7 (0.6)	NA
Inflatable bladders –	3	4.3 (1.2)	8	4.9 (0.6)	0.612		1	5.0 (.)	4	5.3 (0.5)	1.000
Individual items											
VRE software	9	5.1 (1.5)	15	4.7 (1.4)	0.467		2	4.0 (2.8)	7	5.1 (1.1)	0.889
Taking off socket and harness	9	4.4 (0.9)	16	5.7 (1.3)	**0.006**		2	4.5 (2.1)	7	6.0 (0.8)	0.444
Level of waterproofing	7	3.1 (1.2)	16	4.8 (1.4)	**0.020**		2	3.5 (3.5)	8	5.4 (1.2)	0.578

the material of hand cover item of the Cosmetic Covering subscale, the Suspension subscale, and 1 of its items (putting on socket and harness). There were no statistically significant differences by control type on the Batteries, Tactor, or Other Controls subscales, their items, nor on any miscellaneous item. At EOA, there were no significant differences in Usability ratings among TH amputees by control type.

Comparisons of subscales and items from the DEKA Satisfaction measure (Table 4) revealed significant differences by control type in the TR group at EOA. EMG-PR users had significantly worse ratings on 4 items from the Overall Subscale (hardware reliability, pinch grip, weight of arm, and wrist display grip indicator), the EMGs subscale and its 2 items (myoelectric controls and EMG speed), the Suspension subscale and 2 of its items (putting on harness and stability of socket), and 2 miscellaneous individual items (taking off socket and harness and level of waterproofing.) There were no significant differences by control type on the Batteries, Cosmetic Covering, Overall Cosmesis, Tactor, and Other Controls subscales. EMG-PR users with TH amputation had significantly worse ratings on 2 items from the Overall Satisfaction subscale (full arm system, and wires, cables), the Batteries subscale and 1 of its items (internal battery life) at EOA.

Descriptive statistics for EMG-PR Usability and Satisfaction subscales and items available are shown in Tables 5 and 6. Wilcoxon signed-ranks paired comparisons (not shown) found no significant differences between EOA and EOB. However, paired ratings of 3 of 4 subscales were lower at EOB (Fig 1). Only the Calibration Satisfaction subscale improved at EOB.

Spearman correlations between EMG-PR related Usability and Satisfaction subscales and ratings of skill level, comfort, weight, and TAPES score (Table 7) showed a statistically significant and strong correlation between the EMG-PR Satisfaction and the TAPES ($r = 0.84$, $p = 0.01$), but no other significant correlations. There were differences by control type in preference for DEKA Arm with a greater proportion of subjects with TR amputation using IMU controls preferring all features of the DEKA Arm except appearance (Fig 2). All subjects with TH amputation, regardless of control type, preferred the function of the DEKA hand and wrist to their own prosthesis. Subjects with TH amputation using IMU controls were more likely to prefer the other features of the DEKA Arm (Fig 3).

IV. DISCUSSION

This study utilized structured survey items and quantitative metrics to compare usability and satisfaction by control type. We found that after laboratory training EMG-PR users rated their skill of using the DEKA Arm as ‘‘fair’’, whereas IMU users rated their skill as ‘‘good’’, despite the fact that EMG-PR users received more training than IMU users. This suggests that more prosthetic training is needed for EMG-PR, but that training may not yield equivalent results. No data is available on the optimal amount of training needed for EMG-PR control, and it is likely that amount of training needed would vary by amputation level and number of prosthetic DOF. EMG-PR users rated the DEKA Arm as ‘‘heavy’’, whereas IMU users rated it as ‘‘a little heavy’’. EMG-PR users also rated the socket as less comfortable as compared to IMU users (both sub-groups scores in the ‘‘tolerable’’ range).

TABLE 5. Scores of EMG-PR related usability items at EOA and EOB, all participants.

