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Cognitive Characteristics Associated With Device Adoption, Skill Retention, and Early Withdrawal From a Study of an Advanced Upper Limb Prosthesis

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Objective: The aim of the study was to examine the role of cognition in device adoption, skill retention, and withdrawal from a study of an advanced upper limb prosthesis (the DEKA Arm).

Design: T tests and Wilcoxon rank-sum tests were used to compare test performance among study completers and noncompleters. Multivariable regression analyses were used to predict study withdrawal and DEKA Arm skill retention.

Results: Compared with self-withdrawn participants, those who were withdrawn by study staff performed significantly worse on tests indexing processing speed, set-shifting, and memory encoding. The DEKA Arm configuration (transradial, transhumeral, shoulder—based on amputation level) was a stronger predictor of skill retention than neuropsychological test performance.

Conclusions: Frontally-mediated cognitive skills may influence the successful adoption of the DEKA Arm. The DEKA Arm configurations at higher amputation levels (e.g., shoulder) appear to be more strongly associated with prosthetic skill retention than users' cognitive status. This may be due to noncognitive user demands (e.g., device weight) statistically masking the discrete influence of cognitive status on skill retention at higher configuration levels. Neuropsychological assessment warrants consideration as a valuable tool in rehabilitation settings to assist in functional device candidacy evaluations.

Key Words: DEKA Arm, Advanced Prosthetics, Cognition, Executive Function

(*Am J Phys Med Rehabil* 2019;98:879–887)

Recent US military engagements in Iraq and Afghanistan have involved a higher frequency of combat-related amputations relative to prior conflicts.¹ This change is due in part to improvements in body armor and battlefield medical care and associated increases in combat survival rates among US service members.² Despite these advancements, however, the patterns of injuries sustained in combat have evolved alongside the proliferation of improvised explosive device use by enemy combatants. Indeed, existing protective equipment continues to leave soldiers' limbs susceptible to blast forces.

Although the rate of traumatic amputation is greater in lower compared to upper limbs, upper limb amputees are likely to have greater disability and are less likely to return to service than individuals with lower limb amputations.³ This may be attributable to less advanced rehabilitative programs for upper versus lower limb amputees (possibly due in part to relatively higher rates of lower limb amputation and, consequently, more attention given to lower limb prosthetic technology development), increased functional limitations of upper versus lower limb prosthetic use (e.g., due to greater manual dexterity and

sensory demands), and decreased ability to perform activities of daily living and job responsibilities dependent on hand use.^{4–6} Upper limb prostheses offer a limited number of hand and wrist movements, making it challenging to position the hand in space or grasp and manipulate objects of varying shapes. Studies in civilian populations reveal that many individuals with upper-limb amputation choose not to use prosthetic devices, with rates of primary rejection (never using a prosthesis) or abandonment (receiving a prosthesis, but choosing to stop using it) ranging from 17–80%.⁷ Collectively, these trends have promoted the advancement of research addressing adoption of upper-limb prosthetic devices and functional outcomes in both veteran and civilian populations.^{2,8}

Researchers have identified a variety of factors associated with likelihood of rejecting upper limb prosthesis use. These include: amputation level, female gender, perceived functional limitations of existing devices, and inadequate training.^{9–11} Regarding amputation level, rejection rates are lowest for those with transradial (TR) amputations and highest for those with transhumeral (TH) or shoulder level amputations as well as

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This study was supported by VA RR&D A9226, VA RR&D A9264A-S, VA RR&D, and A9280-N.

Jacob Lafo and Frantzy Acluche are in training.

Financial disclosure statements have been obtained, and no conflicts of interest have been reported by the authors or by any individuals in control of the content of this article.

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ISSN: 0894-9115

DOI: 10.1097/PHM.0000000000001220

more distal level (partial hand) amputations.^{12–16} Matching patients to the optimal upper limb prosthesis configuration for their amputation level and providing them with sufficient prosthetic training and expectation-setting may be key to preventing device abandonment.

