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Original Research

Comparison of DEKA Arm and Body-Powered Upper Limb Prosthesis Joint Kinematics

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KEYWORDS
Kinematics;
Outcome measures;
Prostheses;
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Upper limb

Abstract *Objectives:* To study the effects of advancements in upper-limb prosthesis technology on the user through biomechanical analyses at the joint level to quantitatively examine movement differences of individuals using an advanced upper-limb device, the DEKA Arm, and a conventional device, a body-powered Hosmer hook.
Design: Clinical measurement.
Setting: Laboratories at the United States Food and Drug Administration.
Participants: Convenience sample of participants (N=14) with no upper limb disability or impairment.
Interventions: All participants were trained on either an upper limb body-powered (n=6) or DEKA Arm (n=8) bypass device.
Main Outcome Measures: Participants completed the Jebsen-Taylor Hand Function Test (JHFT) and targeted Box and Blocks Test within a motion capture framework. Task completion times and joint angle trajectories for each degree of freedom of the right elbow, right shoulder, and torso were collected and analyzed for range of motion, mean angle, maximum angle, and angle path length during each task.
Results: Significant differences between devices were observed across metrics in at least one task for each degree of freedom. Completion times were significantly higher for DEKA users (eg, 30.51±19.29s vs 9.30±1.44s) for JHFT—simulated feeding. Some kinematic measures, such as angle path length, were significantly lower in DEKA users, with the greatest difference in the right elbow flexion path length during JHFT—Page Turning (0.29±0.14 units vs 0.11±0.04 units).

List of abbreviations: DOF, degree of freedom; JHFT, Jebsen-Taylor Hand Function Test; RoM, range of motion; tBBT, targeted Box and Blocks Test; ULA, upper limb amputee.

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Conclusions: Results from this work elucidate the effect of the device on the user's movement approach and performance, as well as emphasizing the importance of capturing movement quality into the assessment of function for advanced prosthetic technology to fully understand and evaluate potential benefits.

As upper-limb prosthesis technology continues to advance, amputees and their care teams are faced with an increasing number of devices from which to choose. Although improvements in technological capabilities are obvious in newer devices, how these changes affect the user and his or her performance is less clear. Work is needed to differentiate these devices not only in terms of technology, but also in terms of effects on the user. Previous work has made use of survey results to compare satisfaction between device types, but quantitative, objective measures of how user movements differ between devices are less common.[1-4]

The evaluation of joint biomechanics can provide a means to objectively quantify the effect of the device on the user and performance. This quantification may be important to better understand the higher risk of musculoskeletal and overuse injuries that are common in this clinical population.[5]. A few groups have been using motion capture systems to quantitatively assess joint biomechanics and kinematics, but the breadth of technology explored in these studies limits our understanding of how different devices affect use. One such study of the DEKA Arm[a] demonstrated a decrease in movement quality as measured by the smoothness of the wrist joint center trajectory during use compared with conventional prostheses such as body-powered or myoelectric devices.[6] Other studies have examined kinematics for older devices or modalities but did so without the explicit goal of comparing devices across the technological spectrum.[7-10] Therefore, this work presents a biomechanical comparison of 2 devices, a basic body-powered device and an advanced externally powered device (DEKA Arm), to examine the underlying functional and biomechanical differences these devices elicit in their users.

The standard body-powered device represents one of the oldest and simplest active prosthesis designs. For transradial amputees, the device typically features 1 controllable degree of freedom (DOF), namely the opening or closing of the terminal device.[11] Despite remaining relatively unchanged for decades, the body-powered device remains popular.[12,13] On the other end of the technological spectrum, the DEKA Arm represents one of the most advanced, externally powered, upper limb prostheses on the market. Two inertial measurement units are generally used to control each DOF.[14] Initial studies have demonstrated that 88% of users preferred the DEKA Arm over their existing prosthesis after a trial period[15] and that users self-report improved activity performance with the DEKA Arm compared with their existing prosthesis.[1] Despite these findings, a 2-part study of the DEKA Arm assessing a number of patient-reported outcomes and performance-based measures after in-laboratory training and home use found no significant improvements in dexterity or function compared with conventional prostheses, such as body-powered and myoelectric-controlled devices.[2] In theory, the additional DOFs of this advanced device should reduce the burden on more proximal joints, but no study has tested this effect thus far.

With more complex and expensive devices reaching the market, there is an increased need to vet and understand the effects of newer devices on users. By examining devices across the technological spectrum using quantitative motion analysis tools, we aim to determine in what manner increased controllable DOFs and advanced technology affect the biomechanics of movement for unilateral object manipulation tasks. Results from this study can be used to isolate the effect of prosthetic designs on movement, thereby providing insight for improved rehabilitation protocols and guidance on design features in need of improvement in upper limb prostheses. To our knowledge, this is the first study to examine the DEKA arm device at the level of joint kinematics and the first to compare 2 device types under strict training controls to isolate differences in performance and resulting biomechanics.

