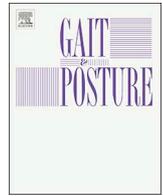




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## Characterization of normative angular joint kinematics during two functional upper limb tasks

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### ABSTRACT

**Background:** Optical motion capture is a powerful tool for assessing upper body kinematics, including compensatory movements, in different populations. However, the lack of a standardized protocol with clear functional relevance hinders its clinical acceptance.

**Research question:** The objective of this study was to use motion capture to: (1) characterize angular joint kinematics in a normative population performing two complex, yet standardized upper limb tasks with clear functional relevance; and (2) assess the protocol's intra-rater reliability.

**Methods:** Twenty non-disabled adults performed the previously developed Pasta Box Task and Cup Transfer Task. The kinematics of the upper body were captured using an optoelectronic motion capture system and rigid plates with reflective markers. Angular joint trajectories, peak angle, range of motion (RoM), and peak angular velocity were extracted for the trunk, shoulder, elbow, forearm, and wrist. Intra-class correlation was used to assess the intra-rater reliability of the kinematic measures.

**Results:** Both tasks required minimal trunk motion. Cross-body movements required greater RoM at the trunk, shoulder, and elbow joints compared to movements in front of the body. Reaches to objects further away from the body required greater trunk and elbow joint RoM compared to reaches to objects closer to the body. Transporting the box of pasta required the wrist to maintain an extended position. The two different grasp patterns in the Cup Transfer Task forced the wrist into a flexed and ulnar-deviated position for the near cup, and an extended and radial-deviated position for the far cup. For both tasks, the majority of measures displayed intra-class correlation values above 0.75, indicating good reliability.

**Significance:** Our protocol and functional tasks elicit a degree of movement sensitivity that is not available in current clinical assessments. Our study also provides a comprehensive dataset that can serve as a normative benchmark for quantifying movement compensations following impairment.

## 1. Introduction

Sensorimotor dysfunction of the upper limb is common for a wide variety of disorders, ranging from stroke [1] to amputation [2]. Impairments in arm function disrupt normal reach and grasp, altering typical movement patterns at the elbow, shoulder, and trunk [3]. These motor compensations [4,5] can be maladaptive and result in

musculoskeletal pain or overuse injuries [4]. Current best practice for preventing overuse injuries includes early symptom detection and treatment, retraining proper movement patterns, and lifestyle changes [6]. However, to prescribe and evaluate restorative interventions, it is critical to be able to accurately assess limb use patterns and to characterize underlying motor strategies.

Several upper limb performance tests exist that are designed to

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assess global upper limb function [7,8]; however, they do not quantify specific changes in joint movement [9]. An effective method of quantifying upper limb movement is to use motion capture for tracking upper body segments [10]. Analysis of the three-dimensional (3D) angular kinematics provides insight into limb use patterns and underlying motor control strategies. Specifically, range of motion (RoM) has shown to indicate active joint range, motor control, muscle power, and an individual's ability to complete a task [11]. RoM has been used in non-disabled individuals [12] and those with impairments [13] to quantify proximal joint adaptations required to successfully complete a task [5], and to identify altered movement strategies with different interventions [14]. In addition to RoM, other clinically meaningful outputs of 3D kinematic analysis include joint angle profiles [5,9,14], peak joint angle needed for task completion [15], and peak angular velocity [13]. Joint angle profiles allow to visualize limb movement patterns. Given that upper limb movement is not cyclical, many different joint movement strategies can be selected to successfully complete a task, which is reflected in joint angle profiles [5]. Peak joint angle is indicative of the extreme of joint movement required for a given task. This measure also allows to see the direction of compensation among individuals with impairments [13,15]. Finally, peak angular velocity is a valuable measure to investigate muscle torque production [16] and has been found to be the best measure to discriminate between non-disabled individuals and those who have suffered a stroke [13]. Integrating these kinematic measures into the assessment of populations with upper limb impairments can allow accurate quantification of movement compensations during specific tasks.

Due to the complexity of upper body movement and the ability to complete a task using variable strategies, comparison across studies is, however, difficult [17]. Most studies employ different kinematic protocols, including a variety of movement tasks and marker sets [12,18], and lack distinct, clinically based assessment routines [9]. The development of reliable kinematic protocols for assessing goal-oriented functional movements is important for clinical practice [9] – as such protocols can lead to a wider use of motion capture in clinical environments. Protocols must also exhibit consistency and reliability [9,17], and establish a normative dataset in controls [9].

In the interest of developing a reliable, ecologically valid upper limb kinematic assessment with clinical relevance, we have previously developed a task protocol using optoelectronic motion capture and a simple-to-use cluster marker set [19] for two standardized functional tasks [20]. The tasks incorporate complex movements, fulfilling clinicians' goals to simulate real-world environments. Secondly, the functional task movements, while complex, are highly standardized and constrained, allowing segmentation into simple movement phases for meaningful 3D kinematic analysis. Thirdly, our tasks elicit multi-dimensional movements of the entire upper limb kinematic chain, such as cross-body movements, reaching to different heights, and arm rotations, to challenge various upper limb impairments. A previous study by Valevicius et al. used this novel protocol to demonstrate the reliability of hand kinematics in non-disabled individuals, including hand trajectory, hand velocity, and grip aperture [20]. However, this protocol has not yet been applied to fully characterize the movement of the upper body's kinematic chain.