Recent advances in functional capabilities of upper limb prostheses have emerged in the context of government initiatives to improve quality of life in veteran populations. One device, the DEKA Arm (a.k.a., the LUKE Arm), was developed in conjunction with the Defense Advanced Research Project Agency (DARPA) “Revolutionizing Prosthetics” program to address increased rates of upper-limb amputation in U.S. combat troops.¹⁰ More recently, this device has become commercially available. Salient positive attributes of the DEKA Arm include multifunction grasp patterns and a powered wrist joint. Given that lack of functionality was previously identified as a contributing factor in prosthesis rejection, some expected that a device that affords greater functionality would be more readily and widely accepted. An analysis of data from the VA Home Study of the DEKA Arm,¹⁶ however, suggested that many potential users of this device may not adopt it due to dissatisfaction with its characteristics, including its weight, appearance, and/or concerns about its reliability. Given this finding, and the fact that advanced upper limb prostheses are costly and require extensive training, a subsequent study explored whether there were specific patient characteristics that predict likelihood of adoption of this device.¹⁵ The overarching goal of that investigation was to identify factors that may assist clinicians in better matching patients with the DEKA Arm versus more traditional prosthetic devices. The study showed that individuals who were already prosthesis users were 5.2 times as likely as compared with nonusers to continue participation in a home study of the DEKA Arm. The study also found that those with a history of musculoskeletal problems (such as neck or back pain) were 0.2 times as likely to continue participation relative to individuals without a history of these problems. The findings of this study show that prior prosthesis use and history of musculoskeletal pain may help predict future adoption of the device. However, these earlier analyses did not control for baseline cognitive status, which may directly influence the operation and subsequent adoption of a complex prosthesis. Indeed, it is intuitive that learning to manually operate a heavy, multigrip prosthetic device with multiple foot controls is a cognitively demanding process.

Addressing this consideration, additional studies examined cognitive predictors of skilled use of the DEKA Arm and found that baseline performance on measures of attention and processing speed predicted users’ level of proficiency.^{13,14} These results corresponded with observations in a case study of the DEKA Arm use in an amputee with a history of traumatic brain injury (TBI).¹² This individual demonstrated both objective and qualitative cognitive deficits during DEKA Arm training. Because of these deficits, study staff determined the participant to be unsuitable for independent home use because of safety concerns and questionable judgment. In separate analyses, individuals who withdrew from participation during the home use portion of the study showed performance declines on prosthetic skill tests after the first 4 wks in comparison with function after the completion of prosthetic training.⁹ Although cognitive status was not specifically examined in those analyses, it was hypothesized that cognitive impairment could be associated with reduced adoption

of the DEKA Arm and greater loss of prosthetic skills during independent use after the completion of structured training.

In accordance with this hypothesis, the overall objective of this study was to further the understanding of the role of cognition in the adoption and skill retention of an advanced upper limb prosthesis (i.e., the DEKA Arm). Specifically, this study aimed to (a) compare cognitive profiles of device users who completed all aspects of a home study to those who did not, (b) determine whether cognitive performance predicted premature withdrawal from the study, and (c) evaluate the relationship between cognition and prosthetic skill in the first month after discharge from prosthetic training to home use.

METHODS

The DEKA Arm

This study provides a brief description of the DEKA Arm; a full description has been reported in a previous article.¹⁰ The DEKA Arm has multiple powered degrees of freedom. It is available in the following three configurations: radial configuration (RC) appropriate for transradial level amputations; humeral configuration (HC) suitable for transhumeral level amputations; and a shoulder configuration (SC) for shoulder disarticulation, forequarter, and short transhumeral level amputations. All configuration levels allow for six powered hand grip movements, wrist flexion/extension with radial and ulnar deviation, and forearm pronation/supination. Humeral configuration and SC DEKA Arms include powered elbow flexion/extension and humeral internal/external rotation movements. Powered shoulder movements (abduction/adduction and flexion/extension) are available in the SC DEKA Arm. Powered shoulder (not including abduction/adduction) and elbow movements are operated instantaneously via an end point control system that guides the SC DEKA Arm into a specific position.¹¹ All configurations are controlled using inertial movement units (IMUs) worn on the top of the shoes. Various control schemes are available in which the shoe-top IMUs are partly or fully supplemented by surface electromyography, pneumatic bladders, and manual switches, as needed.

The DEKA Arm differs from other commercially available devices in a number of ways. For example, it is the only device operated primarily with IMU foot controls, whereas other devices are typically operated by body powered harnesses and/or myoelectric controls. The DEKA Arm has a 2 degree of freedom (DOF) powered wrist, whereas currently available devices have at most one degree of freedom wrists, controlled passively or by powered movement.