Methods

Participants

A convenience sample of 14 participants with no upper limb disability or impairment and no previous prosthesis experience were included in the study. For this study, we considered upper limb disability or impairment to be a musculoskeletal or neurological injury or disorder that would limit range of motion, strength, or elicit pain, or an upper limb amputation. This study also required a substantial amount of time to train and test the bypass devices (see the Training section below). Therefore, any participant who could not commit to the time requirements was excluded from participation. Twelve participants were right-handed ($98.15+6.41$ laterality), 1 was left handed (-80 laterality), and 1 was indeterminate (0 laterality) per the Edinburgh handedness survey.[16] All participants used a right-handed device on their right arm regardless of handedness.[16] Eight participants (3 women, 5 men; mean age, 31.13 ± 14.49y) were trained and tested on the radial configuration DEKA Arm bypass. Six participants (3 women, 3 men; mean age, 28.67 ± 3.27y) were trained and tested on the transradial body-powered bypass. The study was approved by the Institutional Review Board of the Food and Drug Administration. All subjects provided written informed consent before participating in the study.

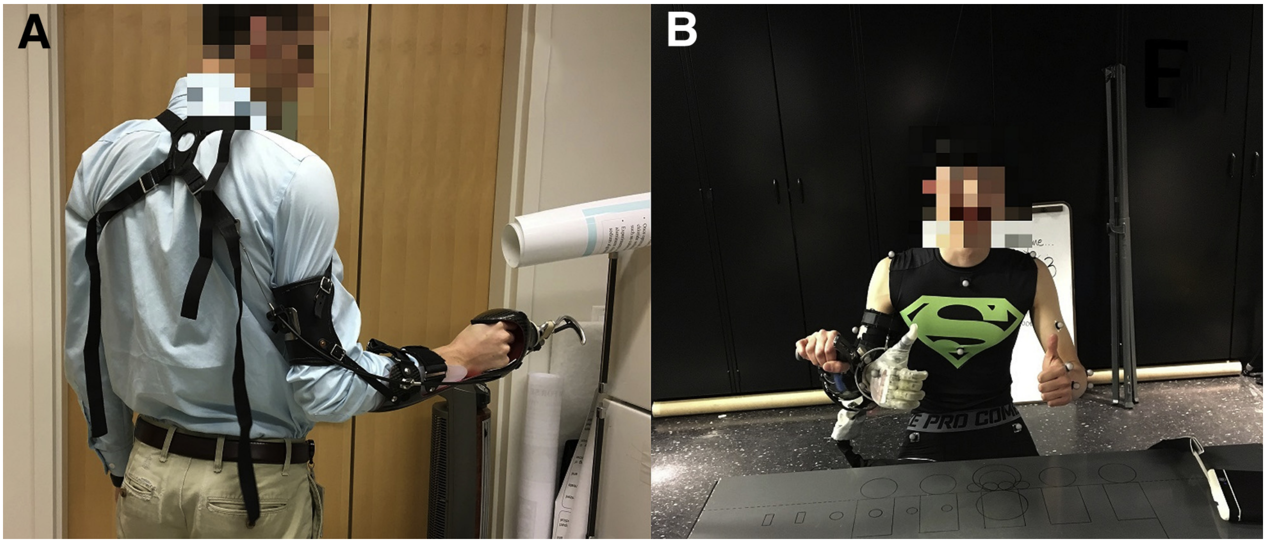

Fig 1 Bypass prostheses. (A) Rear view of the donned body-powered bypass prosthesis. (B) Front view of the donned DEKA arm prosthesis.

Bypass prostheses

Bypass prostheses were used in this study (fig 1) to facilitate recruitment of novel device users. The bypass device allows an able-bodied user to operate a prosthesis with the same controls an amputee would use and has frequently been used in the prosthesis research communities to assess learning, training efficacy, terminal device use, and performance.[7,17-20] Both bypasses used were transradial devices. The body-powered bypass prosthesis was provided by Arm Dynamics. The device features a voluntary open Hosmer 5X Hook[b] terminal device that is distally offset. The device is operated by creating tension in a control cable connected to a figure-8 harness through a variety of movements. For each subject, the difference between the length of the left arm (from shoulder to middle finger tip) and the length of the right arm with the body-powered bypass was measured to assess the potential effect of the distal offset in movements. On average, the difference between limb lengths was 9.25 cm. We note that all tasks performed in this study were unilateral, and participants were able to position themselves at a comfortable distance from the table edge to complete each task. Therefore, we felt that the effect of the distal offset on task performance was minimal. Although the length of the residual limb with a prosthesis should ideally be similar to the sound arm, the difference in limb length may be representative of actual issues that arise when fitting a prosthesis user with different technologies, as the ability to adjust prosthesis component length for certain devices has been recommended in several studies.[21,22]

