Biomechanical Analysis of Body Movements of Myoelectric Prosthesis Users During Standardized Clinical Tests

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***Abstract*— *Objective:* The objective clinical evaluation of user's capabilities to handle their prosthesis is done using various tests which primarily focus on the task completion speed and do not explicitly account for the potential presence of compensatory motions. Given that the excessive body compensation is a common indicator of inadequate prosthesis control, tests which include subjective observations on the quality of performed motions have been introduced. However, these metrics are then influenced by the examiner's opinions, skills, and training making them harder to standardize across patient pools and compare across different prosthetic technologies. Here we aim to objectively quantify the severity of body compensations present in myoelectric prosthetic hand users and evaluate the extent to which traditional objective clinical scores are still able to capture them. *Methods:* We have instructed 9 below-elbow prosthesis users and 9 able-bodied participants to complete three established objective clinical tests: Box-and-Blocks-Test, Clothespin-Relocation-Test, and Southampton-Hand-Assessment-Procedure. During all tests, upper-body kinematics has been recorded. *Results:* While the analysis showed that there are some correlations between the achieved clinical scores and the individual body segment travel distances and average speeds, there were only weak correlations between the clinical scores and the observed ranges of motion. At the same time, the compensations were observed in all prosthesis users and, for the most part, they were substantial across the tests. *Conclusion:* The sole reliance on the currently available objective clinical assessment methods seems inadequate as the compensatory movements are prominent in prosthesis users and yet not sufficiently accounted for.**

***Index Terms*—Prosthetics, bionic hand, myocontrol, body compensation, motion capture, SHAP, CPRT, box and blocks**

I. INTRODUCTION

BIONIC hands are the state-of-the-art solution for mitigating the devastating consequences of an upper limb deficiency [1]. They consist of electromechanical robotic grippers which are controlled through a direct association with the electrical activity of the remnant muscles of the stump (electromyography – EMG) [2]. To enable control over a larger number of degrees of freedom (DoFs), a switching mechanism (e.g., a co-contraction) and a state-machine algorithm can be employed [3]. Consequently, an assistive system is established that can potentially restore control over multiple gestures (e.g., hand open/close and wrist rotation).

While robust, this direct control approach provides limited dexterity, with a single DoF control available at a time. Significant efforts have therefore been invested in advancing control algorithms [4]. This has resulted in more capable systems, however, the abandonment rates of bionic hands by the users remain high [5], [6].

The reasons for the difficult translation of perceived improvements brought by advanced prosthetic technology in long-term user benefits range from the lack of a user-centered approach throughout the design and development process [7] to limited and inconsistent evaluation approaches [8], [9]. For example, the definition of good prosthesis performance substantially differs between researchers and clinicians, as well as across healthcare systems [10], [11]. The clinical scores, while arguably seen as the more real-world oriented ones, have also limitations. These metrics tend to be either subjective, though with a potential for a more holistic evaluation, or otherwise objective but with a narrow evaluation scope. The

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subjective metrics rely on the evaluator to interpret the observed overall performance of the users throughout the tests. The objective metrics are strictly based on the time to complete predefined tasks [11], and thus tend to capture only a limited aspect of performance, such as execution speed.

For instance, clinical tests such as the Assessment of Capacity for Myoelectric Control (ACMC) [12] and the Activities Measure for Upper Limb Amputees (AMULA) [13] prompt evaluators to account for the quality of the movements performed by the prosthesis users as well as their skillfulness of device manipulation in order to compute the final score. This is useful as it provides an opportunity to assess and include performance contributing factors, such as body compensation. Yet, these metrics are dependent on the evaluator's training and experience, which is suboptimal. On the other hand, scores obtained using objective tests, such as the Southampton-Hand-Assessment-Procedure (SHAP, comprehensive test consisting of a number of manipulation and activities of daily living tasks) [14], the Clothespin-Relocation-Test (CPRT, combined test of hand and wrist function involving relocation of variably graded clothespins) [15], and the Box-and-Blocks-Test (BBT, pick and place test focused on relocation of a number of blocks over a barrier) [16], which are purely time-based, leave evaluators with little information on the overall quality of the prosthesis user's movements. Specifically, it has been discussed that all current clinical tests may under-represent the capabilities of the latest prosthetic developments [17], [18]. This in itself can have significant impact on the development of the field as well as the level of care that is currently provided to those in need of upper limb prostheses. Therefore, we have designed a study that allows combined observation of performance parameters captured in both objective and subjective clinical tests in an objectively quantifiable manner. Such arrangement was achieved by continuously capturing the upper body kinematics of both prosthesis users and able-bodied participants during the completion of the three most established objective clinical tests: SHAP, CPRT and BBT. In this way, an unbiased quantitative measure of the movement quality has been estimated in terms of performance- and compensatory movement- related biomechanical features, which included the total travelled distances of individual body segments, their average speeds as well as the overall ranges of motion.

TABLE I
STUDY PARTICIPANTS IN THE PROSTHESIS USERS GROUP

	Age	Gender	Prosthesis Side	Myocontrol Experience (years)	SHAP	CPRT	BBT
P1	49	M	R	1.5	66	21.72	21.00
P2	33	M	L	9.0	72	15.49	24.00
P3	31	M	L	1.0	62	20.25	28.00
P4	21	M	R	9.0	72	21.80	17.00
P5	28	M	R	2.0	60	36.40	13.33
P6	37	F	R	>10	46	27.83	21.00
P7	47	M	L	0.5	53	19.77	15.00
P8	27	M	R	>10	52	23.56	14.67
P9	44	M	R	>10	38	43.40	13.67

Our aims in this study were to investigate 1) the kinematic differences between prosthesis users and a control group (prosthesis induced compensations vs natural movements), 2) the differences in kinematic profiles across various clinical assessment tests, and 3) whether there are meaningful correlations between kinematic measures and traditional objective clinical assessment scores, in terms of both performance-related and compensatory movement-related kinematic measures.

II. MATERIALS AND METHODS

A. Study Participants

Nine below-elbow myoelectric prosthetic users were recruited (P1-P9: 8 male, 1 female, aged 35.22±9.15 years). Details of their limb difference and prosthesis experience are reported in Table I. Across the subject pool, the following Ottobock Healthcare GmbH (Duderstadt, Germany) myoelectric devices were used on a regular basis: SensorHand Speed (3 participants), Electric Greifer DMC Plus (1 participant), DMC plus transcarpal hand (1 participant), Michelangelo hand (3 participants), Bebionic hand (1 participant).