	EOA (N=11)		EOB (N=7)	
	N	**Mn (sd)**	**N**	**Mn (sd)**
Calibration Usability Subscale Scores	8	4.7 (0.7)	5	3.8 (0.6)
Coapt button to initiate calibration	8	5.0 (1.1)	5	4.4 (0.5)
Coapt calibration with video	6	5.2 (0.8)	5	3.2 (0.8)
Coapt calibration with wrist display	5	4.0 (1.6)	3	3.7 (0.6)
Save/delete calibration data	7	4.9 (0.9)	5	3.8 (1.6)
Calibrate using Coapt LED lights	6	4.5 (0.5)	4	3.8 (0.5)
Calibration usability items not included in subscale				
Calibration sound indicator	8	5.5 (0.8)	5	4.4 (0.9)
Coapt calibration	8	4.5 (1.3)	0	NC
Calibration hand movement indicator	8	4.8 (1.3)	0	NC
Calibrate using Coapt software on the laptop	0	NC *	5	4.0 (0.7)
Recognize successful calibration by seeing prosthesis movement after calibration	0	NC	5	4.4 (0.5)
EMG-PR Usability Subscale Scores	8	4.8 (0.8)	5	4.1 (0.5)
Coapt speed	8	4.8 (1.0)	5	3.6 (1.1)
Donning with Coapt electrodes	7	4.9 (1.5)	5	4.4 (0.5)
Reproduce consistent patterns during calibration	6	4.2 (0.8)	5	3.8 (1.1)
Understand grip select indicator lights on the Coapt system	6	4.7 (0.5)	4	4.8 (0.5)
Coapt controls	8	4.4 (1.3)	0	NC
Coapt pattern movement wrist	5	4.2 (1.3)	0	NC
Coapt pattern movement video	5	5.4 (0.9)	0	NC

*NC=data not collected at timepoint

Overall, findings demonstrate that TR amputees using EMG-PR found the DEKA Arm more difficult to use as compared to those using IMUs; rating Overall Usability and the DEKA Arm function, full Arm system, and rotation of the forearm lower than IMU users. EMG-PR users with TR amputation also were less satisfied with the weight, pinch grip, and the wrist display as compared to TR users of IMUs. These findings are interesting, given that weight, pinch grip and the wrist display of both systems were identical. It is possible that the weight of the prosthesis impacted EMG-PR users differentially. This finding is supported by data from our qualitative study in which users explained how the device weight led to fatigue and contributed to problems in consistency of controls operation [17]. However qualitative analyses did not provide insight into why EMG-PR users may have been less satisfied with grip and wrist display. It may have been due to inconsistency of EMG-PR controls. Users of EMG-PR for grip selection selected a muscular pattern that was physiologically unrelated to the action of changing grip. This may have contributed to the lower satisfaction with grips.

In contrast, there were no differences in usability ratings for TH amputees using EMG-PR or IMUs, but statistically significant differences in satisfaction items related to the full arm system, wires and cables, Batteries Subscale and internal battery life. Prior analyses reported that the EMG-PR system drained the internal battery quickly, and provides rich examples of user complaints about the external wires and cables [17].

The EMG-PR specific usability and satisfaction subscales and items developed for this study provided a quantitative assessment of calibration and overall EMG-PR controls function. Subjects were generally neutral about usability. The lowest ratings were for saving and deleting calibration data, reproducing consistent patterns during calibration, and wrist calibration. Qualitative analyses described user challenges with learning to use and using the calibration function, which help to explain these ratings [17]. The EMG-PR system could not save a calibration that had worked well and reload it at another time. This may have made some hesitant to recalibrate when minor problems arose, because they would lose the earlier settings entirely.

The items rated as most usable were using the Coapt video and using the calibration sound indicator. Notably, these features are part of the commercially available control system and presumably have been well tested. Usability items were rated lower at EOB, with all items rated less than "easy". The lowest rated items were calibration with wrist display

TABLE 6. Scores of EMG-PR related satisfaction items at EOA and EOB, all participants.