Study Design

This study analyzed data collected in the VA Home Study of an Advanced Upper Limb Prosthesis. Research activities were approved by the institutional review boards of the Providence VA Medical Center, the James A. Haley VA Hospital, the VA NYHHS, and the Center for the Intrepid at Brooke Army Medical Center. All participants provided written informed consent to confirm their willingness to participate in this study. The VA Home Study was composed of two phases: an in-laboratory portion (part A) and an approximately 12 wks of home use portion (part B). All participants enrolled in part A, and a subset of those

participants continued to part B. Participants who participated in part B returned to the study site for in-person re-evaluations after every fourth week.

Participants

Participants were eligible to enroll in part A if they were 18 yrs and older, had an upper limb amputation at the transradial, transhumeral, shoulder disarticulation, or scapulothoracic (shoulder) level, and could operate the DEKA Arm with the available control schemes (e.g., they had adequate ankle movements to use the foot controls and/or adequate myoelectric signals to operate electromyography controls). Participants were excluded if they had skin conditions preventing socket fitting and/or significant health conditions that limited their participation (e.g., major visual, communication, or neurocognitive deficits). At the end of part A, the study staff and principal investigator determined participants were appropriate for part B if there were no concerns about participants' behavior and they demonstrated adequate skill level (as determined by the study occupational therapist) and sound judgment when problem-solving minor prosthesis problems. Examples of problem-solving included recognizing the signs of a low external battery or IMU control that needed to be charged and then properly placing the components on the correct chargers. Study withdrawal type was classified into two categories based on whether participants' withdrawal from the study was initiated solely by the participant (participant-withdrawn) or by the study staff (staff-withdrawn). The latter included participants who were withdrawn solely by study staff or based on mutual agreement between the study staff and participant.

Data Collection

Neuropsychological Tests

Neuropsychological test data were collected across the study performance sites for this project. Test administrators (typically research assistants or similarly qualified study staff) underwent test administration training during a prestudy launch conference at the coordinating site (Providence VA Medical Center). Participants' raw test scores were tallied at individual study sites and forwarded to the coordinating site, where the study neuropsychologist (SC) verified raw scores and converted them to standardized scores according to test-specific normative data. Neither standardized scores nor performance quality ratings (e.g., "average," "mildly impaired," "superior") were shared with other study staff at study performance sites. Accordingly, study staff at performance sites who were involved in decisions to recommend participant study withdrawal were not privy to the results of cognitive testing.

At study baseline, study staff administered a standardized neuropsychological test battery evaluating the following cognitive domains: attention, processing speed, executive function, and memory. Individual tests are listed and described according to specific cognitive domains in Table 1. Test scores were used in analyses in two different formats. The first score format used participants' raw test scores (i.e., without normative correction) and was used for both aim 1—to evaluate group differences in cognitive performance—and aim 3—to evaluate the relationship between cognitive performance and prosthetic skill retention. The second score format used normatively corrected standardized scores and was used for aim 2—to determine whether cognitive

performance predicted premature withdrawal—and for aim 3. Standardized scores were computed according to published normative data accounting for age, gender, and/or education level. The standardized scores were used to classify study participants as belonging to one of two groups: cognitively normal or cognitively impaired. Participants were classified as cognitively impaired according to modified criteria for the diagnosis of mild cognitive impairment developed by Jak et al.,²² such that impairment was coded if participants obtained at least 2 scores that were at least 1 standard deviation below the normative mean. Participants obtaining 1 or no scores below this 1-standard deviation cutoff were classified as cognitively normal. This dichotomous classification was used to determine whether cognitive status predicted likelihood of study withdrawal (aim 2) and to explore the advantage of using normative versus raw scores to predict prosthetic skill retention (aim 3).