TABLE II
ARM LENGTH INFORMATION OF THE PARTICIPANTS

Index	Prosthesis users (m)	Control group (m)	
1	0.729	0.681	
2	0.685	0.628	
3	0.658	0.711	
4	0.669	0.640	
5	0.658	0.685	
6	0.655	0.693	
7	0.786	0.659	
8	0.701	0.681	
9	0.713	0.566	
mean±SD	0.695±0.043	0.660±0.044	p=0.233

In addition, a control group of nine conventionally abled subjects was recruited (S1-S9: 8 male, 1 female, aged 28.22±4.10 years). Table II shows the statistics of the arm lengths from both the prosthetic users and the control group, and there is no significant difference in this metric between two target groups with the Mann-Whitney test. Before joining the study, all participants read, understood, and signed consent forms approved by the local ethics board of the Medical University of Vienna (Ethics Commission number: 1044/2015).

B. Experimental Setup

Each subject was instructed to perform a set of clinical tests for the evaluation of (prosthesis) hand function. The set included the Southampton Hand Assessment Procedure (SHAP), Clothespin-Relocation Test (CPRT), and Box and Block Test (BBT). A total of one SHAP, and three CPRT and BBT scores were collected for each participant. Prosthesis users were asked to bring their preferred everyday myoelectric device and to have it fully charged in order to comfortably complete all the tests. All systems ended up having motorized grippers though only passive wrist units. Able-bodied volunteers were prompted to conduct the same tests using their non-dominant side for comparison.

An eight-camera optoelectronic system (VICON MX+, Oxford Metrics Ltd., Oxford, UK) was used for capturing body movements. A total of 17 passive reflective markers were placed on each subject and their 3D coordinates were recorded in real-time at 200 Hz sampling rate. The markers were placed according to well-defined anatomical positions (Fig. 1). In case of prosthesis users, the positioning was defined according to the corresponding landmarks identified on the socket and the prosthesis hand. The reference markers were placed above the C7 vertebra, manubriosternal junction, and the acromion processes. Clusters of markers were used to define the centroids of four segments of interest – palm, lower arm, upper arm, and thorax.

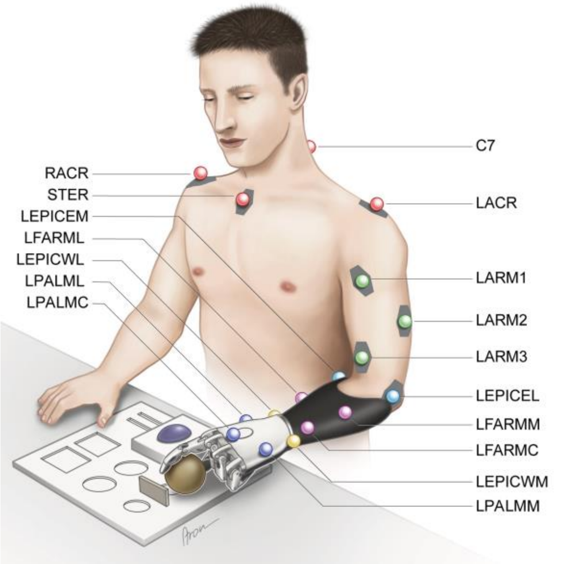

Fig. 1 Definition of the marker set for left arm subjects. The reference markers were placed above the C7 vertebra (C7), manubriosternal junction (STER), and the left and right acromion processes (LACR/RACR) effectively defining the thorax segment. The remaining three arm segments have been defined using the clusters of markers effectively outlining upper arm (LARM1, LARM2, LARM3), lower arm (LFARML, LFARMM, LFARMC – denoting the left lateral, medial, and central marker of the forearm), and palm (LPALML, LPALMM, LPALMC – denoting the left lateral, medial, and central marker of the palm). Finally, sets of markers were placed on the lateral and medial sides of the elbow (LEPICEL/LEPCIEM) and the wrist (LEPICWL/LEPCIWM) epicondyles.

During BBT and CPRT tests, the ground reaction forces were also recorded concurrently using the force plates (ATMI). These measurements were conducted at 1000 Hz with each force plate capturing six analog channels including ground reaction forces in three directions (Fx, Fy, Fz) and corresponding moments (Mx, My, Mz) at its local coordinate system.

C. Clinical Tests

The selected clinical tests - SHAP, CPRT, and BBT – have all been previously validated with myoelectric users and have been singled out due to their objective nature, which does not require experimenter's input in order to form a final score [11].

SHAP is a comprehensive hand function test which was developed, and clinically validated, in order to evaluate the upper limb prosthesis user's manipulation performance [14]. Its maximum score, corresponding to normal hand function, is 100. The SHAP score is calculated based on completion time across 26 tasks out of which 12 are abstract object manipulations (6 heavy and 6 light object variations), and 14 are adaptations of Activities of Daily Living (ADLs).

CPRT is an adapted version of the Royal Graded Pinch Exerciser aimed at evaluating the forearm rotation in combination with variable grip strengths [15]. Its score corresponds to the time needed to transfer four clothespins of various resistances from a horizontal to a vertical bar.

BBT is a widely used clinical test designed to evaluate gross manual dexterity [16]. The BBT score corresponds to the number of wooden cubes (blocks) that the test subject is able to transfer over a designated barrier from one compartment of a large holding box to the other. A single BBT test takes one minute and a total of 100 blocks are provided.

D. Biomechanical Analysis

Biomechanical analysis has been conducted using the recorded marker coordinates and force plate readings collected during the execution of the three clinical tests. The raw motion capture data were first labeled and then any remaining gaps in the traces were interpolated using Vicon Nexus Software. These preprocessed motion data were further analyzed using custom scripts developed in Python [19], NumPy [20] and SciPy [21]. Initially, the marker trajectories and the force plate analog channels were low-pass filtered using a zero-lag, 2nd order Butterworth filter at 6 Hz and 15 Hz, respectively.

Segmental and joint coordinate systems were defined by following the International Society of Biomechanics (ISB) recommendation for shoulder, elbow, wrist and hand, with some adaptation [22]. For left-handed users, the trunk coordinate system was defined by the C7 vertebra, manubriosternal junction, and right acromion process, whereas its location was defined as the mid-point between C7 vertebra and manubriosternal junction - this was assumed as the neck joint for further analysis. The symmetrical arrangement was considered for the right-handed participants. The upright direction vector of the trunk segment was acquired during the static trial for each subject. The left acromion process was assumed as the shoulder joint location for left-handed users (and vice versa for right-handed users). The location of the elbow joint was defined as the mid-point between lateral and medial epicondyle of the humerus, and of the wrist as the mid-point between radial and ulnar styloid. The hand segment was defined as the average of three cluster markers on the dorsal surface of the palm.