	EOA (N=11)		**EOB (N=7)**	
	N	**Mn (sd)**	**N**	**Mn (sd)**
Calibration Satisfaction Subscale Score	8	4.4 (0.9)	5	4.7 (1.3)
Coapt calibration with wrist display	5	3.8 (1.6)	5	5.6 (0.5)
Save/delete calibration data	7	4.1 (2.1)	5	4.2 (2.0)
Calibrate using Coapt LED lights	6	5.5 (0.8)	5	4.2 (1.9)
Calibration satisfaction items not included in subscale				
Coapt button to initiate calibration	8	5.1 (1.5)	5	5.8 (0.8)
Coapt calibration with video	6	4.3 (1.0)	5	5.8 (0.8)
Calibration sound indicator	8	6.0 (0.8)	4	5.3 (1.0)
Coapt calibration	8	4.4 (1.8)	0	NC
Calibration hand movement indicator	8	4.5 (2.1)	0	NC
Calibrate using Coapt software on the laptop	0	NC	5	5.2 (1.9)
Recognize successful calibration by seeing prosthesis movement after calibration	0	NC	5	5.8 (0.8)
EMG-PR Satisfaction Subscale Score	8	5.5 (1.4)	5	5.1 (0.7)
Donning with Coapt electrodes	8	5.3 (2.0)	4	4.8 (1.3)
Reproduce consistent patterns during calibration	6	4.8 (2.0)	3	4.7 (2.3)
Understand grip select indicator lights on the Coapt system	5	6.0 (0.7)	4	5.5 (0.6)
EMG-PR satisfaction items not included in subscale				
Coapt speed	8	5.0 (1.2)	5	5.6 (1.1)
Coapt controls	8	4.4 (1.8)	0	NC
Coapt pattern movement wrist	5	4.4 (1.5)	0	NC
Coapt pattern movement video	4	5.0 (0.8)	0	NC

*NC=data not collected at timepoint

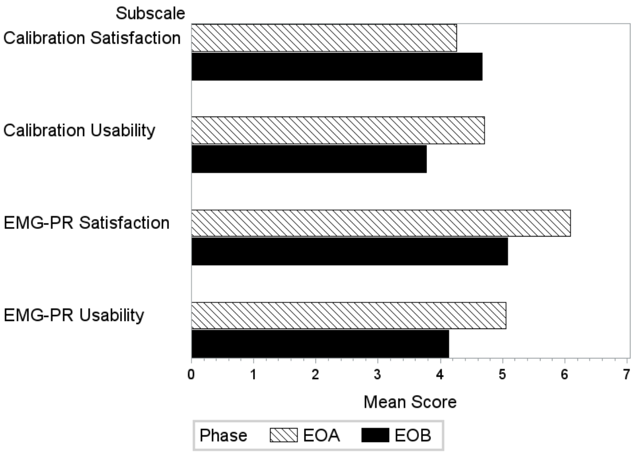

FIGURE 1. Comparison of EMG-PR usability and satisfaction ratings for subjects who completed EOA and EOB ratings.

and Coapt speed. The usability item rated most favorably at the EOB was understanding grip indicator lights.

EMG-PR satisfaction items reflected similar patterns. The lowest rated satisfaction item after training was calibration with wrist display (rated between "mostly dissatisfied" and "mixed"). The highest rated items were using the grip indicator lights on the EMG-PR system and the calibration sound indicator (rated "happy"). The items that users were least satisfied with at the EOB were: save/delete calibration data, and calibrate using the Coapt LED lights. Several EMG-PR items had mean ratings approaching "happy," including using the Coapt button to calibrate, using the video to calibrate, and recognizing successful calibration by seeing prosthesis movement.

Our graphical comparisons illustrate that for those EMG-PR users' ratings of usability and controls satisfaction declined after home use. This suggests that home users may have encountered more problems in operating the device for everyday tasks in a less constrained, more unstructured environment. Additionally, as described in our qualitative study some EMG-PR users encountered multiple technical problems during home use [17]. These problems included issues with inconsistency of controls operation, difficulty using Prototype 2 for direct grip selection, and problems with reliability of connections and wiring.