Performance Outcome Measures

Functional performance with the DEKA Arm was assessed at the end of part A (EOA) and after 4, 8, and 12 wks of home use. The measure of activity performance in this sub-study was the Activities Measure for Upper Limb Amputees (AM-ULA).²³ We analyzed AM-ULA scores at EOA and 4-wk follow-up. These time points were selected for comparison to maximize sample size. The AM-ULA is a condition-specific activity performance measure that has been developed for adults with upper limb amputation. This 18-item measure assesses the following elements of functional performance: ability of the amputee to complete daily activities, speed of performance, movement quality, and skillfulness of prosthetic use and independence. Specifically, the 18 items include the following: brushing/combining hair, putting on a T-shirt, removing a T-shirt, buttoning a shirt, zipping a jacket, putting on socks, tying shoe laces, drinking from a paper cup, using a fork, using a spoon, pouring from a 12 oz can, writing the word "letter" legibly, using a pair of scissors, turning a round doorknob, dialing a touch tone phone, using a hammer and nail, folding a bath towel, and reaching overhead and grasping an object. Higher AM-ULA scores indicated better functional performance. The AM-ULA has excellent test-retest reliability, interrater reliability and internal consistency, and good evidence of validity.²³

Prosthesis Satisfaction

Participants' satisfaction with the prosthesis was measured using the Trinity Amputation Prosthesis and Experience satisfaction subscale, a 10-item measure. The Trinity Amputation Prosthesis and Experience was administered at study baseline.²⁴

Other Participant Characteristics

Given previous findings that individuals who were already prosthetic users and/or had a history of musculoskeletal problems were more likely to continue participation in the home study of the DEKA Arm, data was collected accounting for these characteristics. In addition, participants' prescribed DEKA Arm level was accounted for because rejection rates have been found to vary depending on amputation level in prior studies.

TABLE 1. Neuropsychological measures

		Raw Score Range (Min-Max)
Auditory attention/working memory	WAIS-IV, Digit Span (forward, backward, sequencing) ¹⁷ : Tasks requiring initial registration and manipulation of numeric sequences of increasing span lengths	0–48 0–30
	WAIS-IV, Letter Number Sequencing ¹⁷ : Task requiring mental manipulation and sequential processing of letters and numbers	
Processing speed	OTMT-A ¹⁸ : Timed oral numeric sequencing measure without visual-motor demands	TTC 0–110
Executive function	SDMT ¹⁹ : Timed measure of speeded symbol-digit substitution	
	D-KEFS, Color-Word Interference ²⁰ : Timed oral task assessing cognitive inhibition of prepotent verbal response	0–180 secs 0–180 secs
	D-KEFS, Color-Word Interference (inhibition and inhibition/switching trials) ²⁰ : Timed oral task assessing cognitive inhibition of prepotent verbal response	TTC
	OTMT-B ¹⁸ : Timed oral alphanumeric set-shifting measure without visual-motor demands	
Memory	RBANS, list learning (learning and delayed recall and recognition trials) ²¹ : Task assessing memory for noncontextual verbal information presented in list format	0–40 (learning trial) 0–10 (delayed trial) 0–20 (recognition trial)
	RBANS, story memory (learning and delayed recall trials) ²¹ : Task assessing memory for contextual verbal information presented in narrative prose	0–12 (learning trial) 0–24 (delayed trial)

D-KEFS, Delis-Kaplan Executive Function System; OTMT-A, Oral Trail Making Test – A; OTMT-B, Oral Trail Making Test – B; RBANS, Repeatable Battery for the Assessment of Neuropsychological Status; SDMT, Symbol-Digit Modalities Test; TTC, time to completion in seconds; WAIS-IV, Wechsler Adult Intelligence Scale – Fourth Edition.

Data Analyses

To address Aim 1, *t* tests were used to compare performance (using raw test scores) on individual cognitive measures between two groups of participants: those who completed all aspects of a home study and those who did not. Incomplete study participation (i.e., withdrawal) was defined as follows: discontinuation before (a) completing part A (incomplete A), (b) after completing part A, but before moving on to part B (complete A, no B), and (c) before completing 9 wks of part B (complete A, incomplete B). A flow diagram outlining participation/discontinuation throughout the study is depicted in Figure 1. Among those who withdrew from the study, subgroups were compared based on whether study withdrawal was initiated by the participant only (participant-withdrawn) or by study staff (staff-withdrawn). Wilcoxon rank-sum tests were used for this subgroup analysis to account for small sample size. To address aim 2, a multivariable logistic regression model was used to determine whether cognitive status (impaired vs. nonimpaired) predicted likelihood of study withdrawal. The model was structured with study completion (yes/no) as the dependent variable and the following independent variables: (1) any history of prosthesis use before part A baseline (yes/no), (2) history of musculoskeletal pain (yes/no), (3) arm level of prescribed DEKA Arm, and (4) cognitive impairment (yes/no), based on classification criteria described previously. Post hoc analysis was performed on the logistic regression model to plot the receiver operating characteristics curve to assess the predictive value of adding cognitive impairment to the model.