In this light, the purpose of the present study was to: (1) characterize normative angular kinematics, namely angular joint trajectories, peak joint angle, RoM, and peak angular velocity, for the two standardized functional tasks that fulfill the abovementioned requirements [20]; and (2) assess the intra-rater reliability for peak angle, RoM, and peak angular velocity. Developing a consistent and repeatable test protocol for motion capture of angular kinematics will allow its future application to a variety of upper limb sensorimotor impairments relative to an established normative dataset.

## 2. Methods

### 2.1. Study participants

Twenty non-disabled individuals (9 females and 11 males; 18 right-handed and 2 left-handed; age  $25.8 \pm 7.2$  years; height  $173.8 \pm 8.3$  cm) participated in the study. Participants had no upper body pathology or history of neurological or musculoskeletal injury in the past two years. They provided written informed consent to the experimental procedures, which were approved by the University of Alberta Health Research Ethics Board (Pro00054011), the Department of the Navy Human Research Protection Program (DON-HRPP), and the SSC-Pacific Human Research Protection Office (SSCPAC HRPO).

### 2.2. Experimental setup and procedures

3D marker trajectories were collected at 120 Hz using a 12-camera Vicon Bonita motion capture system (Vicon Motion Systems Ltd, Oxford, UK). A *Clusters Only* kinematic model previously described in Boser et al. was used in the present study [19]. Rigid plates with three or four 11 mm reflective markers were attached to the following upper body segments using hypo-allergenic, double-sided tape: pelvis, trunk, upper arms, forearms (with four markers on each plate), and hands (with three markers on each plate) (Supplementary Material, Fig. S1 & Table S1). A specific calibration pose was recorded prior to data collection. This calibration pose was required to align the axes of rotation of the upper body segments with the global coordinate system. The participant was asked to stand in a modified anatomical pose where the shoulder was at zero degrees of abduction, and the axes passing through the epicondyles and radial and ulnar styloids were aligned with the frontal plane [19].

Two standardized functional upper limb tasks, the Pasta Box Task and Cup Transfer Task (Supplementary Material, Fig. S2), were used in this protocol [20]. For the Pasta Box Task, participants had to reach for a box of pasta positioned on the right-hand side of their body, pick it up and move it to a shelf directly in front of them (*Movement 1*). They then had to return their hand to the initial 'Home' (start) position, reach for the box of pasta again, pick it up, and move it to a higher shelf on the left-hand side of their body (*Movement 2*), thereby crossing the body's midline. Finally, they had to return their hand to 'Home', reach for the box of pasta again, pick it up, and move it to its initial location on the right-hand side of their body (*Movement 3*). For the Cup Transfer Task, participants had to pick up the first cup positioned in the near area of the box on the right side and move it over a partition to a target location on the left side of the box, grasping the top of the cup (*Movement 1*). Next, they had to pick up a second cup from its initial location in the far area of the right side of the box and move it over the partition to a target location on the left side of the box, using a side grasp (*Movement 2*). Participants then had to return their hand to the initial 'Home' position and repeat the sequence in reverse, moving the far cup on the left side back over to the right-side starting position (*Movement 3*), and then the near cup from the left side back over to the starting position on the right (*Movement 4*). The cups were compliant (Dixie® Consumer Products LLC, Atlanta, USA) and filled with therapeutic beads to add an element of risk (spillage) and to require grasp force modulation. For both tasks, the 'Home' position was standardized by attaching it along the near edge of the table top, exactly 12.5" to the right of the table top's center line. Participants started both tasks with their hand at rest on the 'Home' position. Throughout the task, they were simply required to touch the 'Home' position with their hand between 'Movements' and not necessarily come to a complete rest. Task order was block-randomized, with ten participants starting with the Pasta Box Task and ten with the Cup Transfer Task. If an error occurred during a trial, the error

type was recorded, and that trial marked as unsuccessful. Each participant completed the tasks until 20 successful attempts were recorded. Ten participants (5 females and 5 males; 9 right-handed and 1 left-handed; age  $26.4 \pm 6.9$  years; height  $173 \pm 9$  cm) returned for a second testing session several months ( $7.5$  months  $\pm 11$  days) after the initial testing, to assess the intra-rater reliability of the obtained kinematic measures. Repeat sessions were administered by the same assessor as for the initial session.

### 2.3. Experimental data analysis

Marker data were filtered using a 2<sup>nd</sup> order, low-pass Butterworth filter with a cutoff frequency of 6 Hz [10]. Filtered marker data were used to calculate 3D angular joint kinematics. Global and local coordinate systems, Cardan angle rotation sequence, and joint angle computations were implemented following the procedures in Boser et al. [19]. Ten degrees of freedom (DOF) were included in the analysis: trunk flexion/extension, lateral bending, and axial rotation; shoulder flexion/extension, abduction/adduction, and internal/external rotation; elbow flexion/extension and forearm pronation/supination; and wrist flexion/extension and ulnar/radial deviation. The overall, average joint angle trajectories with between-participant standard deviation bands were plotted for each DOF studied. Peak joint angle, RoM, and peak angular velocity values were extracted from joint angle time series of individual trials.