We found differences in device preferences by amputation level as well as control type. These differences suggest that the functionality of the DEKA hand and wrist was perceived as more valuable for those with more proximal amputation, and that TH amputees also preferred IMU over EMG-PR control. All TH amputees preferred the DEKA Arm hand function and wrist function over the function of their own

TABLE 7. Spearman correlations between DEKA Arm usability and satisfaction metrics and other measures used in this study (N=8).

	Calibration usability		EMG-PR Usability		Calibration Satisfaction		EMG-PR Satisfaction	
	r	p	r	p	r	p	r	p
Self-rated skill level using	-0.16	0.70	0.39	0.34	0.11	0.79	0.50	0.21
Rating of socket comfort	-0.22	0.60	0.33	0.42	-0.22	0.59	0.50	0.21
Perception of weight of DEKA Arm	-0.20	0.63	0.22	0.59	-0.64	0.09	-0.09	0.84
TAPES	0.06	0.89	0.60	0.11	0.05	0.91	0.84	**0.01**

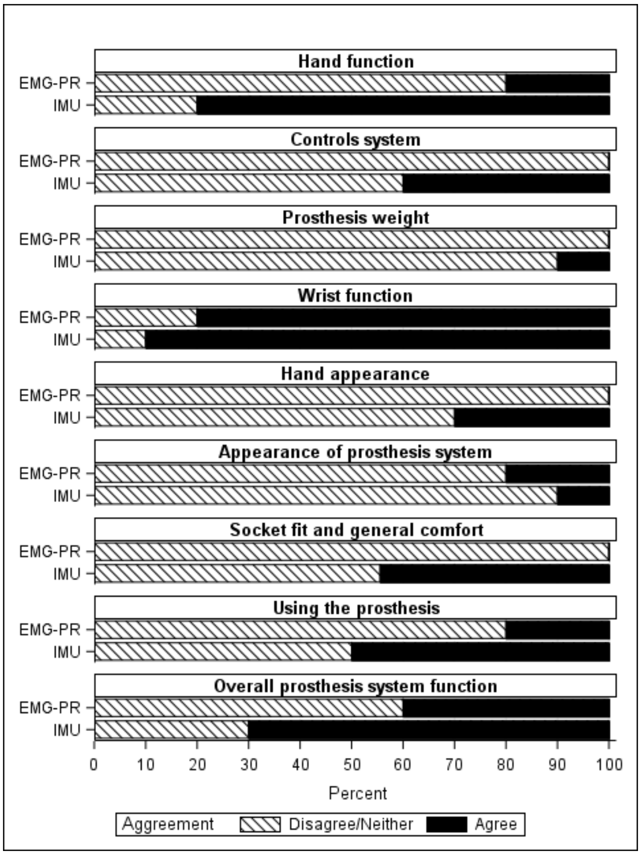

FIGURE 2. TR Prosthesis users: comparison of preference for the DEKA Arm by control type.