To address aim 3, separate univariate linear regressions were conducted to evaluate the relationship between cognitive performance and prosthetic skill retention. These regressions

used raw scores for each cognitive measure as independent variables and week 4 AM-ULA score as the dependent variable. Week 4 scores were chosen as the dependent variable because this time point represented the first reassessment after discharge from the in-laboratory portion of the study and thus the first opportunity to assess retention of skills. Measures that were statistically significant at $P \leq 0.1$ were then included in a multivariable model predicting week 4 AM-ULA score. Next, a model was structured to examine predictors of week 4 AM-ULA score. Independent variables included the statistically significant cognitive measures, DEKA Arm level, and EOA AM-ULA score, because it was expected that EOA AM-ULA would be strongly predictive of week 4 AM-ULA scores. Lastly, we examined the question of whether there would be an advantage of using the dichotomous classification for cognitive impairment as an independent variable, rather than continuous raw scores in predicting week 4 AM-ULA score (dependent variable). Accordingly, a univariate linear regression model was structured with cognitive impairment (yes/no) as the independent variable, and EOA AM-ULA score and DEKA Arm level were sequentially added to the model to observe the impact of these potential confounders.

RESULTS

Sample characteristics are provided in Table 2. The sample included 42 participants, 24 who withdrew (incomplete A; complete A, no B; and complete A, incomplete B; mean age = 47 yrs, 79% male) and 18 who completed the entire study (complete A and B, mean age = 45 yrs, 89% male). Eighteen of the 24 participants who withdrew from the study were classified as

FIGURE 1. Flow diagram outlining participation/discontinuation throughout the study.

TABLE 2. Participant demographics

	Incomplete (<i>n</i> = 24)	Complete (<i>n</i> = 18)	EOA and Week 4 Data (<i>n</i> = 20)	All (<i>N</i> = 42)
	M (SD)	M (SD)	M (SD)	M (SD)
Age	46.7 (15.3)	44.8 (16.0)	43.6 (14.8)	45.9 (15.5)
BMI	26.9 (4.5)	28.3 (5.8)	27.8 (5.5)	27.5 (5.1)
Tapes prosthesis satisfaction	3.7 (1.0)	3.5 (0.7)	3.6 (0.7)	3.6 (0.9)
Months of prosthesis use	225.6 (223.7)	161.1 (191.8)	131.1 (174.4)	190.0 (205.5)
Training visits	6.4 (5.2)	8.6 (3.6)	8.5 (3.5)	7.4 (4.7)
	<i>n</i> (%)	<i>n</i> (%)	<i>n</i> (%)	<i>n</i> (%)
Gender				
Male	19 (79.2)	16 (88.9)	18 (90.0)	35 (83.3)
Female	5 (20.8)	2 (11.1)	2 (10.0)	7 (16.7)
Race				
White	17 (70.8)	16 (88.9)	17 (85.0)	33 (78.6)
Black	4 (16.7)	2 (11.1)	3 (15.0)	6 (4.3)
Mixed/other	3 (12.5)	0 (0.0)	0 (0.0)	3 (7.1)
Education				
<High school	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
High school completed	6 (25.0)	7 (38.9)	7 (35.0)	13 (31.0)
Some college	9 (37.5)	4 (22.2)	7 (35.0)	13 (31.0)
College or more	9 (37.5)	7 (38.9)	6 (30.0)	16 (38.1)
DEKA Arm configuration level				
RC	11 (45.8)	10 (55.6)	12 (60.0)	21 (50.0)
HC	4 (16.7)	6 (33.3)	5 (25.0)	10 (23.8)
SC	9 (37.5)	2 (11.1)	3 (15.0)	11 (26.2)
Prosthesis use at baseline				
Nonuser	10 (41.7)	2 (11.1)	4 (20.0)	12 (29.6)
User	14 (58.3)	16 (88.9)	16 (80.0)	30 (71.4)

BMI, body mass index; M (SD), mean (standard deviation); TAPES, Trinity Amputation Prosthesis and Experience.

participant-withdrawn and 6 were classified as staff-withdrawn. Twenty participants (mean age = 44 yrs, 90% male) had AM-ULA data at both EOA and week 4 time points. Seventy-one percent of participants were prosthesis users at baseline.