The joint angles for nine degrees of freedom (DoFs) of interest were estimated in accordance with the ISB recommendations with minor adaptions [22], [23]. Trunk (trunk flexion-extension, trunk side bending, trunk axial rotation), elbow (elbow flexion-extension), forearm (forearm pronation-supination), and wrist (wrist flexion-extension) angles were obtained by calculating the Euler angles with Z-X-Y order [22]. For shoulder DoFs (shoulder flexion-extension, shoulder abduction-adduction, shoulder axial rotation), the angles were estimated by the Euler angles with X-Z-Y order [24], [25]. For the estimation of forearm pronation-supination angle, the upper arm and the hand coordinate systems were directly considered in order to ensure the consistency between prosthesis users and control group. For each DoF, the total range of motion (RoM) has been calculated across different trials in each test.

In addition to the estimation of nine joint angles, the total travelled distance and the average speed at major joint locations were also retrieved [26]–[30]. The total travelled distance was obtained by the summation of discrete travelled distances from all available samples in time. The average speed was calculated by dividing the total travelled distance by the total execution time for each individual task. The total travelled distance has been considered for both the entire tests as well as on per item basis for BBT and CPRT (individual block or clothespin).

In order to understand the compound full body compensation during prosthesis use, we analyzed the properties of the center of pressure (CoP) in the two standing tests - BBT and CPRT. Given that SHAP was conducted in an unconstrained sitting position we have excluded it from this investigation. The following relevant metrics were calculated: sway area, total travelled distance, and the average speed [31]–[34]. The CoP total travelled distance was obtained as the summation of all discrete CoP displacements in time across the total CoP trajectory from its initial to its final position. The CoP average speed was calculated as the CoP total travelled distance divided by the completion time of a trial. The CoP sway area was considered to be the area of the 95% prediction ellipse of the CoP positions [34].

E. *Statistical Analysis*

For the BBT and CPRT tests, each subject performed three consecutive trials. The kinematic measures and clinical scores were averaged across these repetitions. In contrast, for SHAP, the kinematic measures were averaged across all SHAP tasks (26 in total) for each subject, thus corresponding to the overall SHAP score.

During the comparison of kinematic measures and clinical scores between the prosthetic users and the control group, due to the small sample size (9 participants in each pool), the non-parametric Mann-Whitney test was used. Within each subject group, Friedman test was applied and followed by the post-hoc Wilcoxon signed-rank sum test with Bonferroni correction in order to compare the three clinical tests in terms of kinematics.

The levels of statistical difference were classified as significant ($P < 0.05$), substantially significant ($P < 0.01$) or highly significant ($P < 0.001$). The estimation of correlations between the kinematic measures and the clinical assessment scores was done using Spearman's correlation coefficients [35]–[37].

TABLE III
CLINICAL ASSESSMENT SCORES

Task	Control group (mean±SD)	Prosthesis users (mean±SD)	P-value
BBT (# blocks)	73.074±8.644	18.630±5.149	***P<0.001
CPRT (seconds)	5.515±0.728	25.580±8.922	***P<0.001
SHAP	103.333±1.803	57.889±11.624	***P<0.001

Descriptive statistics of the clinical assessment scores between control and amputee groups.

III. RESULTS

A. *Clinical assessment scores*

Highly significant differences were found between the prosthetic users and the control group across all three clinical scores, as shown in Table III. Moreover, a higher variability in the performance of prosthesis users was present across most of the tests, as can be seen from the standard deviation values across the scores.

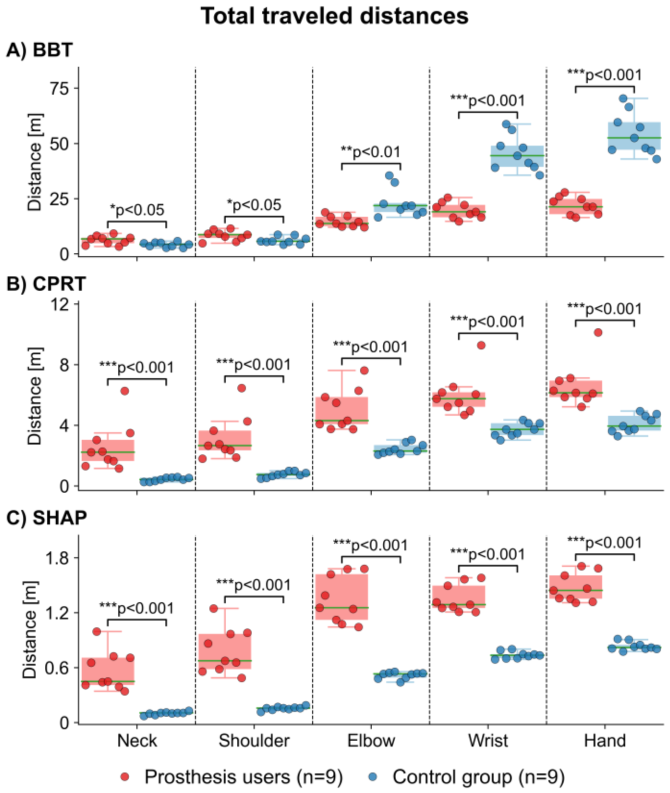

Fig. 2 Total travelled distance at major locations in the upper body during the clinical assessment tests. Dots represent the individual values per subject in their respective groups, and asterisks (*) indicate the presence and level of statistical difference between the highlighted groups. The box plots denote the range between the first and the third quartile of the relevant observations and the corresponding whiskers mark the spread of the captured data outside these limits. Finally, the median value of each set is indicated with a green line.

B. *Subject group specific kinematic analysis*

The total distances traveled by each major joint and body segment for individual subjects in both groups is shown in Fig. 2 for each clinical test. For BBT, the differences between prosthesis users and control group of travelled distance of the neck and shoulder joints were significant ($p < 0.05$), whereas the difference in the elbow joint was substantially significant ($p < 0.01$). The differences at effector locations (wrist and hand) were highly significant ($p < 0.001$). The control group showed greater travelled distances for the elbow, wrist, and hand area during the BBT test. Conversely, the prosthesis users consistently exhibited significantly larger travelled distances ($p < 0.001$) across all major locations during CPRT and SHAP tests.

