11-29-2020

Biomechanical Comparison of the Validity of Two Configurations of Simulators for Body-Powered Hand Prostheses

Camille Bennett
Loyola Marymount University, cbenne13@lion.lmu.edu

Amanuel Matias
Loyola Marymount University

Brendan Smith
Loyola Marymount University

Jenevieve Roper
Loyola Marymount University

Stephen Estelle
Loyola Marymount University

Loyola Marymount University
University Honors Program

Biomechanical Comparison of the Validity of Two Configurations of Simulators for Body-Powered Hand Prostheses

A thesis submitted in partial satisfaction

of the requirements of the University Honors Program

of Loyola Marymount University

by

Camille Bennett

March 23, 2021

Biomechanical Comparison of the Validity of Two Configurations of Simulators for Body-Powered Hand Prostheses

Amanuel Matias, Camille Bennett, Stephen Estelle, Jenevieve L. Roper, and Brendan W. Smith, *Member, IEEE*

***Abstract*—Simulators are often used in prosthesis research to evaluate new devices or characterize aspects of prosthesis use, so as to recruit participants without amputations. Simulators, in general, must locate the prosthesis somewhere other than where the intact biological limb exists. In this study, we compared two configurations of simulators for hand prostheses to determine which leads to more natural elbow and shoulder kinematics, and in turn, which is the more valid simulator. One configuration located the prosthesis in-line with the forearm, beyond the biological hand; the other located it beside the hand. We measured the kinematics of 12 non-amputee participants during three clinical tests of hand-arm dexterity, which were completed *1*) using each simulator configuration with a body-powered Hosmer 5X hand prosthesis and *2*) using the biological hand with a wrist brace. The beside-the-hand configuration resulted in kinematics that were more similar to those measured with the biological hand, particularly during the Box and Blocks Test, which involved the largest range of arm motion of those studied. Therefore, we concluded that simulators with the beside-the-hand configuration are likely to better emulate the use of hand prostheses for activities involving a wide variety of arm movement. We suggest using this configuration in general, except when arm movement is of secondary importance and when this configuration would be obstructive, visually or otherwise.**

I. Introduction

In 2005 the prevalence of upper limb loss in the U.S. was 541,000 [1], with trauma, cancer, and vascular complications identified as the leading causes of amputation [2]. Undergoing an upper extremity amputation has the potential to substantially limit an individual's functional abilities and to have major ramifications on their quality of life. Yet, although the use of prostheses offers benefits of restored function, increased autonomy, greater likelihood of returning to employment, and overall improved quality of life; the rates of long-term use of upper extremity prostheses are still relatively low, between 27-56% [3].

While a number of prosthetic devices have been designed for and adopted by people with upper limb amputations, the most widely used is the body-powered hand prosthesis. Still, the rate of rejection for this kind of device ranges from 16-58%, with reasons for rejection including the unattractiveness of the device, pain or discomfort while using the prosthesis, or dissatisfaction with the training received in learning how to use the device [4]. It therefore seems likely that improvements to the design and functionality of body-powered prostheses may enhance rates of prosthesis use and satisfaction by amputees.

Upper limb prosthesis simulators, also referred to as able-bodied adaptors, are often used for research and development purposes because they allow subjects with intact hands to use prosthetic devices. Testing new designs for hand prostheses on people without an amputation can potentially avoid imposing an unnecessary burden on people with amputations to serve as test subjects throughout the design process. Certainly it is imperative to include the end user of any assistive or rehabilitative technology in the various stages of the design process to provide valuable insights [5]. However, after identifying the product needs with prospective end users, it often becomes ideal to work out basic mechanics of a device without recruiting populations with the corresponding amputation. In the case of Smit et al., 12 non-amputee subjects were chosen to test a body-powered prosthesis simulator; this was helpful because it allowed for the evaluation of a newly designed prosthetic hand without imposing a burden on subjects with upper extremity amputations [6]. Then the optimization of various well-functioning design alternatives can be completed with possible end users.

Prosthesis simulators have been used to address a number of research questions. Some studies have used simulators to develop and assess terminal devices [6], [7] and prehensors [8]. Other studies have assessed newly developed simulators themselves, as in the case of Chua et al., where the goal of the study was to design and evaluate the functionality of a haptic body-powered prosthesis simulator [9]. Simulators have also been used to gain insight about the learning processes of non-amputees during prosthetic simulator training [10] and the acquisition of prosthetic skills in body-powered prosthesis users [4].