The DEKA Arm bypass was provided by DEKA and Next Step Bionics. The device was offset 10 degrees medially from the subject's forearm. Similar to other medially offset bypass devices that were designed to maximize prosthesis incorporation, the bypass was designed to be collinear with the axis of rotation of the elbow.[23] Because of the weight of the device, a tool-balancer harness system and elbow brace were used to reduce strain on the user's arm. Control and operation of the device has been described in great detail elsewhere.[14] In all following kinematic analyses, the bypass prosthesis is treated as the limb in question instead of the able-bodied users existing limb within the device.

Training

Participants completed the training protocol outlined by Bloomer et al.[24] The protocol required participants to complete 10 sessions with a duration of 2 hours each sessions to balance the amount of time typically provided to train bypass prosthesis users on devices (up to several weeks)[7,19] and the time commitment of the study participants. Training activities focused on basic object manipulation tasks and activities of daily living while emphasizing thoughtful planning before attempting a task, such as prepositioning of the terminal device specifically for the body-powered device or determining the appropriate grip to use for the DEKA arm. DEKA participants completed 2 additional orientation sessions before the standard protocol to address the added device complexity before donning the device. For more details on the training approach used for participants in this study, please see Bloomer et al.[24]

Motion capture framework

A Vicon motion capture system[c] consisting of 8 B10 Bonita optical cameras was used to capture subject movements. The cameras sampled at a rate of 150 Hz and were positioned to optimize the targeted capture volume. The system was calibrated before collecting data from each participant according to the manufacturer's specifications. A digital video camera was also used to provide frontal recordings of the participant performing each test to aid in the segmentation of tasks (see the Kinematic data analysis section).

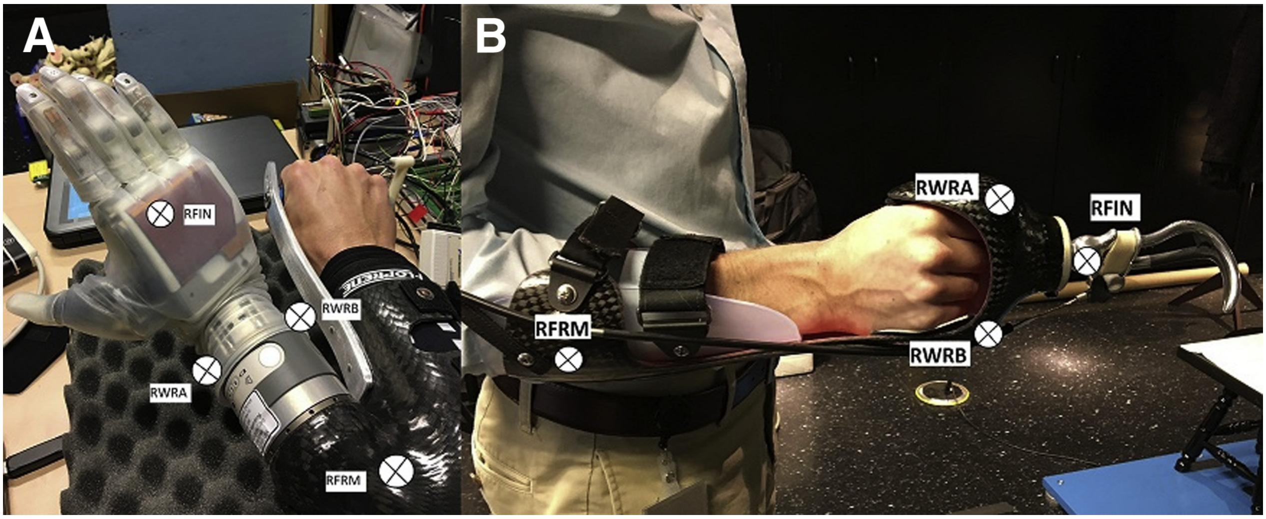

Fig 2 Bypass marker locations. DEKA bypass device (A) and body-powered device (B) with marker locations indicated. Abbreviations: RFIN, right finger; RFRM, right forearm; RWRA, right wrist A; RWRB, right wrist B.