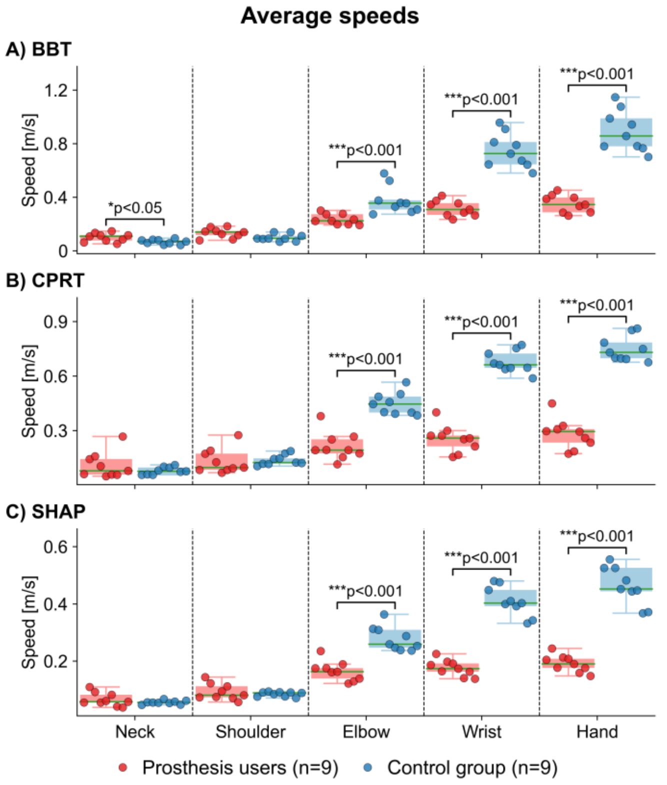

Fig. 3 Average speed at major locations in the upper body during the clinical assessment tests. Dots represent the individual values per subject in their respective groups, and asterisks (*) indicate the presence and level of statistical difference between the highlighted groups. The box plots denote the range between the first and the third quartile of the relevant observations and the corresponding whiskers mark the spread of the captured data outside these limits. Finally, the median value of each set is indicated with a green line.

Fig. 3 shows the average speed at major locations in the upper body during BBT, CPRT, and SHAP tasks. During the BBT, the two groups exhibited significantly different velocities of the neck ($p < 0.05$), which was not the case at the shoulder joint. Still, all the joints and segments of the lower arm of the prosthesis users moved at highly significantly lower average speeds ($p < 0.001$) across all block transfers. For both CPRT and SHAP tests, there was no significant difference at both neck and shoulder joints between the two groups, though again the control group was highly significantly faster ($p < 0.001$) across the remaining lower arm locations.

The angular RoM for all considered DoFs, across both subject groups and tests, is shown in Fig. 4. Prosthesis users exhibited significantly larger RoMs for all trunk directions regardless of the test. Similar results were obtained for the shoulder abduction-adduction DoF, while the shoulder axial rotation was only significantly greater in the same group during BBT. For the shoulder flexion-extension DoF, this was true only during BBT and CPRT, but not SHAP. Conversely, for the elbow flexion-extension DoF, the control group exhibited significantly larger RoM during CPRT, yet no difference was observed in other tests. Furthermore, RoMs of forearm pronation-supination and wrist flexion-extension of the same group were significantly larger in comparison with prosthesis users.

The compound full body movements have been observed through several CoP metrics during BBT and CPRT tests, as shown in Table IV. Across both tests, the prosthesis users exhibited significantly larger sway area than the control group (BBT: $p < 0.01$; CPRT: $p < 0.05$). Similarly, the same group had a significantly larger CoP travelled distance per each item across both tests ($p < 0.001$). While there was no difference during BBT, the prosthesis users had also a significantly larger CoP total travelled distance during CPRT. However, there were no significant differences in the CoP average speed across the tests.

TABLE IV
CoP METRICS ACROSS STANDING CLINICAL TESTS

		Prosthesis Users (mean±SD)	Control Group (mean±SD)	Significance
BBT	Sway area $[m^2]$	0.012±0.010	0.002±0.001	**p<0.01
	Dist. per item $[m]$	0.302±0.136	0.077±0.020	***p<0.001
	Total distance $[m]$	5.567±2.150	5.657±1.752	p=0.773
	Average speed $[\frac{m}{s}]$	0.090±0.035	0.093±0.029	p=0.847
CPRT	Sway area $[m^2]$	0.015±0.017	0.004±0.002	*p<0.05
	Dist. per item $[m]$	0.474±0.333	0.108±0.024	***p<0.001
	Total distance $[m]$	1.895±1.332	0.431±0.097	***p<0.001
	Average speed $[\frac{m}{s}]$	0.080±0.054	0.079±0.020	p=0.290

C. Test specific kinematic analysis

A similar trend was observed when investigating the average speeds of all considered body locations during the execution of individual tests, as shown in Fig. 5. Namely, prosthesis users moved significantly slower ($p < 0.05$) during the SHAP in comparison to BBT. For the control group, the movements of all considered body segments and joints during SHAP were consistently significantly slower ($p < 0.05$) in comparison to CPRT, and also to the BBT for elbow, wrist, and hand. The average speeds of shoulder movement in this group during BBT were significantly slower ($p < 0.05$) than during completion of CPRT.

When analyzing angular RoM of joints and segments of interest per individual test, SHAP yielded the smallest values across both subject groups (Fig. 6). This difference was consistently significant ($p < 0.05$) with respect to at least one of the other two tests.