Despite the advantages of prosthesis simulators for skill learning and developmental purposes, they pose a key challenge to the design of optimal prostheses: the biological hand is located where the prosthesis would normally be worn by its end user. Therefore, simulators must place the prosthesis somewhere else. Most researchers have utilized simulators that locate the prosthesis in line with the arm, but out past the hand, effectively lengthening the forearm [4], [7]–[10]. This would be expected to alter the biomechanics of how subjects using a simulator complete tasks relative to users with an amputation. This would be a concern if these differences in biomechanics alter the ideal design of the prosthesis being tested.

An alternative to this placement is to position the simulator somewhere beside the biological hand. This approach, used in a study by Smit et al. [6], maintains the effective length of the forearm, but no longer places the prosthesis in line with the

A. Matias and B. W. Smith are with the Mechanical Engineering Department, Loyola Marymount University, Los Angeles, CA 90045 USA (phone: 310-258-5555; e-mail: brendan.smith@lmu.edu).

S. Estelle was with the Mechanical Engineering Department, Loyola Marymount University, Los Angeles, CA 90045 USA.

C. Bennett and J. L. Roper are with the Health and Human Sciences Department, Loyola Marymount University, Los Angeles, CA 90045 USA (e-mail: jenvevieve.roper@lmu.edu).

forearm. This placement, would therefore be expected to create a slight change in joint angles relative to users with an amputation, but may preserve other kinematic features that depend on the ratio of upper- and forearm lengths. It remains unknown which configuration of simulator more dramatically alters the biomechanics of using the prosthesis, relative to the in-situ placement.

The goal of this study is to determine which configuration of simulator for a hand prosthesis, either locating the prosthesis beyond the biological hand or beside the biological hand, results in more natural elbow and shoulder kinematics. We hypothesized that placing the hand prosthesis beside the biological hand, thus preserving forearm length, would lead to more natural biomechanics. That is, we expected that the small offset in effective forearm angle would have a less dramatic impact on overall arm kinematics than altering the balance between upper- and forearm lengths. For one, the angular offset caused by placing the prosthesis beside the hand can ostensibly be replicated by natural arm movement, which would suggest that such offsets can be accommodated without substantively altering the inverse kinematics of the controlling hand, i.e., prosthesis, position.

II. Methods

A. Experimental Hardware

We designed two, 3D printed, hand prosthesis simulators which represent the two most common configurations of simulators seen in literature. One, simulator, with the "beyond-the-hand" configuration (**Fig. 1a)**, located the hand prosthesis out in front of the user's biological hand, by approximately 15 cm, in line with the participant's forearm. This effectively lengthened the forearm. The other simulator, with the "beside-the-hand" configuration (**Fig. 1b)**, located the hand prosthesis equidistant from the participant's elbow as the biological hand. This effectively offset the user's forearm by a small rotation, while maintaining its length. The angle was chosen to mitigate physical and visual obstruction for the Box and Blocks Test.

Both simulators were donned by tightening two cuffs around the participant's forearm, adjusted to sit on the soft tissue below the wrist and near the base of the forearm. Each cuff consisted of a contoured plastic piece that flared out into