Aim 1 Results

There were no significant differences in performance on individual cognitive measures (raw scores) between the complete and incomplete groups (Table 3). However, among the incomplete group, staff-withdrawn participants had significantly worse scores on list learning, story memory, OTMT-B, and SDMT relative to participant-withdrawn participants (Table 4).

Aim 2 Results

Cognitive impairment classification (impaired vs. unimpaired) was not a significant predictor of withdrawal ($OR = 1.2$, $P = 0.79$). Its inclusion in the model (not shown) did not change the AUC or the receiver operating characteristics curve accuracy index (0.77) over the control variables alone.

Aim 3 Results

Univariate regressions identified three neuropsychological measures (raw scores) that predicted week 4 AM-ULA score with statistical significance ($P \leq 0.1$): list learning, list recall, and list recognition. As expected, EOA AM-ULA score and DEKA Arm level were predictive of week 4 AM-ULA score in univariate regressions (Table 5). Although list learning, list recall, and list recognition were significant predictors ($P \leq 0.01$) in the unadjusted univariate models (not shown), their effects were not significant in the multivariable models (Table 5), even when EOA AM-ULA score and DEKA Arm level were removed from the model. End of part A AM-ULA score and DEKA Arm level were significant predictors in the multivariable models. The model that included only DEKA Arm configuration had an R^2 of 0.61. Including the four cognitive variables and EOA AM-ULA score in the adjusted model improved R^2 only slightly to 0.78.

In the regression analysis using cognitive impairment (yes/no) as an independent variable, impairment classification

was negatively associated with week 4 AM-ULA score (Table 6), but the association was not statistically significant. Specifically, a classification of having cognitive impairment was positively (but not significantly) associated with week 4 AM-ULA score after controlling for EOA AM-ULA score and DEKA Arm level. Participants with shoulder ($\beta = -4.70$, $P = 0.0382$) and humeral ($\beta = -5.04$, $P = 0.0120$) DEKA Arm configurations had significantly worse week 4 AM-ULA scores than RC users in this model.

DISCUSSION

The overarching goal of the current study was to advance the understanding of the role of cognitive functioning in the adoption of an advanced upper limb prosthesis. In view of this goal, data from the VA Home Study of the DEKA Arm were analyzed to (a) compare cognitive profiles of participants who either completed or prematurely withdrew from the study, (b) determine whether cognitive status predicted study withdrawal, and (c) examine cognitive predictors of prosthetic skill retention after study completion.

Results revealed that scores on individual neuropsychological measures did not significantly differ between study completers and noncompleters, nor were they predictive of whether participants remained in or withdrew from the study. However, the subgroup of participants who were withdrawn by study staff performed significantly worse than those who self-withdrew on measures engaging frontally-mediated cognitive skills, including processing speed, set-shifting, and initial encoding of verbal information. Although objective test performance did not directly influence staff decisions regarding participant withdrawal, these findings raise the possibility that frontally-based cognitive functioning might influence participants' proficiency or behavior in a way that negatively influences staff perceptions of individuals' ability to appropriately participate in a demanding clinical trial involving skilled use of a technologically advanced prosthetic device. For example, it is possible that frontally-based cognitive limitations undermine participants' behavior and/or judgment in the context of device use, problem-solving, and/or safety in a manner that led study staff to initiate study withdrawal.

TABLE 3. Comparison of neuropsychological test scores by study withdrawal status

	Incomplete ($n = 24$)	Complete ($n = 18$)	<i>T</i> Test
	M (SD) [Range]	M (SD) [Range]	<i>P</i>
Digit span	28.6 (5.5) [16–42]	29.1 (5.1) [17–38]	0.7532
SDMT	60.1 (19.1) [24–95]	59.6 (12.1) [46–94]	0.9274
OTMT-A	7.1 (1.3) [5–9]	6.8 (1) [5–9]	0.4553
OTMT-B	37.2 (27.3) [15–121]	29.7 (6.7) [21–45]	0.1474
Response inhibition	60.2 (18.7) [34–108]	58.1 (23) [30–136]	0.7461
Response inhibition/switching	68.3 (24.2) [38–143]	70.6 (25.3) [38–154]	0.7661
List learning	28.2 (5.6) [17–37]	29.2 (5.6) [19–38]	0.5648
List recall	6.4 (2.9) [0–10]	7.2 (2.3) [2–10]	0.3690
List recognition	19.6 (0.8) [17–20]	19.7 (0.5) [19–20]	0.5265
Story learning	17.4 (4.5) [6–22]	18.2 (3.5) [10–23]	0.5127
Story recall	9.1 (2.7) [4–12]	9.7 (2.6) [3–12]	0.4865