Using hand velocity, object velocity, and grip aperture, trial data were segmented into reach, grasp, transport, and release phases and time-normalized following the procedures in Valevicius et al. [20]. Each phase was illustrated in a different color in the figures, to enhance visual interpretation. For the purpose of 3D kinematic analysis, data were analyzed by 'Movement', consisting of a set of reach, grasp, transport, and release phases. The 'Return to Home' motion after specific movements was not considered a phase within a 'Movement' and was therefore not included in the analysis; however, this motion was still included in the graphical presentation of the angular kinematics using a different color. The Pasta Box Task and Cup Transfer Task were comprised of 3 and 4 movements, respectively.

### 2.4. Statistical analysis

Statistical analysis was completed using the SPSS software (IBM Corporation, Armonk, NY, USA). Intra-rater reliability was assessed by calculating the intra-class correlation (ICC) for model (2,k), the standard error of measurement (SEM), and the minimal detectable change (MDC) [21] between the first and second session of the ten returning participants. SEM was calculated as the square root of the mean square error term from the analysis of variance [21]. MDC was calculated using the equation  $MDC = SEM \cdot 1.96 \cdot \sqrt{2}$ , where 1.96 is the z-score associated with the 95% confidence interval [21]. ICC, SEM, and MDC values were obtained for peak joint angle, RoM, and peak angular velocity. ICC values above 0.90 were considered to show reasonable agreement for clinical measurements, above 0.75 good reliability, and below 0.75 poor to moderate reliability [22]. F-Tests ( $p < 0.05$ ) were performed to check for the validity of the ICC values.

## 3. Results

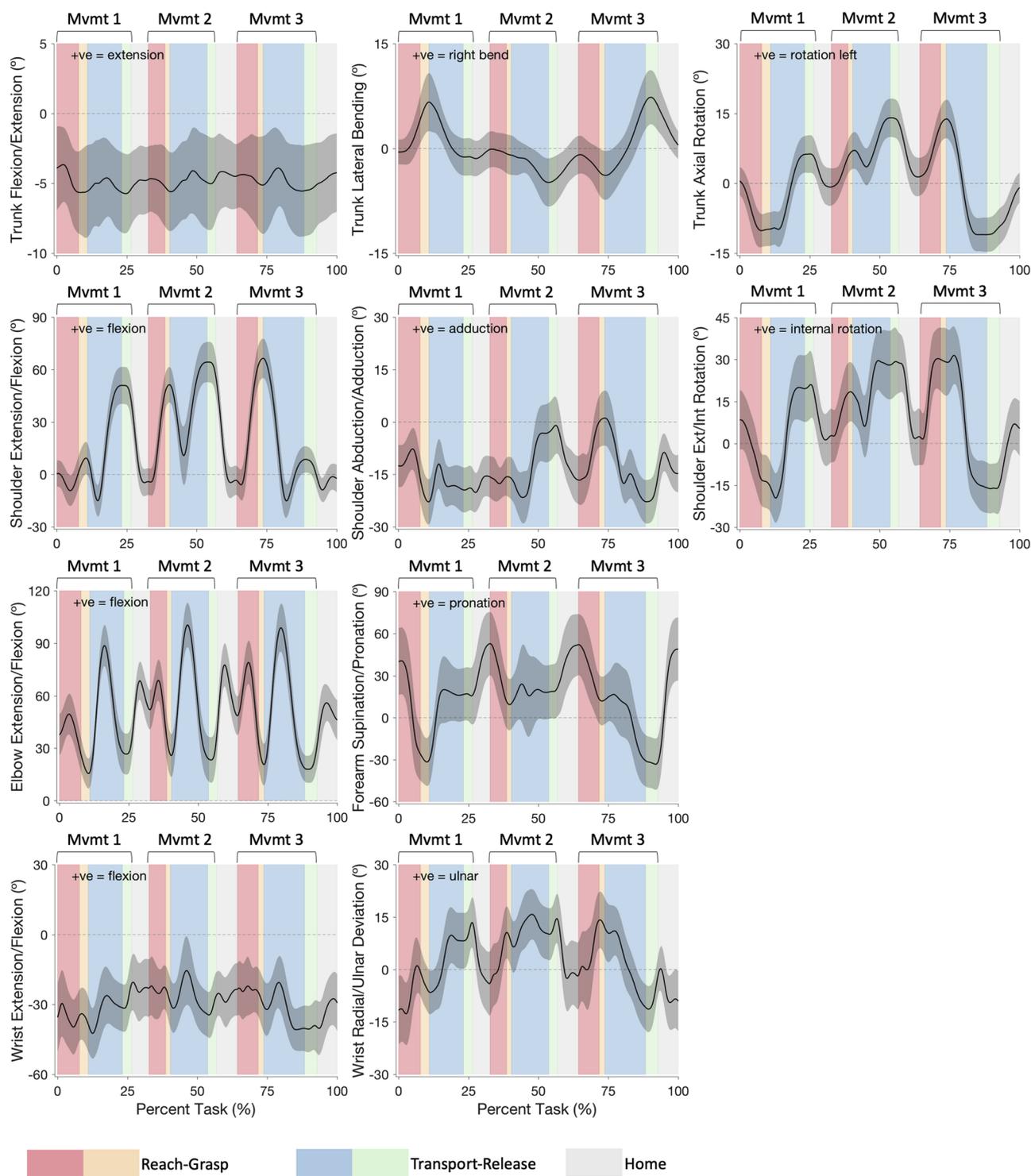
### 3.1. Pasta Box Task

Angular joint trajectories for the Pasta Box Task are shown in Fig. 1. The mean peak angle, RoM, and peak angular velocity, along with their between-participant standard deviation and within-participant variability, are listed for each movement of the Pasta Box Task in Table 1. There was very little trunk flexion/extension across all movements, with only  $4 \pm 1$  to  $5 \pm 2$  degrees of RoM. The trunk distinctly bended and rotated to the right during Movement 1 reach and Movement 3