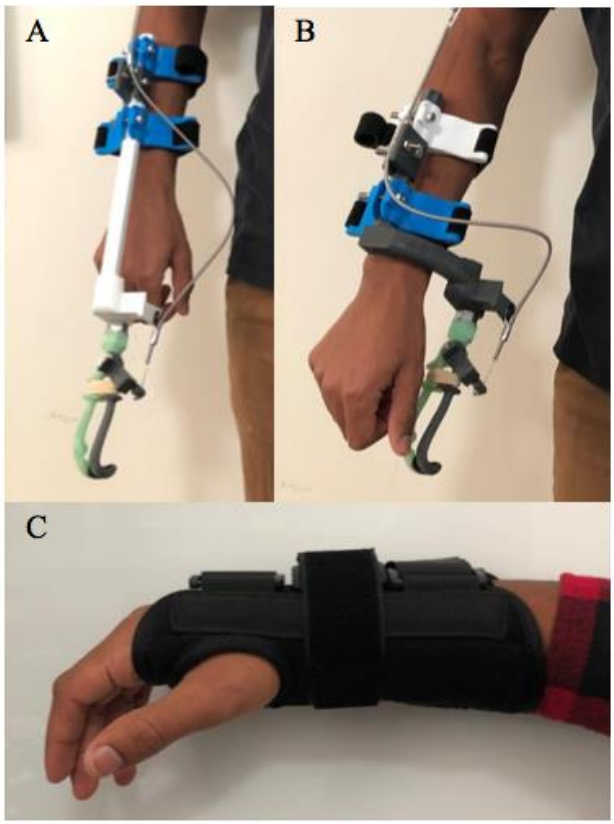

Figure 1. Two configuration of hand prosthesis simulators used during this study. Arm kinematics were measured while participants performed three clinical tests with each. Kinematics with each simulator were compared to arm kinematics when participants completed each of these test using their biological hand. **(A)** The beyond-the-hand configuration located the hand prosthesis in line with forearm, effectively extending forearm length. **(B)** The beside-the-hand configuration located the prosthesis internal and anterior to the biological hand, preserving forearm length, but applying an offset to effective forearm angle. **(C)** Participants wore a wrist brace to immobilize their wrist while completing experimental tasks with their biological hand, to limit arm movement to the elbow and shoulder.

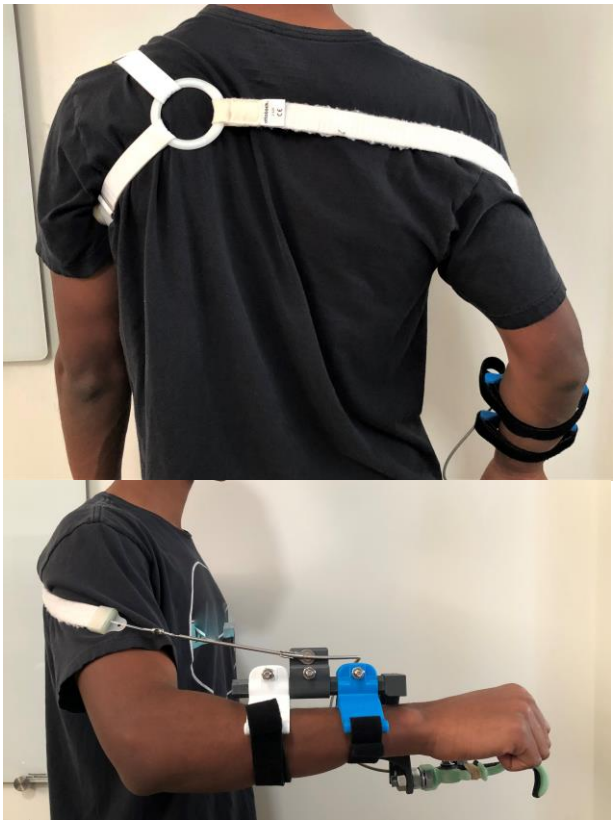

Figure 2. Configuration of body-powered prosthesis harness that participants used to open and close the hand prosthesis during this study. For right handed participants, all in this study, the harness was looped around the left shoulder and tightened such that internal rotation of the left shoulder would open the prosthesis when the arm was extended to a neutral position relative to the experimental tasks. The harness was connected to a Bowden cable whose housing was anchored to one point on top of either simulator and another near the thumb of the prosthesis. As the length between the harness loop and the first anchor lengthened, the prosthesis opened. Soft backed hook-and-loop straps were used to secure two cuffs (white and blue) to each participant's arm to prevent sliding or rotation over their arm.

two attachments for the hook-and-loop straps, that were tightened to secure the cuff.

For use in this experiment, we 3D printed a hand prosthesis based on a scanned copy of the Hosmer 5X body-powered hand prosthesis (Hosmer Dorrance Corp., USA). The base of the prosthesis was modified so that it could be bolted onto either prosthesis simulator. A70 durometer adhesive back rubber was affixed to the tip of both hooks of the prosthesis, similar to the Hosmer design, to aid in gripping the blocks, pegs, and checkers of the various clinical tests used during this experiment. Participants wore a figure-9 style Ottobock 21A36 Below-Elbow Harness (Ottobock, Germany), which allowed them to open the hook of the prosthesis by various combinations of extending the arm ipsilateral to the simulator and internal rotation of the contralateral shoulder (**Fig 2)**.

Participants also completed the experimental task using their biological hand, while wearing a wrist brace (Featol, USA) to immobilize their wrist (**Fig 1c)**. During this condition, tasks were completed using shoulder and elbow movement, wrist pronation/supination, and thumb-index finger pinch grip.

B. Participants

We conducted this study using a sample population of 12 right-handed, non-amputee participants (6 male, 6 female; 18-22 years of age). During this study, the prosthesis simulators were worn on the right arm, as this was the dominant side for all participants. All participants reported having no current injuries to either arm. Each participant gave written informed consent and all procedures were approved by the Institutional Review Board of Loyola Marymount University, LMU IRB 2019 SP 74.

C. Clinical Tests

We used three clinical tests to compare the biomechanics and dexterity with each configurations of simulator. These tests are commonly used in prosthesis research, as they are understood to be representative of activities of daily living.