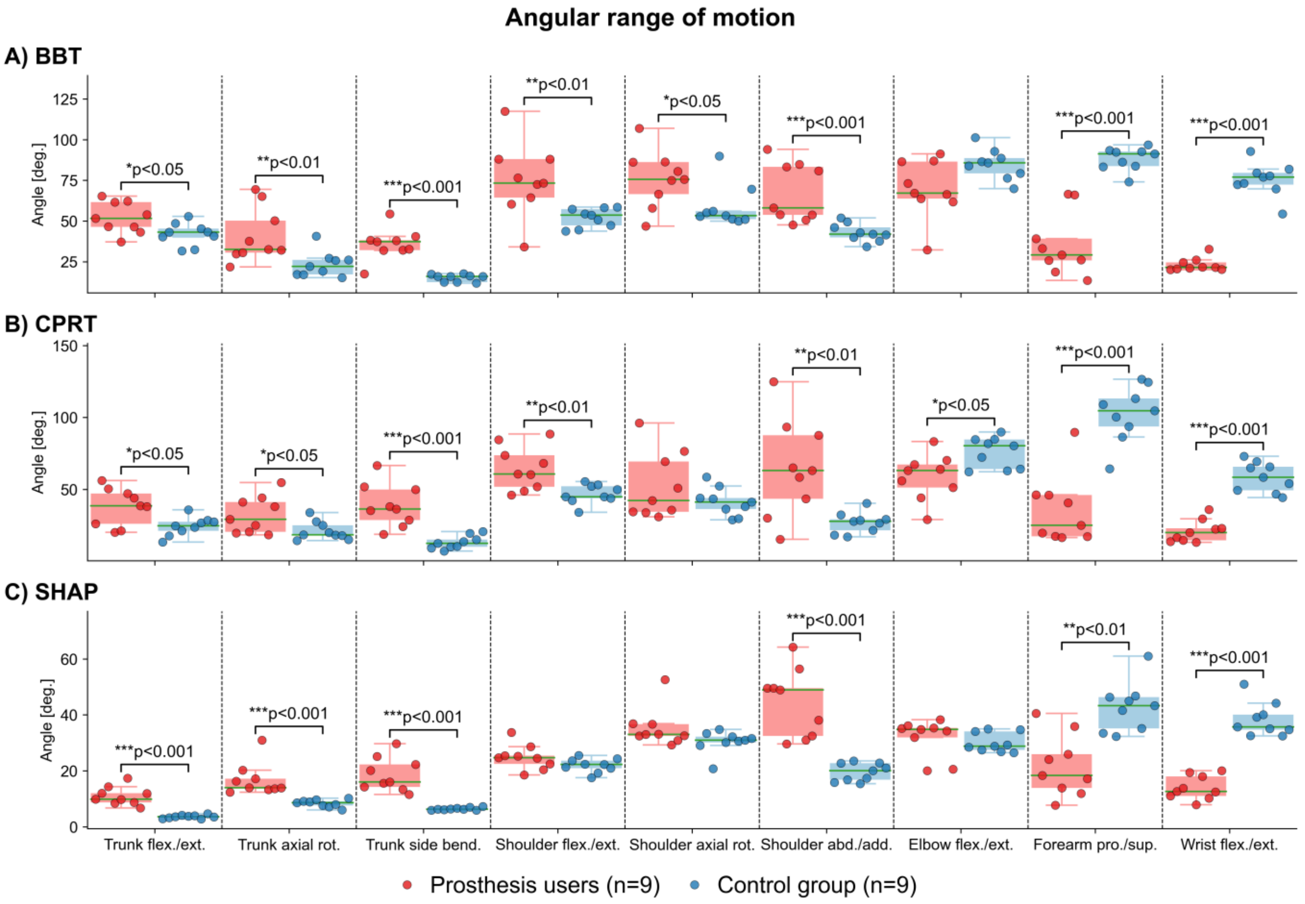

Fig. 4 Angle Range of Motion for 9 degrees of freedom in the upper body. Dots represent the individual values per subject in their respective groups, and asterisks (*) indicate the presence and level of statistical difference between the highlighted groups. The box plots denote the range between the first and the third quartile of the relevant observations and the corresponding whiskers mark the spread of the captured data outside these limits. Finally, the median value of each set is indicated with a green line.

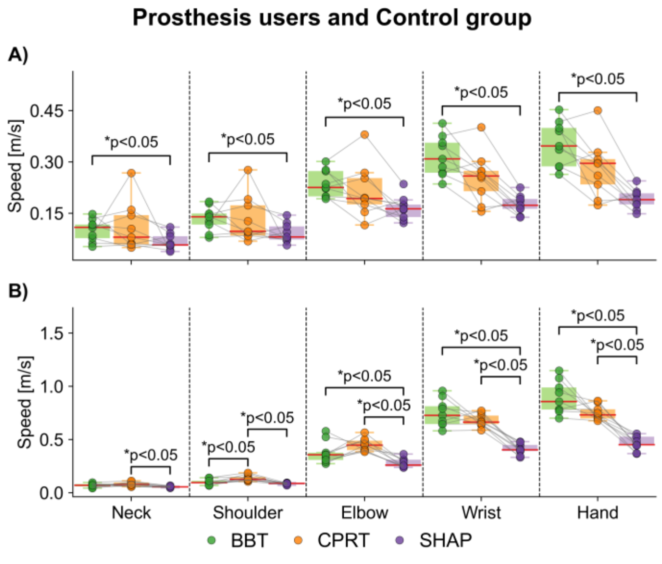

Fig. 5 Difference in average speed at major locations in the upper body between the clinical assessment tests. A) prosthesis users, and B) control group. Dots represent the individual values per subject in their respective groups, and asterisks (*) indicate the presence and level of statistical difference between the highlighted groups. The box plots denote the range between the first and the third quartile of the relevant observations and the corresponding whiskers mark the spread of the captured data outside these limits. Finally, the median value of each set is indicated with a red line.

TABLE V

CORRELATION BETWEEN THE CLINICAL ASSESSMENT SCORES AND THE TOTAL TRAVELLED DISTANCE. THREE ASTERISKS (***) INDICATE A CORRELATION THAT IS SIGNIFICANT AT THE 0.001 LEVEL, TWO ASTERISKS (**) AT THE 0.01 LEVEL, AND ONE ASTERISK (*) AT THE 0.05 LEVEL

		Neck	Shoulder	Elbow	Wrist	Hand
BBT	Prosthesis	0.360	0.485	0.787 (*)	0.879 (**)	0.879 (**)
	Control	-0.109	-0.360	0.142	0.276	0.360
CPRT	Prosthesis	0.333	0.300	0.467	0.183	0.183
	Control	0.550	0.617	0.500	0.767 (*)	0.883 (**)
SHAP	Prosthesis	-0.100	-0.243	-0.293	-0.393	-0.460
	Control	-0.633	-0.481	-0.127	-0.430	-0.025

D. Correlation between kinematic measures and clinical assessment scores

Further analysis of the test specific kinematics indicated a certain degree of correlation between the clinical assessment scores and the considered kinematic features (from Table V, Table VI, and Fig. 7). Correlation coefficients were regarded as high (0.7 to 1.0), moderate (0.5 to 0.7), low (0.3 to 0.5) or negligible (0.0 to 0.3) [30].