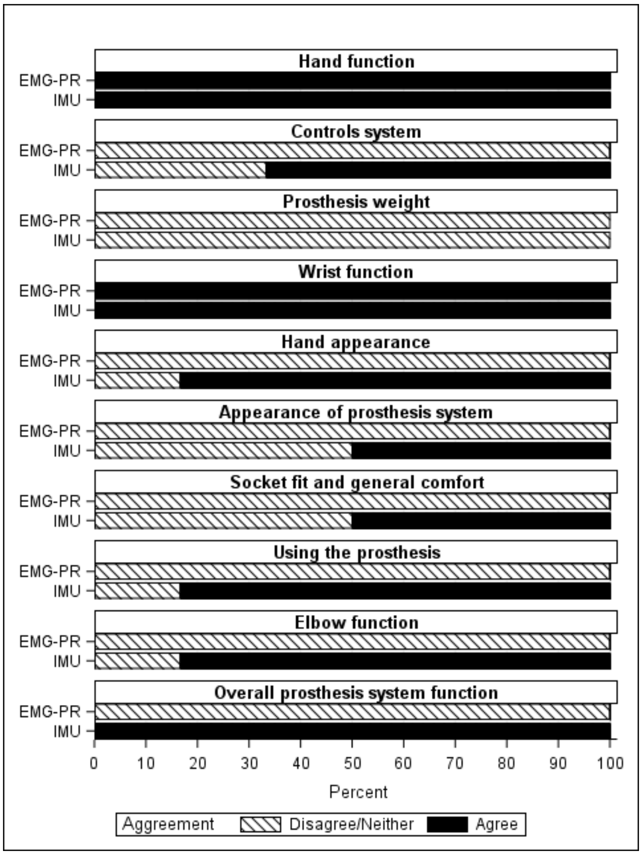

FIGURE 3. TH Prosthesis users: comparison of preference for the DEKA Arm by control type.

terminal devices and prosthetic wrists, regardless of control type. For TR amputees, a higher proportion of IMU users preferred the DEKA hand.

The majority of TR amputees using either control type preferred the DEKA Arm's wrist function. There were no TH amputees using EMG-PR who preferred the overall prosthesis function, whereas 40% of TR amputees preferred it. There were no TH amputees using EMG-PR who said that they enjoyed using the DEKA Arm more than their own device, but 20% of TR amputees using EMG-PR did.

The findings reported in this paper complement findings from other evaluation approaches. Our in-depth qualitative study describing users' perspectives on the EMG-PR controls [17] reported results that help to explain some of the ratings, such as challenges controlling multiple muscular patterns mapped to the EMG-PR controls. Our analysis comparing observational and self-report measures of function and quality of life reported that TR amputees using EMG-PR had worse dexterity (and activity performance (as compared to IMU users. But there were no differences observed for those with TH amputation [18]. Together, these analyses provide a comprehensive evaluation of EMG-PR control of the DEKA Arm as well as direct comparisons to IMU control of the DEKA Arm. These findings generally support the superiority of IMU control of the DEKA Arm, particularly for users with TR amputation.

While this study provides novel data and presents a broad array of outcome metrics that were triangulated with other analyses, it has several limitations. First, the EMG-PR controls used in this study were experimental prototypes;

TABLE 8. Test statistics for EMG-PR usability and satisfaction subscales, and items not included in subscales due to item test correlations r<0.50.

	Item-test	**Item-rest**	**Alpha (if item removed)**	**Alpha**
Calibration Usability Subscale				0.80
Coapt button to initiate calibration	0.79	0.48	0.76	
Coapt calibration with video	0.58	0.39	0.81	
Coapt calibration with wrist display	0.90	0.75	0.63	
Save/delete calibration data	0.58	0.23	0.76	
Calibrate using Coapt LED lights	0.83	0.74	0.78	
Calibration usability items not included in subscale				
Calibration sound indicator				
EMG-PR Usability Subscale				0.64
Coapt speed	0.72	0.49	0.57	
Donning with Coapt electrodes	0.80	0.51	0.64	
Reproduce consistent patterns during calibration	0.82	0.69	0.50	
Understand grip select indicator lights on the Coapt system	0.68	0.56	0.59	
Calibration Satisfaction Subscale				0.92
Coapt calibration with wrist display	0.96	0.78	0.74	
Save/delete calibration data	0.97	0.85	0.91	
Calibrate using Coapt LED lights	0.87	0.72	0.99	
Calibration satisfaction items not included in subscale				
Coapt button to initiate calibration				
Coapt calibration with video				
Calibration sound indicator				
EMG-PR Satisfaction Subscale				0.82
Donning with Coapt electrodes	0.96	0.85	0.46	
Reproduce consistent patterns during calibration	0.91	0.74	0.65	
Understand grip select indicator lights on the Coapt system	0.75	0.67	0.91	
EMG-PR satisfaction items not included in subscale				
Coapt speed				