transport (to the side table), whereas, during Movement 2 transport and Movement 3 reach (across the body), the trunk distinctly bended and rotated to the left (Fig. 1). All three movements started with the shoulder in a near neutral position, reaching peak flexion when grasping ( $67 \pm 11$  degrees) or releasing ( $65 \pm 12$  degrees) the box on the raised shelves in front of the participant. The same was observed for peak shoulder internal rotation values ( $34 \pm 11$  degrees), particularly for movements to the second shelf requiring a cross-body reach. The shoulder maintained a mostly abducted position throughout the task, with peak shoulder abduction occurring during Movement 1 reach ( $-25 \pm 7$  degrees) when picking up the box of pasta from the side table. Greater than 90 degrees of peak elbow flexion was required to transport the box of pasta (Fig. 1). When grasping or releasing the box, the elbow was closer to full extension (minimum flexion angle:  $15 \pm 8$  degrees). Each movement started with the forearm in a pronated position and progressively supinated throughout the reach. Movement 3 required the greatest range of pronation/supination ( $90 \pm 16$  degrees). The wrist was in extension for the entirety of the task, with the least amount of wrist extension displayed during Movement 2 transport ( $-11 \pm 14$  degrees). Reaching for the box on the cart shelves required wrist ulnar deviation (peak angle:  $19 \pm 8$  degrees) and placing the box back on the side table required wrist radial deviation (peak angle:  $-12 \pm 7$  degrees). Trunk DOFs displayed the lowest angular velocities ( $14 \pm 4$  to  $60 \pm 11$  degrees/sec). For shoulder, elbow, and wrist joints, flexion/extension movement displayed the largest peak angular velocities, indicating faster angular changes in the sagittal plane of motion. Overall, largest angular velocity values (above 250 degrees/sec) were observed for elbow flexion/extension.

### 3.2. Cup Transfer Task

Angular joint trajectories for the Cup Transfer Task are shown in Fig. 2. The mean peak angle, RoM, and peak angular velocity, along with their between-participant standard deviation and within-participant variability, are listed for each movement of the Cup Transfer Task in Table 2. The trunk started and ended in a near neutral position for all DOFs. The trunk progressively rotated to the left during Movements 1 and 2 and progressively rotated back towards a neutral position during Movements 3 and 4. Across all trunk DOFs, interacting with the far cup in Movements 2 and 3 required larger RoM than in Movements 1 and 4 ( $9 \pm 4$  and  $10 \pm 4$  degrees versus  $3 \pm 2$  and  $5 \pm 3$  degrees for flexion/extension;  $7 \pm 3$  and  $6 \pm 2$  versus  $5 \pm 2$  and  $4 \pm 1$  degrees for lateral bending;  $11 \pm 3$  and  $17 \pm 4$  versus  $9 \pm 3$  and  $8 \pm 2$  degrees for axial rotation) and displayed larger peak angular velocities. Movements 1 (RoM:  $62 \pm 13$  degrees) and 3 (RoM:  $73 \pm 10$  degrees) required large magnitudes of shoulder flexion. Movements 1 and 2 transport, when moving the cups from the right side to the left side, required the shoulder to adduct, and Movements 3 and 4 transport required the shoulder to abduct. Placing and reaching for the near cup on the left side of the box required the greatest amount of shoulder internal rotation during Movements 1 ( $44 \pm 15$  degrees) and 4 ( $46 \pm 15$  degrees). Every reach and transport displayed a peak in elbow flexion. Greater magnitudes of elbow flexion were required to transport the near cup as opposed to the far cup (Fig. 2). Moving to the far-left target during Movements 2 and 3 required the elbow to be nearly extended (minimum flexion angle:  $11 \pm 8$  and  $9 \pm 8$  degrees). The top grasp required more forearm pronation (peak angle:  $51 \pm 21$  degrees) and the side grasp forced the forearm to stay in a supinated position (peak angle:  $-14 \pm 19$  degrees). The different grasp patterns also required distinct wrist motions: the top grasp required the wrist to be flexed (peak angle:  $45 \pm 14$  degrees) and ulnar-deviated (peak angle:  $28 \pm 12$  degrees), whereas the side grasp forced the wrist into an extended (peak angle:  $-33 \pm 10$  degrees) and radial-deviated position (peak angle:  $-9 \pm 9$  degrees). Trunk DOFs displayed the lowest peak angular velocity values ( $11 \pm 4$  to  $40 \pm 9$  degrees/sec). Shoulder abduction/adduction displayed the lowest angular velocities for shoulder DOFs. Reaching for the cups from



**Fig. 1.** Pasta Box Task angular joint trajectories are presented for trunk flexion/extension, lateral bending, and axial rotation; shoulder flexion/extension, abduction/adduction, and internal/external rotation; elbow flexion/extension and forearm pronation/supination; and wrist flexion/extension and ulnar/radial deviation. The group mean is plotted as a solid black line and between-participant standard deviation (SD) as grey shading. Each movement is segmented into reach (red), grasp (orange), transport (blue), and release (green) phases. Times when the hand returned to the “Home” starting position are shaded grey. Movements (Mvmt) are indicated above the respective phases in a bracket.

the ‘Home’ position displayed larger shoulder flexion/extension peak angular velocities ( $222 \pm 55$  degrees/sec), whereas changing the grasp to pick up the next cup in Movements 2 and 4 displayed larger shoulder internal/external rotation angular velocities ( $168 \pm 33$  degrees/sec). For the elbow and wrist joints, movement in flexion/extension displayed larger angular velocities than forearm pronation/supination or radial/ulnar deviation.