Table V shows that, during completion of the BBT, the prosthesis user performance was highly correlated with the amount of movement at the subject's elbow ($r = 0.787$), wrist

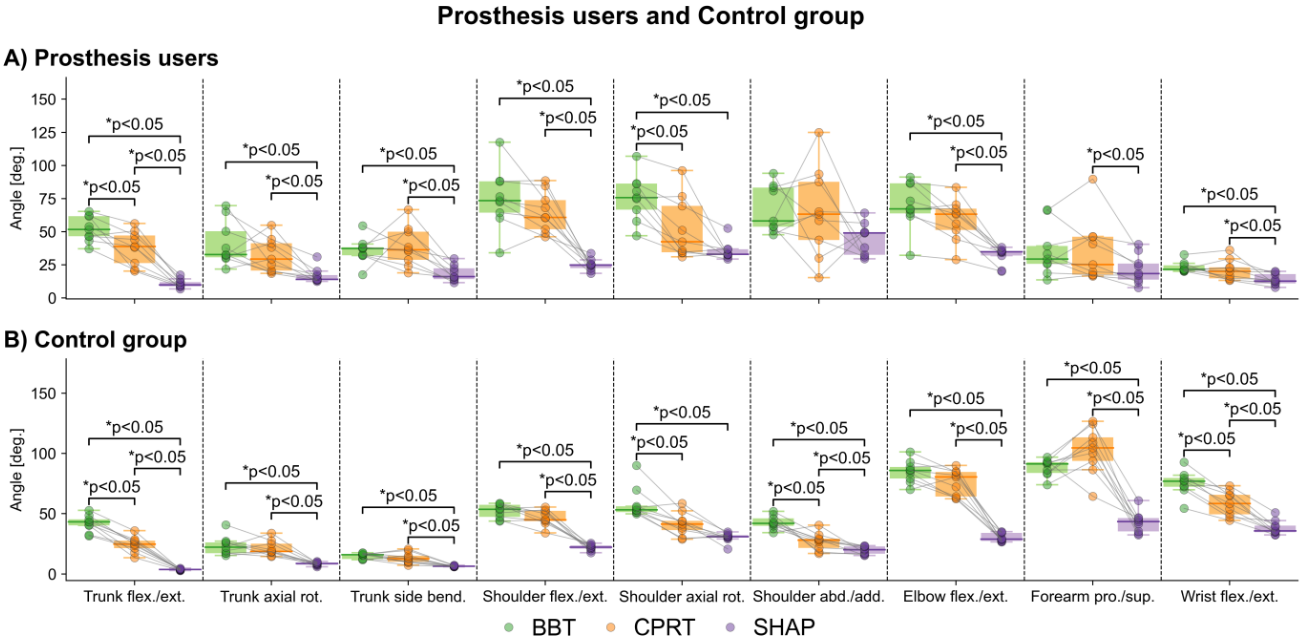

Fig. 6. Difference in angle range of motion between the clinical assessment tests. A) prosthesis users, and B) control group. Dots represent the individual values per subject in their respective groups, and asterisks (*) indicate the presence and level of statistical difference between the highlighted groups. The box plots denote the range between the first and the third quartile of the relevant observations and the corresponding whiskers mark the spread of the captured data outside these limits. Finally, the median value of each set is indicated with a bolded line.

$(r = 0.879)$, and hand $(r = 0.879)$. Moreover, the traveled distance of wrist $(r = 0.767)$ and hand $(r = 0.883)$ of subjects belonging to the control group was highly correlated with the completion rate during CPRT. SHAP performance of prosthesis users showed low negative correlation with the amount of movement of their wrist $(r = -0.393)$ and hand $(r = -0.460)$ area, whereas in the control group there were moderate and low negative correlations with the amount of movement of their neck $(r = -0.633)$ and shoulder $(r = -0.481)$, respectively.

Table VI shows that, similarly to traveled distance, the average speed of elbow $(r = 0.787)$, wrist $(r = 0.929)$, and hand $(r = 0.879)$ locations during BBT task were highly correlated to the respective performance of prosthesis users. On the other hand, CPRT scores of the same subjects were highly negatively correlated with the velocities of the wrist $(r = -0.733)$ and hand $(r = -0.800)$ area. Finally, the speeds of the same segments exhibited high positive correlation with SHAP performance across all subjects irrespective of their group ($r = 0.812$ for wrist and $r = 0.812$ for hand in prosthesis users, $r = 0.836$ for elbow, $r = 0.962$ for wrist, and $r = 0.962$ for hand in control group).

TABLE VI

CORRELATION BETWEEN THE CLINICAL ASSESSMENT SCORES AND THE TOTAL AVERAGE SPEED. THREE ASTERISKS (***) INDICATE A CORRELATION THAT IS SIGNIFICANT AT THE 0.001 LEVEL, TWO ASTERISKS (**) AT THE 0.01 LEVEL, AND ONE ASTERISK (*) AT THE 0.05 LEVEL.

		Neck	Shoulder	Elbow	Wrist	Hand
BBT	Prosthesis	0.360	0.435	0.787 (*)	0.929 (***)	0.879 (**)
	Control	-0.109	-0.301	0.142	0.360	0.360
CPRT	Prosthesis	-0.267	-0.383	-0.633	-0.733 (*)	-0.800 (**)
	Control	0.250	0.267	-0.433	-0.283	-0.200
SHAP	Prosthesis	0.243	0.243	0.410	0.812 (**)	0.812 (**)
	Control	0.000	0.532	0.836 (**)	0.962 (***)	0.962 (***)

Considering BBT, Fig. 7 indicates that the elbow flexion-extension DoF showed a moderate positive correlation $(r = 0.695)$ with the achieved performance in the control group. On the other hand, SHAP scores of subjects in the control group exhibited moderate negative correlation $(r = -0.617)$ with the RoM of the forearm pronation-supination. Apart from prosthesis user's CPRT performance which was moderately correlated $(r = 0.667)$ with their trunk axial rotation, no major compensatory movement related DoFs (including trunk flexion-extension, trunk axial rotation, trunk side bending, and shoulder abduction-adduction) showed any significant correlation with any of the considered clinical scores.

IV. DISCUSSION

This study investigated the kinematic features of prosthesis users during completion of three commonly applied objective clinical tests evaluating upper limb performance. Given the nature of these tests and their primary focus on the task completion time, we argue that significant performance aspects are commonly missed, leaving users and prosthetic practitioners with an incomplete picture of the level of achieved functional rehabilitation. To investigate this claim we have conducted a series of experiments involving commonly applied clinical tests and extensive motion capture analysis.