The Box and Block Test (BBT), which assesses unilateral gross manual dexterity [11] has been used to test hand function of patients in clinical and occupational therapy settings, including patients with stroke and Parkinson disease. Additionally, BBT has been identified as a useful test in examining function of upper extremity prostheses in amputee patients [12]. BBT was conducted according to established clinical practice: participants attempted to transfer as many blocks as possible between two containers, separated by a short wall, and the number of blocks moved in one minute was recorded. Any blocks dropped outside of the box were not included in the participant's total block count. The prosthesis was oriented on the simulator so that its prongs were vertical, aligned with the blocks, to reduce the need for pronation/supination, which is not available to body-powered prosthesis users. In the braced biological hand condition, pronation/supination played little role, making it a viable surrogate for arm movement by prosthesis users.

The Jebsen-Taylor Test of Hand Function (JTTHF) assesses unimanual hand function and has been shown to be representative of activities of daily living [13]. It has also been useful for evaluating hand prosthesis, despite being time consuming to administer [6], [7]. JTTHF consists of seven subtests. In this study, we used only one subtest, "JTTHF-checkers", which we expected would be most effective for assessing upper-limb prosthesis use for activities of daily living, along with the two other tests in our protocol. This subtest required participants to stack four checkers on a marked spot. The checkers were initially placed 10 cm apart on a table, in a line that was 10 cm nearer to the participant than the marked spot where they were to assemble the stack. Like BBT, the prosthesis was oriented to reduce the need for pronation/supination.

The Nine Hole Peg Test (NHPT), which measures finger dexterity [14], has also been used to assess upper limb prostheses and proves to be advantageous due to its short administration time [6], [12]. NHPT was conducted using a modification in which the pins started in a custom peg board (**Fig. 3**) and moved to the clinical peg board during the test. This custom board was similar to the clinical peg board, except that it angled each of the eight outside pegs 30° from vertical. For this test, the participant's time to relocate the 9 pegs from one board to another was recorded. If a peg was dropped, the experimenter restored the peg to its original location. The goal for the modified peg board was to remove the prohibitive challenge of picking up horizontal pins from a tray and rotating them to the vertical position to insert into the peg board—this would require participants either to develop a technique of grabbing each peg by the end and relaxing the grip until it fell vertical, or to perform dramatic rotations of the arm. We considered the alternative of moving pegs from one vertical peg board to another, but this would remove the rotation aspect from NHPT, which differentiated it from BBT and JTTHF-checkers. The modified peg board retained the need to rotate pegs in all directions, but to a reduced degree. This rotation limited the value of the braced hand condition as a surrogate for arm movement by prosthesis users, since the task benefited from pronation/ supination. Instead, the goal for including NHPT was to compare participants' compensation with each simulator for their reduced capacity for pronation/supination, akin to that of body-powered prosthesis users.

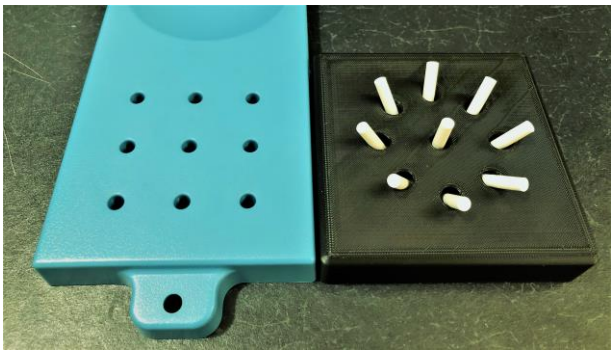

Figure 3. Modified Nine Hole Peg Test used in this study. The pegs begin in the board on the right. Each outside peg is oriented 30° outward from the center vertical peg. The time to move these 9 pegs, in any order, to the left board was recorded as the score.

D. Experimental Procedure

Each participant completed 21 experimental trials, three for each clinical test (BBT, JTTHF-checkers, NHPT) using each simulator configurations, and once each using their biological hand with wrist brace. The order of the three tests was always: BBT followed by JTTHF-checkers followed by NHPT. All trials for each clinical test were completed consecutively, as were all trials for each simulator or the biological hand. The ordering of the three conditions (two simulator conditions and biological hand) was randomized and balanced within the participants of each sex.