### 3.3. Variability and intra-rater reliability

For both tasks, between-participant variability was typically larger than within-participant variability (Tables 1 and 2). For the trunk DOFs, the absolute between-participant variability was below 5 degrees for peak angle and RoM. The majority of the remaining DOFs displayed an absolute between-participant variability of over 5 degrees. Forearm

**Table 1**

Pasta Box Task measures for peak angle (degrees), range of motion (degrees), and peak angular velocity (degrees/sec) are presented for trunk flexion/extension, lateral bending, and axial rotation; shoulder flexion/extension, abduction/adduction, and internal/external rotation; elbow flexion/extension and forearm pronation/supination; and wrist flexion/extension and ulnar/radial deviation. Data are presented, for movements, as group means and between-participant standard deviations (SD). Average within-participant variability (WPV) is also presented for each measure.

Trunk		Flexion/extension		Lateral bending		Axial rotation	
	Movement	Mean ± SD	WPV	Mean ± SD	WPV	Mean ± SD	WPV
Peak angle (degrees)	1	-2.5 ± 2.7	1.2	6.8 ± 4.1	1.5	6.6 ± 4.0	1.2
	2	-3.0 ± 2.7	1.2	0.4 ± 2.5	1.0	14.4 ± 4.2	1.2
	3	-2.5 ± 2.6	1.2	7.5 ± 3.9	2.2	14.0 ± 4.2	1.2
Range of motion (degrees)	1	5.2 ± 2.2	1.3	8.7 ± 3.2	1.4	17.9 ± 2.5	1.5
	2	3.6 ± 1.1	0.9	5.5 ± 1.8	1.1	15.3 ± 3.1	1.4
	3	4.8 ± 1.3	1.2	11.7 ± 2.8	2.2	25.9 ± 3.7	1.7
Peak angular velocity (degrees/sec)	1	20.9 ± 7.7	5.4	22.7 ± 6.7	5.4	44.7 ± 7.3	6.7
	2	15.8 ± 5.3	3.8	13.6 ± 3.7	3.0	34.2 ± 7.6	4.8
	3	19.9 ± 5.7	4.3	22.1 ± 4.7	6.8	59.9 ± 10.7	8.4
Shoulder		Flexion/extension		Abduction/adduction		Internal/external rotation	
	Movement	Mean ± SD	WPV	Mean ± SD	WPV	Mean ± SD	WPV
Peak angle (degrees)	1	51.5 ± 10.5	2.2	-6.1 ± 4.7	1.5	22.5 ± 11.7	2.2
	2	64.8 ± 11.5	1.9	0.2 ± 7.3	2.2	32.0 ± 11.2	1.9
	3	66.6 ± 11.3	2.1	2.4 ± 6.8	2.2	33.8 ± 11.0	2.0
Range of motion (degrees)	1	68.0 ± 7.7	2.9	19.1 ± 6.5	2.1	42.9 ± 8.6	2.8
	2	70.7 ± 9.8	2.8	24.3 ± 8.3	3.2	31.8 ± 6.5	2.8
	3	83.3 ± 11.8	4.2	27.2 ± 8.9	3.0	52.4 ± 7.7	3.0
Peak angular velocity (degrees/sec)	1	186.4 ± 35.9	15.8	72.3 ± 20.8	9.6	141.2 ± 30.0	16.0
	2	191.1 ± 37.0	14.3	75.8 ± 28.9	11.0	116.2 ± 19.7	14.7
	3	221.3 ± 39.6	20.4	94.7 ± 28.2	11.2	167.6 ± 31.2	20.1
Elbow/Forearm		Flexion/extension		Pronation/supination			
	Movement	Mean ± SD	WPV	Mean ± SD	WPV		
Peak angle (degrees)	1	89.3 ± 11.8	3.3	42.9 ± 23.3	3.9		
	2	101.0 ± 12.7	3.0	53.3 ± 22.5	2.5		
	3	100.1 ± 13.9	3.8	53.3 ± 21.9	2.8		
Range of motion (degrees)	1	74.2 ± 10.1	3.5	76.2 ± 14.6	5.6		
	2	79.5 ± 9.4	3.5	49.8 ± 16.6	5.6		
	3	85.5 ± 11.6	4.7	89.5 ± 16.3	6.2		
Peak angular velocity (degrees/sec)	1	260.3 ± 48.4	20.6	293.0 ± 63.5	45.6		
	2	257.9 ± 43.4	18.6	164.0 ± 51.4	29.8		
	3	256.2 ± 43.3	18.4	175.2 ± 42.6	37.0		
Wrist		Flexion/extension		Radial/ulnar deviation			
	Movement	Mean ± SD	WPV	Mean ± SD	WPV		
Peak angle (degrees)	1	-17.6 ± 13.5	4.4	14.9 ± 7.8	2.4		
	2	-11.3 ± 13.6	5.1	18.9 ± 7.7	2.7		
	3	-12.9 ± 10.5	6.7	16.9 ± 7.6	3.0		
Range of motion (degrees)	1	28.5 ± 7.8	4.8	29.6 ± 5.7	3.2		
	2	24.8 ± 8.2	5.2	23.4 ± 7.2	3.7		
	3	31.3 ± 7.1	7.4	29.2 ± 4.3	3.3		
Peak angular velocity (degrees/sec)	1	126.9 ± 29.0	27.0	103.2 ± 36.9	22.8		
	2	113.8 ± 33.4	22.8	88.4 ± 21.9	18.5		
	3	115.8 ± 33.7	36.9	108.6 ± 23.4	29.7		