The trend of compensatory movements depends on task types and available prosthesis functions [18] and thus we have decided to capture a whole range of activities by relying on three difference clinical assessments. The study of compensatory movements has been of interest across various research disciplines due to numerous reasons [26, 27, 28, 29, 30, 32, 35, 36, 38, 39, 40, 41, 42]. However, no previous research has provided such detailed analysis of myoelectric prosthesis users. We have specifically targeted the below-elbow myoelectric prosthesis users, in contrast to other studies that

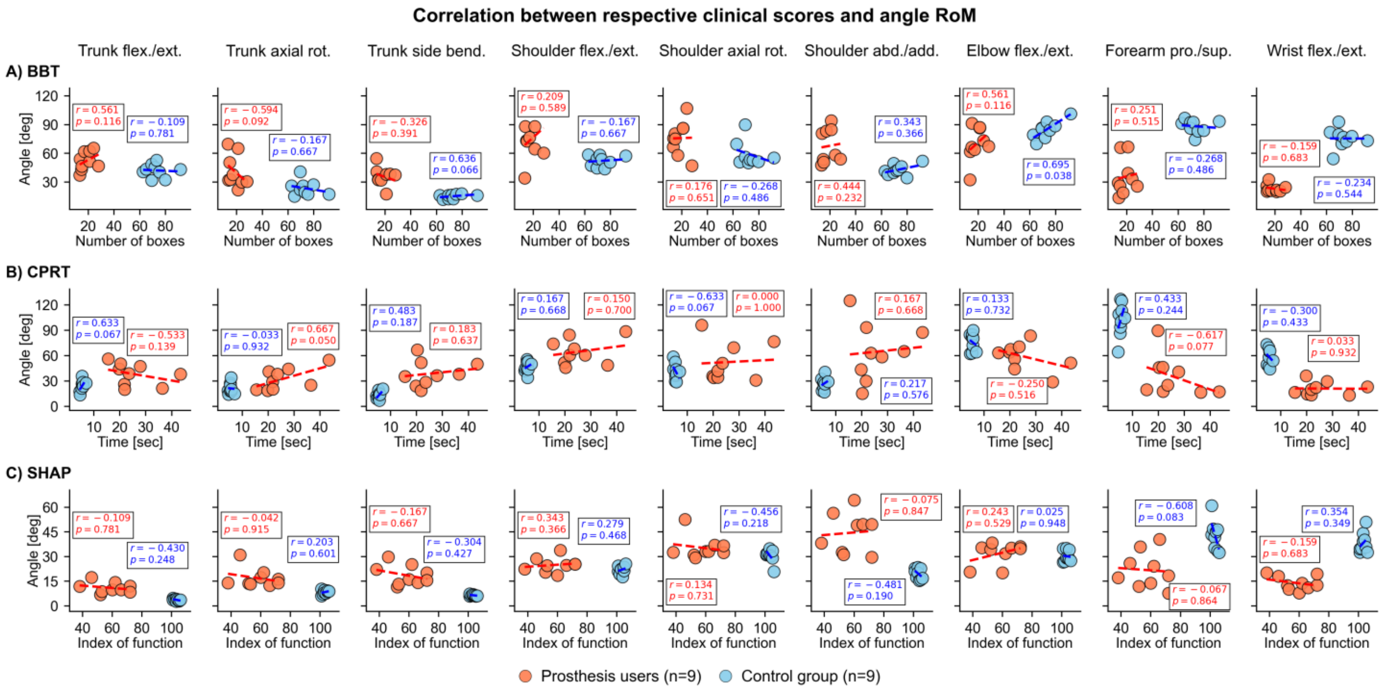

Fig. 7 Correlation between the clinical assessment scores and the angle range of motion (RoM) for each body segment and the considered assessment score.

recruited body-powered prosthesis users [27, 29, 36] or stroke survivors [26, 30, 35]. Moreover, we have decided to focus on strictly objective clinical assessments [28, 32, 41], thus eliminating the need for subjective scoring provided by a trained evaluator. Finally, even though some previous studies have indeed recruited a similar study population and have used some of the tests investigated in this study [38, 39, 40, 42], we have uniquely performed all of them together and in full, alongside a gender matched control group, allowing for a truly extensive analysis and insights.

Previous studies investigated correlations between clinical assessment scores across various upper limb impairments and angular RoM [30, 36]. However, none of those have covered neither the variety of functional tasks, as it has been done here, nor the specific subject pool to the same extent. For instance, while performing similar analysis in stroke survivors only shoulder and elbow DoFs during functional assessments have been investigated [30]. Another study did consider a compound body compensation in limb absent population [36], however the authors focused only on body powered prosthesis users and relied on just the AMULA score.

In our study, nine prosthesis users completed three objective clinical tests, achieving scores that are in agreement with those reported in previous studies [11], [32]. A control group of nine conventionally abled subjects provided normative expectations for each test.

Indeed, it would have been beneficial if the study population was larger, however, this cohort is greater and more coherent than most of those commonly reported in the field. Similarly, while the considered clinical tests might not cover the full battery of evaluation tools that might be at our disposable, they do form a subset of the most commonly applied ones that also engage the user in various ways across all relevant DoFs. Still, in future it would be worth expanding the study by including the subjective clinical tests as well.

The analysis of correlation between the achieved clinical scores and the exhibited angular range of motion indicated only a poor association. In fact, the results shown in Fig. 7 highlight a moderate correlation of trunk axial rotation with CPRT for prosthesis users. For the control group, the same analysis indicates a highly positive correlation for elbow flexion/extension during BBT, and a moderate negative correlation of forearm pronation during SHAP. Therefore, the objective clinical assessment scores used in this study (BBT, CPRT and SHAP) do not seem to reflect upon major body movements (trunk flexion/extension, trunk axial rotation, trunk side bending and shoulder abduction/adduction) which are known to be primary contributors to compensatory strategies in amputees and as such are, to an extent, accounted for in the more subjective clinical evaluation metrics [45].

Looking further into kinematic strategies of prosthesis users, we observed differences with respect to the control group that were not necessarily captured by the clinical scores. For instance, prosthesis users showed significantly larger angular RoM in the compensatory movement associated DoFs, such as trunk flexion/extension, trunk axial rotation, trunk side bending and shoulder abduction/adduction, across all clinical tests (Fig. 4). This is likely a result of the missing forearm pronation/supination and wrist flexion/extension across the considered prosthetic devices, where in fact this group expresses lower RoM values. Shoulder flexion/extension seems to be significantly more prominent in prosthesis users during BBT and CPRT whereas there was no substantial difference between the two groups during completion of SHAP. Such outcome is likely somewhat influenced by the fact that the first two tests are conducted in the standing position. This provides prosthesis users with fewer constrains, so that in turn they might choose to leverage and supplement their limited distal function with increased shoulder movements. In fact, during BBT, prosthesis users also showed significantly greater RoM for shoulder axial rotation. Conversely, during CPRT, the control group showed larger reliance on the more distal DoFs with significantly greater elbow flexion/extension RoM.