During the experimental session, participants first provided informed consent. Then the motion capture markers were placed before seating them in a fixed base chair in front of a table on which the clinical tests were administered. Prior to trials with a prosthesis simulator, the simulator and body-powered harness were donned. The harness was adjusted until the prosthesis' hook was just closed when the arm was in a neutral position above the table, and began to open when the participant extended their arm from this neutral position or rotated their shoulder. Participants were asked to pick up and release BBT blocks, and the harness was iteratively adjusted until this motion was comfortable. This also served to familiarize participants with the operation of the body-powered prosthesis. Participants then completed a calibration movement for the motion capture system, which consisted of standing with arms straight down, then walking in a 5-meter straight line, turning, and returning to the starting point. Between simulator conditions, the motion capture calibration was repeated.

E. Data Collection

Motion capture is often used to evaluate movement quality of joints during prosthesis use, such as by comparing the kinematics between related or putatively representative tasks [12], [15], [16]. We included accelerometry-based motion capture (Xsens, USA) in our experimental design to collect kinematic data used to compare the validity of the simulator configuration. Motion capture markers were placed according to manufacturer specifications, with a compression shirt and various straps with hook-and-loop style fasteners for each sensor, with the exception that the forearm marker was placed anterior, rather than posterior, to accommodate the simulator (**Table I**). Clinical test scores from each trial were also recorded for secondary analysis.

F. Data Analysis

Each participant's kinematics while completing each clinical test with their biological right hand (while wearing the brace to immobilize the wrist) served as benchmarks against which their kinematics for that test, with each simulator configuration, were assessed. For this study, we defined the more valid simulator configuration as the one with greater kinematic similarity to the biological hand, as defined below.

Manufacturer software was used to calibrate the motion capture sensors and calculate joint angles (Xsens, USA). Similarity was assessed via the average and range of motion (RoM) of four joint angles: elbow flexion/extension and shoulder flexion/extension, adduction/abduction, and internal/external rotation (defined as ordered Euler angles). For each joint angle, the average value of that angle was calculated throughout the course of each experimental test, from the beginning to the completion of the test. The range of motion was calculated as the difference between the 5^{th} and 95^{th} percentile values of the joint angle measured during that time span, to exclude any outlier movements.

TABLE I. MOTION CAPTURE MARKER POSITIONS

Marker	Landmark Description
Forehead	Most comfortable position
Sternum	Flat, medially located on chest
Shoulder	Scapula
Upper arm	Lateral side, equidistant between elbow and shoulder marker
Fore arm	Anterior flat side of wrist
Hand	Anterior side of hand
Pelvis	Flat on sacrum

We conducted an exploratory analysis to compare the kinematic similarity between each simulator configuration and the biological hand. For each combination of clinical test (BBT, JTTHF-checkers, NHPT) and joint angle, a two-tailed, paired Student's t-test was used to compare each kinematic measure (average, RoM) between each simulator configuration and the biological hand, and between the two configurations themselves. Average and RoM were computed by averaging the results from the second and third trial with each clinical test, i.e., excluding the first trial as training. Scores for each clinical test were also compared between the two simulator configurations, also using paired t-tests. Due to multiple comparisons, 27 for each clinical test, $\alpha = 0.002$ was used as a benchmark for significance within each clinical test.

III. RESULTS AND DISCUSSION

During BBT, elbow and shoulder kinematics appear to have been more natural with the beside-the-hand configuration than with the beyond-the-hand configuration. Neither configuration significantly affected the range of motion (RoM) of either the elbow or shoulder, but the beyond-the-hand configuration dramatically increased the average shoulder extension, and was usually accompanied by increases in elbow flexion (**Table II**). This is consistent with the forearm being pulled backward to counteract the forward positioning of the prosthesis, and with the need to approach the box from a steeper angle to access blocks, given the lengthened forearm. As discussed above, the kinematics with the braced biological hand were regarded as a surrogate for those of body-powered prosthesis users during BBT for two reasons: *1*) the brace restrained participants' wrist flexion/extension and limited them to using a pinch grip, and *2*) although the brace permitted pronation/supination, this was expected to have had little impact on shoulder and elbow kinematics during BBT.

In contrast to the dramatic changes in kinematics with the beyond-the-hand configuration, the primary kinematic change observed with the beside-the-hand configuration during BBT was a comparably small increase in shoulder internal rotation, accompanied by small increases in shoulder extension, and a trend toward elbow extension. Together, these changes would counteract the angular offset from locating the prosthesis on the radial side of the biological hand. The increased internal rotation is also consistent with rotating the prosthesis down

into the box, which suggests that the choice of where beside the hand to position the prosthesis does itself impact arm movement. For instance, placing the prosthesis on the ulnar side would likely counteract this increase in internal rotation.