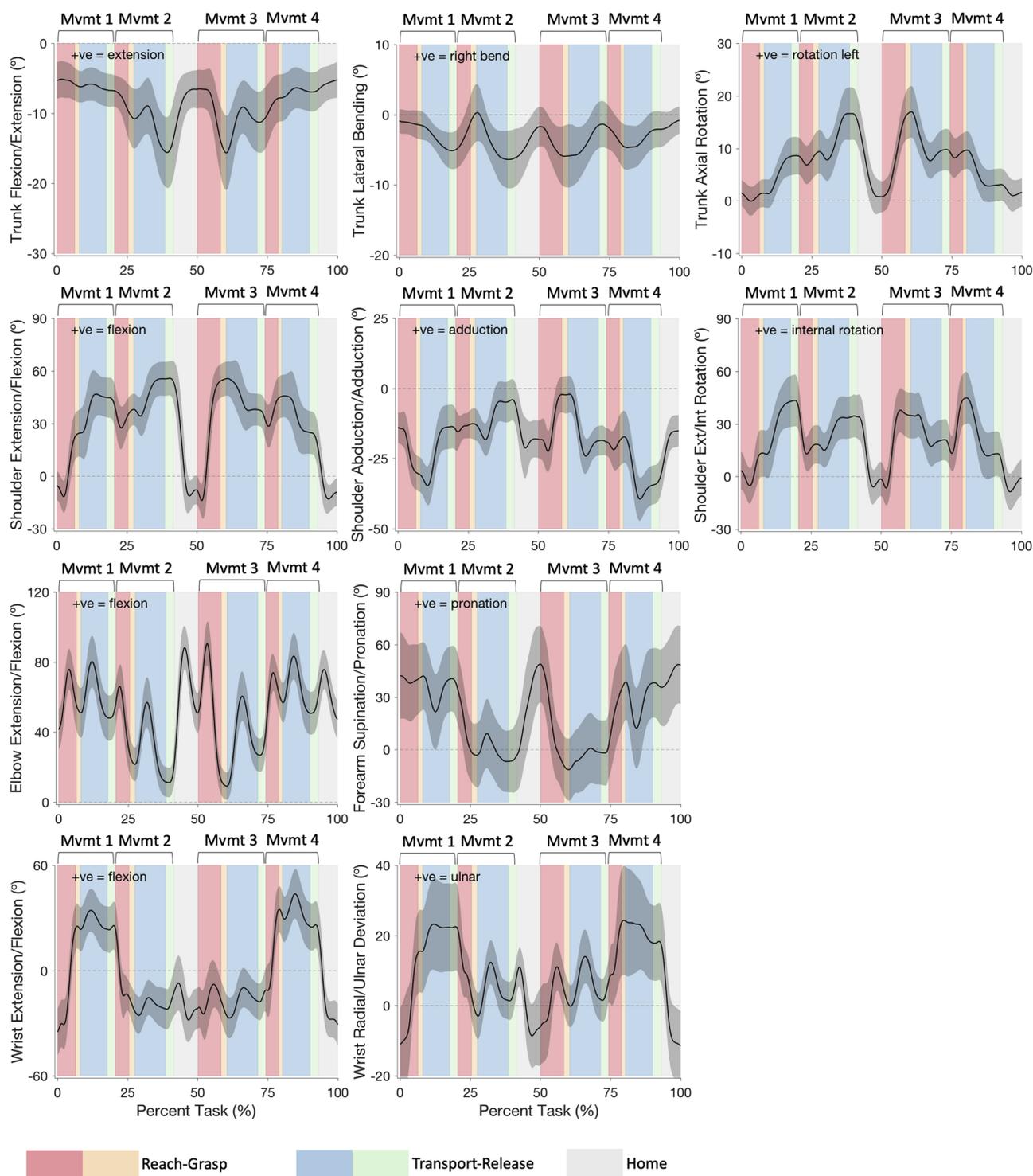
pronation/supination displayed the largest between-participant variability. The majority of DOFs exhibited a within-participant variability for peak angle and RoM that was below 5 degrees.