As expected, the resultant kinematic behavior also depended on the conducted clinical test. In order to avoid the dependency on the number of target objects and the total duration of each individual test, a comparison of angular RoM among BBT, CPRT and SHAP for both prosthesis users and control group was made. For instance, the overall RoM across all DoFs was the smallest in SHAP regardless of subject group (Fig. 6). This is likely related to the fact that SHAP is a sitting table-top based test, requiring much smaller operational volume than BBT and CPRT. Furthermore, across all subjects, significant differences in trunk flexion/extension and shoulder axial rotation RoMs were observed between BBT and CPRT. The larger values observed during BBT are likely resulting from the subject's tendency to bend over the horizontally placed box and transport blocks axially, while upright position is likely more beneficial for the front facing CPRT task. Interestingly, the prosthesis users utilized shoulder abduction/adduction across the tests, while there were significant differences in the control group with BBT requiring the largest RoM. All these differences indicate that there is not a single test among the considered three that is able to cover the full range of kinematic expressions potentially required to comprehensively describe the performance of a prosthesis user.

While the considered clinical assessment scores may not fully capture the trend of compensatory movement angular RoMs, they did correlate with some performance-related kinematics measures. For instance, as it was expected, higher BBT scores were indicative of longer distances covered by relevant limb segments (Table V). At the same time, higher CPRT scores were accompanied by larger travel distances. Finally, SHAP scores were inversely correlated with the observed body segment travel distances.

Higher BBT scores were also representative of higher velocities of each individual body segment (Table VI), as indeed subjects tended to move faster in order to transport more blocks during the set time period of the test. Similarly, faster CPRT times were followed by overall faster movements. Given that SHAP too is a time-based assessment protocol, it exhibits the same trend, where higher scores stem from overall faster movements.

Across all clinical tests, the two subject groups coordinated their bodies in a significantly different manner, also when considering the travel distances of individual body segments (Fig. 2). These values, captured across the entirety of the performed tasks, match those previously reported in similar studies [17], however, in order to achieve the same scores, prosthesis users traveled longer distances at all inspected upper body areas than the control group, as shown in Fig. 8 (for BBT and CPRT) and Fig. 2 (for SHAP). In particular, during BBT, the control group presented larger total traveled distances, whereas the prosthesis users showed greater total traveled distances for CPRT and SHAP. This difference arises from the fact that the number of transported blocks is the effective measure of performance in BBT. Therefore, the total traveled distance for the control group in BBT was also bigger relative to the number of boxes than that of prosthesis users. Given that both BBT and CPRT comprise mostly repetitive actions, a consideration of exhibited kinematics per individual item (block or clothespin) across three repetitions for each subject has been made. Fig. 8 shows the distance traveled per each item at major locations during BBT and CPRT. Unlike the total distance traveled depicted in Fig. 2, the distance values per each item for BBT at every major location of the control group are always lower than for the prosthesis users.

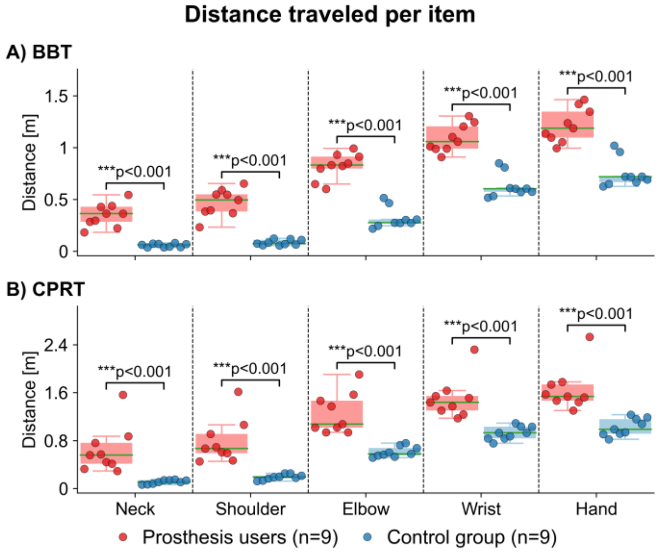

Fig. 8. Distance travelled per each item at major locations in the upper body during BBT and CPRT.

When the velocities of individual body segments were considered, the two groups expressed significantly different behavior across all three clinical tests in more distal sections of the observed limb (Fig. 3). The prosthesis users moved their elbow, wrist, and hand substantially slower than the control group. Interestingly, during BBT execution, prosthesis users moved their neck significantly faster in comparison. Still, regardless of the test, the average speed of individual segments increased from neck to wrist in both groups (Fig. 3).

CoP related metrics showed that prosthesis users tended to engage into larger, more compound body motions when completing the standing tests. The sway area and the travelled distance per each item for BBT and CPRT of prosthesis users was significantly bigger than that of the control group (Table IV). This indicates that the core motions were preferred when engaging in the prosthesis use, while the control group tended to rely on more static postures. Interestingly, there was no significant difference in the CoP average speed for BBT and CPRT between the subject groups.

V. CONCLUSION

In this study, we have recruited myoelectric prosthesis users and conventionally abled subjects for completing the full set of BBT, CPRT, and SHAP tests. We have recorded the relevant body kinematics during these tests with the aim to investigate the kinematic behavior of the subjects during the tests. Our analysis has shown weak correlation between the clinical assessment scores and the compensatory movements measured by the expressed RoM, indicating that traditional evaluation techniques do not capture the prosthesis user performance in a sufficiently descriptive way. Still, other performance-related kinematic measures, such as individual body segment traveled distances and related average speeds, did show some degree of correlation with the clinical assessment scores. This was particularly true for the more distal locations (those affected by the limb absence), such as wrist and hand area. Furthermore, we showed that these extensive kinematic measures are able to highlight and quantify the differences between prosthesis users and control group. This can be of potential interest in the future, as an evaluation tool for designing more functional systems and rehabilitation therapies. However, the sheer complexity of the set-ups applied here and the need for multiple evaluation tests in order to capture the full kinematic expression of the users, is likely to prevent direct translation of these techniques into clinical practice. Yet, the tools and observations made in this study are relevant for reconsidering and potentially redesigning currently applied performance metrics.

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