M (SD), mean (standard deviation); OTMT-A, Oral Trail Making Test – A; OTMT-B, Oral Trail Making Test – B; SDMT, Symbol-Digit Modalities Test.

TABLE 4. Comparison of neuropsychological test scores for participants who withdrew or were withdrawn by study staff

	Staff-Withdrawn (<i>n</i> = 6)	Participant-Withdrawn (<i>n</i> = 18)	<i>T</i> Test	Wilcoxon Rank-Sum
	M (SD)	M (SD)	<i>P</i>	<i>P</i>
Digit span	27.5 (7.5)	28.9 (4.9)	0.5883	0.6633
SDMT	44.7 (17.0)	65.2 (17.3)	0.0190*	0.0454*
OTMT-A	7.7 (1.6)	6.9 (1.2)	0.1869	0.1819
OTMT-B	60.6 (40.7)	29.0 (15.3)	0.1173	0.0274*
Response inhibition	69.3 (22.2)	57.2 (17.0)	0.1728	0.2045
Response inhibition/switching	86.8 (37.1)	62.1 (15.0)	0.1661	0.1715
List learning	23.0 (6.2)	29.9 (4.2)	0.0053*	0.0192*
List recall	5.0 (2.8)	6.9 (2.8)	0.1680	0.1490
List recognition	19.3 (0.8)	19.7 (0.8)	0.4061	0.1735
Story learning	14.3 (4.0)	18.4 (4.3)	0.0531	0.0375*
Story recall	7.3 (3.3)	9.7 (2.3)	0.0672	0.1199

*Significant *P* value for *t* test/Wilcoxon rank-sum test.

M (SD), mean (standard deviation); OTMT-A, Oral Trail Making Test – A; OTMT-B, Oral Trail Making Test – B; SDMT, Symbol-Digit Modalities Test.

Previous research is supportive of the view that among other contributory factors, cognitive impairment interferes with the procedural steps (i.e., learning, execution, and retention) required to successfully operate the DEKA Arm. In a study investigating cognitive predictors of DEKA Arm user performance, Hancock et al.¹⁴ found that baseline scores on measures of attention, processing speed, and memory were associated with objective indices of manual dexterity, ability to complete activities of daily living, and skillfulness of device use administered after device training. A separate case study of DEKA Arm in-laboratory training by Barredo et al.¹² identified deficits in memory encoding and executive function among a series of interactive factors (e.g., limited assumption of typical adult responsibilities) relevant to the determination that a participant was not an appropriate candidate for home use of the device. Paralleling the participant's objective cognitive impairments, anecdotal observations by occupational therapist supervisors detailed the participant's proneness to low frustration tolerance,

memory lapses, and poor application of safety knowledge when faced with challenging tasks.

Although definitive conclusions cannot be drawn regarding the causative relationship between cognitive test performance and real-world functioning in single case studies (or even those involving larger samples), consideration of the ecological validity of test scores is a developing focus of neuropsychology, particularly in rehabilitative settings. Indeed, neuropsychologists are specifically trained to make clinical inferences regarding such relationships and therefore may be optimally suited to provide valuable information in the context of functional device candidacy evaluations. Assessment of cognitive functioning may be particularly warranted in military rehabilitation settings, as veteran populations are associated with increased rates of mental health disorders and other medical conditions affecting cognition, including TBI.²⁵

Results of the analyses addressing cognitive predictors of DEKA Arm skill retention at study follow-up (aim 3) suggest

TABLE 5. Multivariable linear regression of week 4 AM-ULA score (*n* = 20)