The Plug-in-Gait upper body model from Vicon was applied to each participant and used to analyze movement. Twenty-seven reflective markers were placed on anatomical landmarks on the participant per the model documentation.[25] Briefly, head markers were placed on the right and left temples and on the right and left sides of the back of the head; torso markers were placed on the spinous process of C7 and T10 vertebrae, right scapula, xiphoid process, and sternal notch; hip markers were placed on the right and left anterior superior iliac spine and on the right and left posterior superior iliac spine; and upper arm markers were placed on the acromioclavicular joint, lateral surface of upper arm, and lateral epicondyle of the elbow joint. Markers distal to the right elbow required special consideration because of the bypass device (forearm, wrist, and finger). Locations for these markers are shown in figure 2. The model was calibrated using subject-specific measurements (weight; height; hand, wrist, and elbow width; and shoulder offset).

Functional tests

Each participant performed 2 trials of each task in the Jebsen-Taylor Hand Function Test (JHFT) and the targeted Box and Blocks Test (tBBT).[26,27] All tests were performed unilaterally with the device in question. The JHFT consists of 7 timed tasks meant to represent a variety of hand activities and is validated in the upper limb amputee population.[28] For the purposes of this study, only 3 tasks were analyzed. These tasks were chosen for their relatively low inter- and intrasubject variability[29] and their varying demands from fine to gross motor tasks. The 3 tasks are described below.

- JHFT 2—page turning: participants flipped over 5 notecards (3x5cm) arranged in a row using any technique, starting with the leftmost card and moving right.
- JHFT 4—simulated feeding: participants used a spoon to pick up 5 kidney beans (1 at a time) spaced 2 inches apart and dropped them into an empty can, starting with the rightmost bean and moving left.
- JHFT 7—heavy cans: participants lifted 5 filled cans (1 at a time) approximately 1 inch onto a board, starting with the rightmost can and moving left.

The tBBT required participants to transport 16 wooden blocks (2.5 x 2.5 x 2.5 cm) over a partition as quickly as possible. Blocks were initially organized in 4x4 grid on the right side of the partition. Participants were instructed to transport the blocks to their mirrored position on an outlined 4x4 grid on the left side of the partition. Participants began with the bottom row, picking up blocks from left to right, before advancing to the above row of blocks until all blocks are transported. Time to transport all 16 blocks was recorded.

JHFT tasks were performed in a seated position. The table height was adjusted so that the participant's elbows were at a 90-degree angle when resting their hands palm down on the tabletop. The tBBT was performed from a standing position. The table height was adjusted to 10 cm below the anterior superior iliac spine to ensure consistent relative height. Both tasks equate shorter times with improved function and dexterity while mimicking daily tasks. Subjects were able to position themselves a comfortable distance from the table in order to maximize object manipulation efficiency with the bypass prostheses. For the body-powered bypass, this helped to reduce the effect of the distal offset on induced proximal joint movement.

Kinematic data analysis

A XYZ Euler angle decomposition was used to calculate joint-angle trajectories. For this study, 3 joints or body segments were examined: the torso, right shoulder, and right elbow. These joints were chosen based on literature demonstrating how movements at these joints are exaggerated with the loss of more distal DOFs.[30] Torso angles were calculated relative to a global coordinate system.

Right shoulder and right elbow angles were calculated relative to upper arm and torso segments and upper arm and forearm segments, respectively. The elbow was considered a hinge joint with 1 DOF, whereas the shoulder was considered a ball and socket joint. Both the shoulder and torso had 3 DOFs. Model validation and kinematic parameter calculations have been described previously in greater detail.[31] Angles were quantified accordingly for each joint: right elbow flexion (+) and extension (-); right shoulder flexion (+) and extension (-), abduction (+) and adduction (-), and internal rotation; torso forward flexion (+) and extension (-), lateral bending left (+) and right (-), and rotation left (+) and right (-).

A fourth order, zero lag, low-pass Butterworth filter at 6 Hz was used to filter kinematic data. Because of the repetitive nature of the tasks, trials were manually segmented into individual actions based on the video recordings of the task. Segment start was defined as the initiation of the approach to manipulate an object and segment end was defined as the release of that object. The number of segments per task varied with the number of objects manipulated. For example. the JHFT Task 2 (page turning) required the participant to flip 5 notecards and was, therefore, divided into 5 segments. Segments were time normalized to percent task completion for plotting purposes only, with 0% representing segment start and 100% representing segment end (supplemental fig S1, available online only at http://www.archives-pmr.org/).