The only difference between clinical test scores was a marginally higher BBT score with the beside-the-hand configuration. Given the multiple comparisons in this study, this result should not be taken in isolation. But a higher score was consistent with the observation that kinematics with the beside-the-hand configuration were more natural.

During JTTHF-checkers, both simulator configurations led to dramatic changes in average joint angles of the shoulder and elbow. Both configurations also reduced joint RoM by half or more. Here, the beside-the-hand configuration resulted in greater increases in average shoulder flexion and elbow extension than the beyond-the-hand configuration. However, neither configuration resulted in kinematics that resembled those with the braced biological hand. This might be explained by noting that JTTHF-checkers was likely the simplest of the clinical tests used in this study. It required less control over prosthesis orientation, as each checker could be grasped identically from any direction per its radial symmetry. This appears to have prompted participants, who had no prior experience with body-powered prostheses, to minimize their arm movement during this test. This could help them maintain tautness in the body-power harness, near the threshold for opening and closing the prosthesis as they grabbed each checker and release it without knocking the stack over.

During NHPT, both simulator configurations resulted in small, significant changes in arm kinematics relative to the biological hand. The changes in average joint angle are consistent with the compensation for the prosthesis location, as described for BBT, but here there were no significant differences between the two configurations themselves. Both simulators also significantly reduced the RoM of both the shoulder and elbow, here by about one-third. Recall that for NHPT, kinematics with the braced biological hand were less valid as a surrogate for those of prosthesis users, given that the brace allowed pronation/supination to help rotate the pegs. Still, these results do provide evidence that neither simulator configuration inherently causes more compensation for the lack of pronation/supination capability when rotating objects by 30-degree with a body-powered prosthesis.

Even though RoM was more dramatically reduced for JTTHF-checkers than for NHPT, absolute RoM with each simulator was quite similar in both tests. This might indicate that for these tests, participants adopted a similar strategy of keeping the arm relatively steady. This steadying of the arm does not appear to have occurred for BBT, when fine control of prosthesis prehension was likely less important given that blocks were grabbed via their larger flat sides and then simply dropped. Greater RoM would also be expected during BBT to navigate over the box walls and central divider.

One last observation was that there was no significant difference in RoM between the two simulator configurations for any of the three clinical tests. Instead RoM appears to depend primarily on the task itself, specifically on the degree

TABLE II. CLINICAL TEST SCORES AND KINEMATIC MEASURES

			Biological Hand[a]			**Δ Beyond-the-Hand[b]**				**Δ Beside-the-Hand[b]**				**Between**
			M	±	SD	M	±	SD	p-value[c]	M	±	SD	p-value[c]	p-value[d]
Box & Blocks Test	Clinical Test Score (# blocks)		50.9	±	7.8	-35.2	±	6.6	**0.000*** **	-32.8	±	3.3	**0.000*** **	**0.049***
	Shoulder Add./Abduction	Avg.	30	±	8	0	±	15	0.94	-1	±	13	0.74	0.75
		RoM	21	±	6	3	±	6	0.063	3	±	7	0.16	0.83
	Shoulder Int./Ext. Rotation	Avg.	38	±	8	-1	±	18	0.89	**11**	**±**	**12**	**0.006** **	**0.005** **
		RoM	22	±	9	1	±	11	0.69	1	±	12	0.81	0.76
	Shoulder Flexion/Extension	Avg.	72	±	8	**-17**	**±**	**10**	**0.000*** **	**-6**	**±**	**6**	**0.011***	**0.002** **
		RoM	21	±	8	2	±	11	0.50	3	±	10	0.32	0.56
	Elbow Flexion/Extension	Avg.	43	±	10	11	±	17	0.053	-5	±	17	0.33	**0.006** **
		RoM	34	±	10	-5	±	14	0.26	-5	±	9	0.076	0.91
J-T Test: Checkers	Clinical Test Score (seconds)		3.8	±	1.0	12.8	±	5.0	**0.000*** **	14.0	±	5.4	**0.000*** **	0.53
	Shoulder Add./Abduction	Avg.	23	±	5	-3	±	12	0.35	-5	±	12	0.19	0.59
		RoM	13	±	6	0	±	7	0.94	0	±	7	0.89	0.77
	Shoulder Int./Ext. Rotation	Avg.	19	±	7	**18**	**±**	**14**	**0.001*** **	**24**	**±**	**16**	**0.000*** **	0.20
		RoM	26	±	6	**-14**	**±**	**7**	**0.000*** **	**-13**	**±**	**7**	**0.000*** **	0.97
	Shoulder Flexion/Extension	Avg.	39	±	9	9	±	13	0.040	**16**	**±**	**16**	**0.004** **	**0.031***
		RoM	30	±	9	**-19**	**±**	**11**	**0.000*** **	**-16**	**±**	**11**	**0.000*** **	0.27
	Elbow Flexion/Extension	Avg.	75	±	11	**-18**	**±**	**20**	**0.009** **	**-28**	**±**	**22**	**0.001*** **	**0.015***
		RoM	28	±	10	**-13**	**±**	**13**	**0.004** **	**-12**	**±**	**11**	**0.003** **	0.56
Nine Hole Peg Test	Clinical Test Score (seconds)		12.5	±	1.8	33.7	±	10.3	**0.000*** **	31.3	±	9.3	**0.000*** **	0.54
	Shoulder Add./Abduction	Avg.	25	±	8	-1	±	14	0.73	-4	±	13	0.26	0.26
		RoM	15	±	3	-2	±	5	0.36	-2	±	4	0.17	0.98
	Shoulder Int./Ext. Rotation	Avg.	27	±	8	**10**	**±**	**15**	**0.043***	**8**	**±**	**13**	**0.050***	0.65
		RoM	20	±	7	**-7**	**±**	**6**	**0.002** **	**-8**	**±**	**7**	**0.004** **	0.64
	Shoulder Flexion/Extension	Avg.	56	±	10	-6	±	13	0.14	-2	±	13	0.56	0.10
		RoM	19	±	6	**-8**	**±**	**6**	**0.001*** **	**-8**	**±**	**6**	**0.002** **	0.60
	Elbow Flexion/Extension	Avg.	62	±	11	-4	±	14	0.30	**-10**	**±**	**12**	**0.016***	0.13
		RoM	21	±	4	**-6**	**±**	**6**	**0.005** **	**-4**	**±**	**6**	**0.022***	0.38