For each kinematic measure, values for ICC with 95% confidence intervals, SEM, and MDC are shown in Table 3 (Pasta Box Task) and Table 4 (Cup Transfer Task). For the Pasta Box Task, 52% of measures displayed ICC values above 0.75, and 23% above 0.90, therefore having reasonable agreement for clinical assessments [22]. The highest reliability was observed for shoulder and elbow flexion/extension. ICC values below 0.75 were mostly observed for trunk and wrist DOFs. For the Cup Transfer Task, 54% of measures displayed ICC values above 0.75, and 28% above 0.90. Best reliability was observed for trunk axial rotation and all three DOFs at the shoulder. Reliability for elbow flexion/extension was not as high as for the Pasta Box Task. Forearm pronation/

supination peak angle displayed the greatest SEM values (11–15 degrees) across both tasks. When excluding this DOF, all SEM values for peak angle and RoM were below 8 degrees and 11 degrees for the Pasta Box and Cup Transfer Tasks, respectively. MDC values for peak angle and RoM were below 35 and 41 degrees, with 21 and 29 measures below 10 degrees for the Pasta Box and Cup Transfer Tasks, respectively.

#### 4. Discussion

This study established a normative dataset of 3D angular joint kinematics for two standardized functional tasks, the Pasta Box Task and Cup Transfer Task, with generally good test-retest reliability. The joint kinematic results provided insights into the specific task requirements



**Fig. 2.** Cup Transfer Task angular joint trajectories are presented for trunk flexion/extension, lateral bending, and axial rotation; shoulder flexion/extension, abduction/adduction, and internal/external rotation; elbow flexion/extension and forearm pronation/supination; and wrist flexion/extension and ulnar/radial deviation. The group mean is plotted as a solid black line and between-participant standard deviations (SD) as grey shading. Each movement is segmented into reach (red), grasp (orange), transport (blue), and release (green) phases. Times when the hand returned to the “Home” starting position are shaded grey. Movements (Mvmt) are indicated above the respective phases in a bracket.

for each functional movement.

#### 4.1. Angular joint motion

Overall, minimal trunk movement was required to complete the tasks. However, the Pasta Box Task required a greater range of trunk lateral bending and trunk axial rotation compared to flexion/extension.

For the Cup Transfer Task, movement of the far cup required greater RoM across all trunk DOFs. While trunk movement is not commonly reported in upper limb analyses of non-disabled individuals [9,23], its assessment is important when studying upper limb impairments. When hand function is impaired by neuromuscular or musculoskeletal injury, proximal joints and the trunk are likely to display compensatory motion to successfully complete a task [14,24]. Therefore, inclusion of trunk

**Table 2**

Cup Transfer Task measures for peak angle (degrees), range of motion (degrees), and peak angular velocity (degrees/sec) are presented for trunk flexion/extension, lateral bending, and axial rotation; shoulder flexion/extension, abduction/adduction, and internal/external rotation; elbow flexion/extension and forearm pronation/supination; and wrist flexion/extension and ulnar/radial deviation. Data are presented, for movements, as group means and between-participant standard deviations (SD). Average within-participant variability (WPV) is also presented for each measure.