The mean angle, maximum angle, range of motion (RoM), and angle trajectory path length were calculated to characterize the joint angle trajectories observed for each task and DOF of interest. The mean angle was calculated as the mean of the joint angle trajectory over time within a segment for a given DOF. The maximum angle was the maximum value of the angle trajectory within a segment. RoM was calculated as the difference between the maximum and minimum angles observed in each trial segment for a given DOF. Angle path length was calculated as the length along the joint angle trajectory. To determine angle path length, the difference between angles (θ) of consecutive samples for a given DOF were summed. Values were normalized by the number of samples (N) in a given trial:

$$Angle\ path\ length = \frac{\sum_{i=1}^{N} |\theta(i+1) - \theta(i)|}{N}$$

These metrics were calculated for all segments for a given task and joint DOF. Kinematic measures were chosen based on their acceptance in previous work and conciseness of summary for kinematic trajectories.[8,10,29,32,33]

Statistical analysis

Differences between the body-powered and DEKA participants were evaluated using a rank sum test. Mean values and standard deviations were also calculated for each analysis. Discrete segment and trial results were grouped to form single distributions for each device type, joint, DOF, and task for statistical analysis. Differences between devices for performance assessment (eg, scores on outcome measures) were considered significant at a *P* value less than .05. Although we expect the effect of the distal offset in the body-powered bypass prosthesis on joint range of motion to be minimal because individuals positioned themselves appropriately in front of the table and all tasks were unilateral, the kinematic metrics calculated in this study were considered significant at a *P* value less than .01 to provide more confidence that any differences seen between devices were because of the devices themselves.

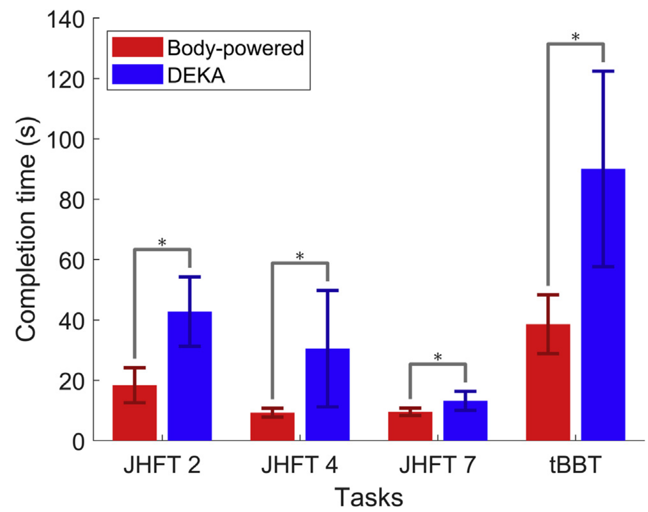

Fig 3 Task completion speed. Time to take completion results for functional tests. Asterisk indicates significance ($P<.05$).

Results

Functional scores

Completion times for the functional measures are shown in figure 3. The time to task completion was significantly higher for DEKA users for all tasks. The largest relative differences were for JHFT 4—simulated feeding, with times 328% higher for DEKA users.

Kinematics

To compare the movement approaches when using different types of prosthetic devices, joint kinematics of the right elbow, right shoulder, and torso were calculated as subjects performed each task. Average joint trajectories for all evaluated joints and tasks can be found in supplemental figure S1. The maximum angle and mean angle metrics provide an indication of where the movement is being performed relative to a "neutral" or 0 degree position. The RoM metric provides an indicator of the extent of the movement envelope. Results for the maximum angle, mean angle, RoM, and angle trajectory path length are provided in table 1.

Differences in movement trajectories varied slightly depending on the task being performed. The tBBT was the only task performed in a standing position. For nearly all DOFs at the elbow, shoulder, and torso, the maximum and mean angles for DEKA users were significantly lower than for body-powered users. This indicates that DEKA users used movements closer to the "neutral" position for the tBBT task. Shoulder and torso rotation maximum angles, however, were higher in DEKA users compared with body-powered users for this task. RoM results show an opposite trend. Body-powered users generally had a smaller RoM at all DOFs, indicating that body-powered users occupied a smaller movement envelope when completing the tBBT task. The normalized angle path length was significantly lower in DEKA users for all DOFs as subejcts performed the tBBT. This result was seen across all tasks and all DOFs, except for torso lateral flexion during JHFT 4—simulated feeding.

The kinematic metrics calculated for JHFT 2—page turn showed similar trends as those seen for the tBBT, but with fewer significant results. The maximum and mean angles were generally lower for the DEKA users, with significant results at the shoulder (abduction and rotation) and torso (lateral flexion). Significanly different RoM values between the DEKA and body-powered users show that DEKA users performed the movement in a tigher envelope with a smaller RoM.

During performance of JHFT 4—simulated feeding, body-powered users had significantly lower maximum and mean shoulder flexion angles and RoM when compared with DEKA users, indicating that the DOF was completed closer to the "neutral" position for body-powered users. For the JHFT 7—heavy cans task, torso lateral flexion maximum and mean angles were significantly larger for the DEKA users.