Modeling Week 4 AM-ULA Score:	EOA AM-ULA Only		DEKA Arm Level Only		Cognitive Variables Only		Cognitive Variables and EOA AM-ULA Scores		Cognitive Variables, EOA AM-ULA Scores, and Level of Prescribed DEKA Arm	
	β	<i>P</i>	β	<i>P</i>	β	<i>P</i>	β	<i>P</i>	β	<i>P</i>
List learning					0.17	0.5387	0.19	0.4037	0.14	0.4106
List recall					0.43	0.4867	−0.40	0.5021	−0.73	0.1123
List recognition					1.13	0.7190	1.76	0.5031	3.90	0.0756
EOA AM-ULA score	0.72	0.0014*					0.70	0.0123*	0.36	0.0896
DEKA configuration										
RC (reference)										
HC			−6.84	0.0004*					−5.25	0.0053*
SC			−6.69	0.0023*					−6.76	0.0040*
Model <i>R</i> ²	0.44		0.61		0.25		0.51		0.78	
Model adjusted <i>R</i> ²	0.41		0.56		0.10		0.38		0.69	

*Significant *P* value.

AMU-LA, Activities Measure for Upper Limb Amputees.

TABLE 6. Association between impairment classification and week 4 AM-ULA scores (results of linear regressions, $n = 20$)

	Cognitive Variables Only		Cognitive Variables and EOA AM-ULA Scores		Cognitive Variables, EOA AM-ULA Scores, and Level of Prescribed DEKA Arm	
	β	P	β	P	β	P
Cognitive impairment classification						
Unimpaired ($n = 25$)						
Impaired ($n = 17$)	-0.60	0.7680	1.96	0.2436	1.12	0.4381
EOA AM-ULA score			0.82	0.0010*	0.41	0.0771
DEKA configuration						
RC (reference)						
HC					-5.04	0.0120*
SC					-4.70	0.0382*
Model R^2	0.01		0.49		0.68	
Model adjusted R^2	-0.05		0.43		0.60	

*Significant P value.

AMU-LA, Activities Measure for Upper Limb Amputees.

that DEKA Arm level was the most salient participant factor influencing retention in this study, as cognitive test scores identified as significant predictors in univariate regression models were no longer significant when arm level was controlled for in multivariable models. This finding raises the possibility that differing user demands associated with anatomically specific DEKA Arm configurations may influence skilled device use, above and beyond users' cognitive status. Relative to the RC, the humeral and SCs allow for an increasing array of powered degrees of movement, such that users are able to control not only wrist position but also elbow and shoulder rotation and flexion/extension. Use of the SC, which represents the most functionally complex configuration, is differentiated from the radial and HCs in that it requires simultaneous, coordinated control of both the shoulder and elbow joints. These operational distinctions may give rise to steeper learning curves, reduced user proficiency, and lower probability of device adoption as functional complexity and device weight increases across configurations. If true, it could be hypothesized that users' cognitive status and prosthetic configuration interact, such that even mild cognitive impairment increasingly impacts DEKA Arm training/use with more complex configurations. Although this hypothesis could not be directly tested in the current study because of sample size limitations, this may represent an important focus of future work.

An additional sample-related limitation of this study relates to the younger age of participants and the limited variability in neuropsychological test performance across individuals. Participants were generally cognitively intact and did not represent a group at high risk for age-associated cognitive disorders, including mild cognitive impairment and dementia. It is possible that recruitment of individuals from a broader age range may have increased variability in objective test performance and, in turn, allowed for greater predictive power in regression analyses examining the relationships between cognitive variables, withdrawal status, and prosthetic skill retention. Beyond these considerations, other factors that may warrant future investigation in studies of the DEKA Arm include participants' psychiatric and personality characteristics. The current study

did not collect data characterizing mood disorders, psychosocial distress, or personality attributes that may contribute to users' ability to appropriately engage in advanced prosthetic training, use, and troubleshooting (e.g., openness to experience, neuroticism, etc.). It is possible that such characteristics interact with or moderate the effects of cognitive impairment on functional capacity in the context of advanced prosthetic use. To supplement data reflecting participant characteristics, future studies should also incorporate rating scales that capture study staff assessments of participants' frustration tolerance, ability to retain new information about the prosthetic device and its use over time, and ability to show good safety judgment and behavior. Such information may help interpret decisions regarding participant withdrawal and shed light on factors important for identifying appropriate advanced prosthetic candidates.

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