that were being used for the first time to operate the DEKA Arm. In contrast, the IMUs had been used with dozens of research participants and were in a more mature phase. Interpretation of findings need to be considered in light of the developmental stage of the controls. Second, users in our study were not randomly assigned to receive IMU or EMG-PR controls. Instead, the study was conducted sequentially, with all IMU users completing first, and then all subsequent subjects assigned to EMG-PR control. Thus, our groups were non-equivalent comparison groups. The EMG-PR group was slightly older, had a smaller proportion of women, and a higher proportion of prosthesis users at baseline. We did not attempt to control for these differences in our analyses due to small sample size. Thus, our conclusions need to be interpreted cautiously and considered preliminary. Both of the subjects with TH amputation had undergone TMR surgery, therefore the findings related to TH amputation and EMG-PR are only generalizable to others with TMR. Although electrode signals could be observed in the laboratory setting to troubleshoot issues as needed, it is possible that problems with electrode contact resulting in signal quality problems that occurred in the home environment could not be observed, and may have negatively impacted user experience.

Our study was specific to EMG-PR control of the DEKA Arm using the prototypes developed for our study. Results, though informative for the field, should not be generalized to EMG-PR control of less complex prostheses or prostheses that are lighter weight. Further research is needed to assess EMG-PR control of other multi-DOF devices with different characteristics. The EMG-PR system interface with the DEKA Arm used in this study was a research prototype, which had not previously been utilized. Several technical issues needed to be addressed as the system was optimized during the study [17]. Our research staff, though trained to utilize the EMG-PR system, were new to implementing it and training subjects to utilize it with the DEKA Arm, whereas IMUs had been well tested in prior DEKA Arm research and staff were very familiar with those controls. It is possible that a future study employing an optimized EMG-PR controls interface with the DEKA Arm would yield different results.

Another limitation is that we have little data to support the reliability and validity of the satisfaction and usability metrics used in this study. We utilized DEKA Usability and Satisfaction scales and items from prior research and found similar patterns. We also created new EMG-PR Usability and Satisfaction subscales for this analysis and presented summary scores from these subscales in several analyses. Three of the four scales had acceptable internal consistency. Although the fourth scale, EMG-PR Usability, had marginal internal consistency, we still reported it, believing that it is simpler to evaluate a multi-item subscale than extra individual items. We were not able to evaluate test-retest reliability of the EMG-PR subscales or any of the items contained within the subscales, and cannot be certain that participants would have answered the same way on subsequent test administrations. Preliminary analyses of concurrent and discriminant validity showed the EMG-PR Satisfaction Subscale was strongly correlated with the TAPES, a validated measure of prosthetic satisfaction. The EMG-PR Usability Subscale was moderately correlated with the TAPES, but this correlation was not statistically significant. However, the correlation analyses in our study were preliminary, and performed with very small samples and were underpowered to detect significant differences.

V. CONCLUSION

This study compared satisfaction and usability of two control methods of the DEKA Arm; EMG-PR and IMUs. Overall, we found that EMG-PR was less well accepted than IMU control. TR amputees rated the ease of use of the IMU-controlled DEKA Arm more favorably than did users of the EMG-PR controlled DEKA Arm, whereas TH amputees rated usability similarly. Despite more training hours, TR amputees who used EMG-PR controls rated their skill with the prosthesis lower than did IMU users. TR amputees using EMG-PR were also less satisfied with the weight, pinch grip, and the wrist display of the DEKA Arm whereas TH amputees were less satisfied with the full arm system, wires and cables, and the battery life. Users of EMG-PR control rated the prosthesis weight and socket comfort less favorably than did IMU users. Finally, we found that user's assessment of usability and satisfaction declined after home use experience for EMG-PR users and that a greater proportion of subjects using IMU controls expressed an interest in receiving a DEKA Arm in the future. Our findings are specific to the EMG-PR control prototypes used in this study and further research is needed to confirm or refute these findings with other EMG-PR control systems, later prototypes of the current EMG-PR system and prosthetic devices with fewer degrees of freedom and lighter weight. Further research is needed to understand how prosthetic controls experience influence users experiences of prosthesis grip, weight and notifications.

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