Discussion

The main goal of this study was to report the joint kinematic and functional differences between 2 prosthetic devices: a conventional body-powered device and a more technologically advanced robotic device (DEKA Arm). To our knowledge, this is the first study to perform a strict comparison of both devices within a motion capture framework. The results of this study demonstrate clearly different functional movement approaches for the 2 devices for some tasks and DOFs, but not for all. A discussion of the implications these results have on prosthetic device design and rehabilitation evaluation is below.

The upper limb is a high DOF system used to accomplish most activities of daily living.[5,34,35] Therefore, upper-limb amputation can severely affect quality of life and functional abilities.[36] The designs of prosthetic devices are growing closer to mimicking an intact hand, both in function and appearance, with the hypothesis that more DOFs and an anthropometric design will enable greater function and reduce the burden on more proximal joints. A recent kinematic study reporting on maximum angle and RoM in individuals with no upper limb disability or impairment for all tasks of the JHFT allows for the qualitative comparison of these values to determine how close the elicited movements are to "normal" movement.[29] The results from this study generally support the previously stated hypothesis, as the more advanced DEKA arm elicited movements closer to normative values. For example, in this study, right elbow flexion RoM during JHFT 4—simulated feeding was significantly greater in DEKA users (38.14$\pm$13.45 degrees) compared with body-powered users (28.71$\pm$5.83 degrees). However, this increased RoM was closer to the normative result of 42.46$\pm$10.04.[29] Overall, of 12 significant differences in RoM between devices for the JHFT tasks, 8 comparisons showed DEKA results closer to normative. A similar trend was observed with the maximum angle metric. Of the 9 significant differences between devices in maximum angle for the JHFT tasks, 5 comparisons showed DEKA results closer to normative.

Although these comparisons allow for a qualitative evaluation of how close prosthesis user movements are to normal movement, there is still a gap in knowledge as to the clinical implications of such movements. These movements may be the result of adaptation to the device and provide the upper limb amputee (ULA) with the most efficient way to complete a task. However, maladaptive compensatory movements repeated multiple times a day may lead to musculoskeletal dysfunction and increased risk of pain. ULAs as a group report more frequent musculoskeletal pain. In previous reports, 6.1% to 24.2% of ULAs were diagnosed with musculoskeletal overuse syndromes.[5,37] Unilateral amputees in particular are 3 times more likely to experience an overuse injury than the average worker.[37] Although this study provides a comparison of the potential compensatory movements used by individuals using these different technologies, more work is needed to determine which repetitive, compensating movements contribute to musculoskeletal issues in this specific population.

Standard time-based outcome measures have been widely acknowledged as having limited scope in assessing functional performance.[38,39] This opinion is demonstrated, specifically for DEKA users, in survey data in which users self-reported improved function with the DEKA device while simultaneously recording equivalent or worse functional scores compared with conventional prostheses.[6] The results of our study demonstrated ubiquitous negative effects on functional scores when using the DEKA device over the body-powered device (fig 3). In our study, DEKA users took twice as long on average to complete a task as body-powered users. Conversely, kinematic results generally demonstrated benefits to DEKA users in terms of movement closer to normative movements. These contradictory results emphasize the importance of capturing some element of movement quality into the assessment of function for advanced prosthetic technology in order to fully understand and evaluate the potential benefits offered by such advancements.

The results of this study may also have implications for device design. As shown in table 1, the device leading to higher maximum angles, mean angles, and RoMs varied depending on the task being performed. The differences observed may be a result of the design of the devices themselves. Video recordings of all subjects performing the JHFT 4—simulated feeding task illustrate the adaptive techniques used by users of the different technologies. During this task, shoulder flexion was significantly higher in DEKA users compared with body-powered users. Because the DEKA hand is an anthropometric hand, subjects were able to hold the spoon for the task as they would in their intact hand. However, digits 2 through 5 on the DEKA hand are rigid, requiring the users to push their arms forward and