M = mean. **SD** = standard deviation. **Avg.** = average of joint angle measured during trial. **RoM** = range of motion defined as range of 5th and 95th percential of joint angle measured during trial.
a. All angles are expressed in degrees, positive values corresponds to adduction/internal-rotation/flexion.
b. Values describe the difference in value with the respective simulator, relative to with the biological hand, positive values indicate an increase in the value with the simulator.
c. Comparison between values with the respective simulator and with the biological hand, two-tailed, paired Student's t-test with df = 11, p<0.05*, p<0.01**, p<0.001***.
d. Comparison between values with the two simulator configurations themselves, two-tailed, paired Student's t-test with df = 11, p<0.05*, p<0.01**, p<0.001***.

to which it requires fine prehension and moving around obstacles. The effects of simulator configuration appear to be limited to offsetting joint angles. For tasks that involve courser prehension and larger movements around obstacles, e.g., BBT, the beyond-the-hand configuration appears to cause greater offset in average joint angle than the beside-the-hand configuration. In contrast, both configurations appear to lead to comparable offsets in tasks requiring less movement. Further investigation is certainly warranted, but these results suggest that a beside-the-hand configuration can be used to more accurately emulate the use of body-powered prostheses over a wider range activities of daily living, even if some activities are relatively insensitive to simulator configuration.

One limitation of this study is that it was conducted with a body-powered hand prosthesis, for which shoulder and arm movement were required to open and close the prosthesis. As such, our conclusions are most relevant to future work involving body-powered prostheses. A natural extension for this study would be to repeat the experiment with a robotically actuated hand prosthesis to inform the use of simulators when designing myoelectric and robotically actuated prostheses. This would have the added benefit of isolating the effects of prehension and simulator configuration on arm movement.

Another limitation is that the wrist brace used to emulate prosthesis use by people with amputations did not restrict wrist pronation/supination. Future work could use a brace that restricts pronation/supination. Then stronger within-subject comparisons could be made for tasks that engage pronation/supination, such as the modified NHPT used here. Future work could also compare simulator use directly with prosthesis use by people with hand amputations. One might recruit participants with hand amputations and position a prosthesis in the beyond-the-hand and beside-the-hand locations with adaptors that attach directly to the participants' own harness. In combination with the current work, such a study would provide valuable insights into the validity of these simulator configurations in emulating prosthesis use by both first-time and experience prosthesis users.

IV. Conclusion

The goal of this study was to compare the biomechanical validity of two configurations of prosthesis simulator, which allow people with intact biological hands to use body-powered hand prostheses during research and development. Kinematic analysis supported our hypothesis that configurations that locate the prosthesis beside the hand are in some situations more biomechanically valid than the more commonly used configuration that places the prosthesis out beyond the hand. This latter configuration has the effect of lengthening the forearm segment. We found that this can dramatically alter average joint angles, thus making these simulators less valid.