Table 1 Kinematic metrics for body-powered and DEKA bypass users

Joint DOF	Max Angle ± SD (deg)			Mean Angle ± SD (deg)			RoM ± SD (deg)			Normalized Angle Path Length ± SD (deg)		
	BP	DEKA	*P*	BP	DEKA	*P*	BP	DEKA	*P*	BP	DEKA	*P*
tBBT												
R elbow flexion	120.69±9.28*	107.99±6.38*	<.001	106.96±9.97*	93.43±11.07*	<.001	21.11±6.16*	30.55±13.76*	<.001	0.19±0.07*	0.08±0.04*	<.001
R shoulder flexion	17.00±11.04*	31.72±9.67*	<.001	8.68±11.32*	17.82±9.04*	<.001	19.13±6.29*	24.44±8.32*	<.001	0.18±0.08*	0.06±0.03*	<.001
R shoulder abduction	59.79±21.80*	36.52±15.47*	<.001	53.18±21.07*	28.98±13.86*	<.001	12.52±5.97*	17.40±9.52*	<.001	0.10±0.05*	0.05±0.03*	<.001
R shoulder rotation	30.77±9.52	34.42±18.71	.112	24.13±9.39	21.39±15.77	.054	18.41±4.70*	23.15±10.06*	<.001	0.17±0.06*	0.08±0.04*	<.001
R torso forward flexion	26.01±8.34*	19.29±10.60*	<.001	21.09±8.08*	13.08±9.39*	<.001	10.69±3.39*	15.23±6.79*	<.001	0.10±0.05*	0.04±0.03*	<.001
R torso lateral flexion	32.52±6.88*	19.84±6.45*	<.001	19.52±6.62*	11.29±4.30*	<.001	20.80±7.64*	14.06±6.64*	<.001	0.11±0.05*	0.03±0.02*	<.001
R torso rotation	18.15±8.68*	22.34±8.12*	<.001	6.67±8.33*	10.92±7.31*	<.001	19.15±5.93	19.15 ± 6.69	.500	0.13±0.05*	0.05±0.02*	<.001
JHFT 2 – Page Turning												
R elbow flexion	116.18±13.13	113.10±6.87	.220	102.12±13.20	97.88±9.67	.105	33.30±7.39	38.09±18.17	.550	0.29±0.14*	0.11±0.04*	<.001
R shoulder flexion	29.07±11.76	27.73±15.79	.420	11.62±13.24	10.32±11.46	.535	31.77±5.67	30.77±13.10	.440	0.25±0.09*	0.09±0.02*	<.001
R shoulder abduction	58.74±15.57*	42.12±15.76*	<.001	36.74±10.88*	26.04±10.11*	<.001	38.93±11.56*	25.52±13.27*	<.001	0.23±0.07*	0.08±0.03*	<.001
R shoulder rotation	54.09±8.65*	39.65±9.25*	<.001	37.68±8.70*	25.27±9.91*	<.001	34.61±8.37	33.48±10.56	.210	0.27±0.10*	0.11±0.04*	<.001
R torso forward flexion	7.75±3.89	8.89±5.98	.819	3.22±5.19	2.77±5.31	.442	8.07±3.62	11.16±6.39	.010	0.06±0.02*	0.04±0.02*	<.001
R torso lateral flexion	15.39±6.91*	10.09±3.80*	<.001	8.06±3.85*	5.54±4.11*	.001	12.97±5.77*	8.35±4.52*	<.001	0.08±0.03*	0.03±0.01*	<.001
R torso rotation	13.84±10.85	12.39±8.60	.722	2.69±11.97	5.22±9.65	.315	19.20±6.61*	12.04±4.19*	<.001	0.14±0.06*	0.05±0.02*	<.001

(*continued on next page*)

Table 1 (*continued*)

Joint DOF	Max Angle ± SD (deg)			Mean Angle ± SD (deg)			RoM ± SD (deg)			Normalized Angle Path Length ± SD (deg)		
	BP	DEKA	*P*	BP	DEKA	*P*	BP	DEKA	*P*	BP	DEKA	*P*
JHFT 4 – Simulated Feeding												
R elbow flexion	131.09±5.54*	107.07±8.42*	<.001	114.66±7.31*	87.55±12.72*	<.001	28.71±5.83*	38.14±13.45*	<.001	0.22±0.05*	0.14±0.07*	<.001
R shoulder flexion	8.90±5.02*	19.50±8.60*	<.001	-8.69±8.10*	13.00±9.14*	<.001	8.63±4.61*	11.92±6.16*	<.001	0.10±0.04*	0.07±0.03*	<.001
R shoulder abduction	42.19±10.96*	33.09±12.49*	<.001	29.56±9.95*	23.17±12.26*	.002	19.40±8.61	16.20 + 6.81	.030	0.17±0.07*	0.08±0.04*	<.001
R shoulder rotation	23.24±7.37	26.33±6.93	.090	7.76±7.10	8.11±8.62	.691	23.95±6.72*	30.92±10.31*	<.001	0.21±0.05*	0.14±0.06*	<.001
R torso forward flexion	9.69±4.38	8.52±4.46	.060	6.74±3.69*	2.84±6.05*	<.001	7.20±3.74*	12.53±6.12*	<.001	0.08±0.04*	0.05±0.02*	<.001
R torso lateral flexion	7.30±3.67	10.32±7.38	.041	4.13±3.22	4.92±5.59	.491	5.73±4.21*	10.07±5.67*	<.001	0.07±0.04	0.05±0.02	.010
R torso rotation	4.27±3.36	4.82±2.95	.154	-1.48±5.40*	-6.65±4.24*	<.0010	4.70±1.87*	6.42±2.33*	<.001	0.06±0.02*	0.04±0.02*	<.001
JHFT 7 – Heavy cans												
R elbow flexion	112.80±10.78	110.90±5.26	.410	105.95±10.74	102.72±6.54	.260	13.39±4.45	14.07±5.60	.390	0.23±0.12*	0.12±0.03*	<.001
R shoulder flexion	22.13±11.67	17.87±11.40	.572	14.67±11.52	13.15±11.78	.436	14.05±4.86*	10.96±4.80*	<.001	0.19±0.09*	0.09±0.02*	<.001
R shoulder abduction	32.24±12.90	30.17±12.21	.422	28.51±11.74	27.50±12.01	.555	6.80±3.80	5.57±3.77	.040	0.11±0.07*	0.06±0.02*	<.001
R shoulder rotation	34.60±7.06*	20.30±12.49*	<.001	27.31±7.77*	10.84±14.46*	<.001	15.39±4.35	14.67±8.01	.010	0.15±0.05*	0.11±0.03*	<.001
R torso forward flexion	8.93±6.97*	5.09±3.65*	.009	6.47±7.21	2.89±4.75	.029	5.14±3.25	3.72±2.21	.040	0.05±0.02*	0.04±0.02*	.003
R torso lateral flexion	3.62±2.98*	6.18±3.97*	.001	0.65±4.13*	4.15±5.42*	<.001	3.48±2.10*	2.15±1.04*	<.001	0.04±0.02*	0.03±0.01*	<.001
R torso rotation	6.04±4.02	5.53±4.98	.229	-3.10±7.42*	0.95±6.28*	.005	10.89±5.34*	5.48±1.82*	<.001	0.11±0.06*	0.05±0.02*	<.001

* Indicates significance ($P<.001$).

downward more with the DEKA hand in order to get enough clearance to pick up the beans with the spoon. This was also frequently accompanied with increased torso lateral flexion, although not significant. By identifying those features of the device design that alter movement of the user, we can better inform medical device developers on the aspects in need of innovation for both existing and novel technologies.

Study limitations

Both an important control and limitation of this study was the use of bypass prostheses. To strictly compare aspects of performance, control of user experience and training was important. The bypass devices allowed us to more easily recruit novel users with no previous prosthesis experience, ensuring their variability in performance was representative of the sample and not their training. However, our sample ultimately was able-bodied users and the devices were adapted to accommodate existing limbs. This could have numerous effects ranging from increased proprioception and range of motion to lesser motivation to learn the device, all of which need to be considered with such a study. Additionally, only right-hand bypass prostheses were used, but 2 of the participants were not right-hand dominant per the Edinburgh handedness survey. Although a subanalysis on the effect of hand dominance was beyond the scope of this study and not feasible given the small sample size, we acknowledge that hand dominance could affect performance.

Although the effect is expected to be minimal, kinematic results could be affected by bypass design choices. The body-powered device was, on average, 9 cm longer than the subject's residual limb, whereas the DEKA device featured a 10-degree medial offset. Previous research has stated the use of upper limb bypass devices in able-bodied individuals generates comparable results to actual prosthesis users in terms of performance-based outcome measure scores and kinematic profiles.[18] However, no such comparison to actual prosthesis users was made in the current study. To take into account the potential effect of bypass design on movement and to provide more confidence that any differences observed between devices were a result of the devices themselves, the kinematic metrics calculated in this study were considered significant at a more conservative level ($P<.01$). Further research is needed to determine exactly how these offsets affect movement and performance so other statistical adjustments can be made to improve the generalizability of the results to upper limb prosthesis users.

As previously stated, subjects were given the freedom to position themselves an appropriate distance from the table edge in order to complete each unilateral task, permitting personal adaptations. Ultimately, these adaptations do not address all potential differences between a bypass device and an amputee's device. However, given the custom designs and considerations of amputees, and the documented imperfections concerning prosthetic fit and alignment, we believe the results from this study can be used to inform general differences in movement elicited by these 2 different technologies.

Conclusions

Overall, in this study we have reported joint level kinematics for the DEKA Arm for the first time, while highlighting their significance and providing context through a comparison with a commonly used body-powered device. Although additional work is needed to translate this from bypass users to amputees and to further establish the clinical significance of kinematic results, this study elucidates the effect of the device of the user's movement approach and performance.

Suppliers

a. DEKA arm; DEKA Research and Development Corp.
b. Hosmer 5X Hook; Hosmer Dorrance Corp.
c. Vicon motion capture system; Vicon.

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