Specifically, this study provided evidence that the beside-the-hand configuration is more valid for tasks involving a wide range of arm kinematics, such as the clinical Box and Blocks Test, during which the prosthesis must be navigated around obstacles to interact with objects. For tasks in which arm kinematics are less pertinent, such as manipulations with the arm extended, both simulators would likely be of comparable validity. The choice of simulator configuration might then depend on which better positions the biological hand, e.g., so as not to visually or physically interfere with the task being studied. However, absent such constraints, we recommend using a beside-the-hand configuration for its general validity.

Acknowledgment

The authors thank Xiaodong Sun for fabricating 3D printed parts, Brian Mielnicki and Tim Shride of Ottobock for providing support for their body-power harness, and Adam Reed of Xsens for support and loaning the motion capture system and software for use during this study.

References

[1] K. Ziegler-Graham, E. J. MacKenzie, P. L. Ephraim, T. G. Travison, and R. Brookmeyer, "Estimating the Prevalence of Limb Loss in the United States: 2005 to 2050," *Arch. Phys. Med. Rehabil.*, 2008.

[2] F. Cordella *et al.*, "Literature review on needs of upper limb prosthesis users," *Frontiers in Neuroscience*. 2016.

[3] K. A. Raichle *et al.*, "Prosthesis use in persons with lower- and upper-limb amputation," *J. Rehabil. Res. Dev.*, 2008.

[4] L. H. B. Huinink, H. Bouwsema, D. H. Plettenburg, C. K. Van der Sluis, and R. M. Bongers, "Learning to use a body-powered prosthesis: changes in functionality and kinematics," *J. Neuroeng. Rehabil.*, 2016.

[5] M. Hofmann, J. Harris, S. E. Hudson, and J. Mankoff, "Helping Hands: Requirements for a Prototyping Methodology for Upper-limb Prosthetics Users," *34Th Annu. Chi Conf. Hum. Factors Comput. Syst. Chi 2016*, pp. 1769–1780, 2015.

[6] G. Smit, D. H. Plettenburg, and F. C. T. Van Der Helm, "The lightweight Delft Cylinder hand: First multi-articulating hand that meets the basic user requirements," *IEEE Trans. Neural Syst. Rehabil. Eng.*, 2015.

[7] L. Haverkate, G. Smit, and Di. H. Plettenburg, "Assessment of body-powered upper limb prostheses by able-bodied subjects, using the Box and Blocks Test and the Nine-Hole Peg Test," *Prosthet. Orthot. Int.*, 2016.

[8] K. Berning, S. Cohick, R. Johnson, L. A. Miller, and J. W. Sensinger, "Comparison of body-powered voluntary opening and voluntary closing Prehensor for activities of daily life," *Rehab. Res. Dev.*, 2014.

[9] L. K. Chua, J. A. Martinez, and O. Celik, "Haptic body-powered upper-extremity prosthesis simulator with tunable stiffness and sensitivity," in *IEEE Haptics Symposium, HAPTICS*, 2014.

[10] D. L. Weeks, S. A. Wallace, and D. I. Anderson, "Training with an upper-limb prosthetic simulator to enhance transfer of skill across limbs," *Arch. Phys. Med. Rehabil.*, 2003.

[11] V. Mathiowetz, G. Volland, N. Kashman, and K. Weber, "Adult Norms for the Box and Block Test of Manual Dexterity," *Am. J. Ocupational Ther.*, vol. 39, no. 6, pp. 387–391, 1985.

[12] J. S. Hebert and J. Lewicke, "Case report of modified box and blocks test with motion capture to measure prosthetic function," *J. Rehabil. Res. Dev.*, 2012.

[13] R. A. Colyer and B. Kappelman, "Flexor pollicis longus tenodesis in tetraplegia at the sixth cervical level. A prospective evaluation of functional gain," *J. Bone Jt. Surg. - Ser. A*, 1981.

[14] A. Heller, D. T. Wade, V. A. Wood, A. Sunderland, R. L. Hewer, and E. Ward, "Arm function after stroke: Measurement and recovery over the first three months," *J. Neurol. Neurosurg. Psychiatry*, 1987.

[15] S. L. Carey, R. V. Dubey, G. S. Bauer, and M. J. Highsmith, "Kinematic comparison of myoelectric and body powered prostheses while performing common activities," *Prosthet. Orthot. Int.*, 2009.

[16] S. L. Carey, M. Jason Highsmith, M. E. Maitland, and R. V. Dubey, "Compensatory movements of transradial prosthesis users during common tasks," *Clin. Biomech.*, 2008.