Trunk		Flexion/extension		Lateral bending		Axial rotation	
	Movement	Mean ± SD	WPV	Mean ± SD	WPV	Mean ± SD	WPV
Peak angle (degrees)	1	-4.4 ± 2.5	1.1	-0.6 ± 1.8	1.1	8.9 ± 3.6	1.3
	2	-6.4 ± 2.5	1.2	0.4 ± 4.1	1.2	17.0 ± 4.9	1.3
	3	-5.8 ± 2.8	1.1	-0.7 ± 3.1	1.1	17.1 ± 4.9	1.3
	4	-5.8 ± 2.7	1.1	-1.1 ± 2.9	1.0	10.2 ± 3.8	1.0
Range of motion (degrees)	1	3.1 ± 1.5	0.9	4.7 ± 1.9	1.0	9.3 ± 2.5	1.3
	2	9.4 ± 3.8	1.3	7.4 ± 2.5	1.3	10.6 ± 2.7	1.3
	3	10.0 ± 3.8	1.4	6.0 ± 1.9	1.1	16.6 ± 4.0	1.7
	4	4.9 ± 2.6	1.0	3.9 ± 1.4	0.8	7.8 ± 2.3	0.9
Peak angular velocity (degrees/sec)	1	11.8 ± 3.8	3.8	10.6 ± 4.1	2.3	22.0 ± 4.3	3.9
	2	24.2 ± 6.9	3.8	17.6 ± 6.2	3.6	29.3 ± 7.1	4.4
	3	28.8 ± 9.1	4.5	15.6 ± 3.7	3.8	39.9 ± 8.9	5.5
	4	14.3 ± 5.0	4.6	11.4 ± 3.2	2.9	23.6 ± 6.9	3.8
Shoulder		Flexion/extension		Abduction/adduction		Internal/external rotation	
	Movement	Mean ± SD	WPV	Mean ± SD	WPV	Mean ± SD	WPV
Peak angle (degrees)	1	49.0 ± 14.2	2.7	-8.7 ± 4.9	2.1	44.1 ± 14.7	2.6
	2	57.2 ± 10.3	1.8	-2.2 ± 6.6	2.5	42.1 ± 13.4	2.1
	3	57.8 ± 11.0	1.9	-0.6 ± 5.9	2.5	40.9 ± 13.5	3.0
	4	49.3 ± 14.3	3.2	-14.5 ± 6.9	2.4	45.8 ± 14.5	2.7
Range of motion (degrees)	1	61.5 ± 13.2	3.4	26.8 ± 6.9	2.8	50.2 ± 13.8	3.5
	2	31.1 ± 6.7	2.8	18.2 ± 5.5	2.8	31.4 ± 6.8	2.8
	3	73.0 ± 10.1	2.8	27.8 ± 8.5	3.2	48.3 ± 12.1	3.8
	4	30.3 ± 9.1	3.3	25.6 ± 5.8	3.0	38.7 ± 9.5	3.2
Peak angular velocity (degrees/sec)	1	136.0 ± 40.2	14.1	77.6 ± 21.7	9.4	111.6 ± 53.5	16.4
	2	100.4 ± 27.3	13.4	60.8 ± 15.7	10.3	168.0 ± 32.9	20.1
	3	221.8 ± 55.0	22.9	94.5 ± 33.0	11.7	178.7 ± 54.2	21.6
	4	106.3 ± 24.7	13.4	73.7 ± 17.4	9.3	151.5 ± 36.0	19.0
Elbow/Forearm		Flexion/extension		Pronation/supination			
	Movement	Mean ± SD	WPV	Mean ± SD	WPV		
Peak angle (degrees)	1	84.0 ± 12.0	3.1	50.9 ± 21.0	3.2		
	2	69.7 ± 11.3	3.0	35.5 ± 19.3	3.4		
	3	91.8 ± 12.3	3.0	49.8 ± 21.7	3.0		
	4	84.2 ± 13.0	2.7	42.1 ± 20.9	3.3		
Range of motion (degrees)	1	44.4 ± 9.5	3.8	31.6 ± 12.5	4.5		
	2	59.1 ± 7.8	3.6	45.6 ± 12.3	5.6		
	3	82.9 ± 8.9	3.4	63.7 ± 11.4	5.8		
	4	46.1 ± 5.6	3.3	44.7 ± 9.3	5.0		
Peak angular velocity (degrees/sec)	1	165.7 ± 39.4	15.4	111.0 ± 21.7	22.3		
	2	195.7 ± 39.3	19.7	175.3 ± 42.3	36.3		
	3	270.3 ± 51.9	21.3	190.1 ± 46.0	46.1		
	4	216.0 ± 37.3	18.5	179.2 ± 59.4	26.3		
Wrist		Flexion/extension		Radial/ulnar deviation			
	Movement	Mean ± SD	WPV	Mean ± SD	WPV		
Peak angle (degrees)	1	36.4 ± 12.2	4.0	25.5 ± 12.0	3.2		
	2	27.3 ± 13.2	3.5	24.1 ± 10.2	3.1		
	3	0.4 ± 14.4	7.7	15.7 ± 7.2	2.9		
	4	45.1 ± 14.0	3.7	27.8 ± 12.2	2.8		
Range of motion (degrees)	1	74.5 ± 14.2	6.0	38.4 ± 9.5	4.0		
	2	55.7 ± 7.3	4.8	28.0 ± 7.2	3.8		
	3	33.4 ± 10.5	7.6	24.6 ± 6.0	3.8		
	4	61.2 ± 10.2	6.6	23.3 ± 6.2	4.1		
Peak angular velocity (degrees/sec)	1	272.1 ± 69.7	38.7	133.3 ± 37.7	23.4		
	2	263.2 ± 71.1	40.4	121.5 ± 40.6	22.7		
	3	155.9 ± 59.8	47.0	113.7 ± 35.3	25.8		
	4	288.5 ± 61.5	41.0	123.8 ± 35.8	25.6		

motion in non-disabled analyses can serve as a benchmark for comparison to impaired function.

Across all shoulder DOFs, for the Pasta Box Task, reaching from the top shelf of the cart to the side table required the largest RoM,

highlighting how cross-body movements demand large joint exertions. For the Cup Transfer Task, Movements 1 and 3, where the hand left a position at the near edge of the cart (“Home” in Fig. 2), required the largest RoM. The varying requirements across movements indicate how

**Table 3**

For each Pasta Box Task movement, repeatability analysis was performed on peak angle, range of motion, and peak angular velocity for trunk flexion/extension, lateral bending, and axial rotation; shoulder flexion/extension, abduction/adduction, and internal/external rotation; elbow flexion/extension and forearm pronation/supination; and wrist flexion/extension and radial/ulnar deviation. Repeatability measures include intra-class correlation (ICC) with corresponding 95% confidence intervals, standard error of measurement (SEM), and minimal detectable change (MDC). ICC values above 0.90 are presented in bold. ICC values below 0.75 are presented in italics. ICC values that failed the F-test ( $p > 0.05$ ) are presented with an asterisk (\*), indicating the validity of the ICC may be compromised for this result.

Trunk		Flexion/extension			Lateral bending			Axial rotation			
	Movement	ICC	SEM	MDC	ICC	SEM	MDC	ICC	SEM	MDC	
Trunk	Peak angle (degrees)	1	<i>-0.08 (-3.36-0.73)*</i>	1.9	5.3	0.76 (0.02-0.94)	2.7	7.4	<i>0.70 (-0.21-0.93)</i>	2.9	8.1
		2	<i>0.34 (-1.66-0.84)*</i>	2.3	6.3	0.87 (0.47-0.97)	1.1	2.9	<i>0.63 (-0.50-0.91)*</i>	3.4	9.6
		3	<i>0.19 (-2.27-0.80)*</i>	1.8	4.9	0.75 (0.01-0.94)	2.9	8.0	<i>0.52 (-0.95-0.88)*</i>	3.7	10.2
	Range of motion (degrees)	1	0.81 (0.22-0.95)	1.5	4.0	<i>0.54 (-0.86-0.89)*</i>	2.4	6.6	<i>0.45 (-1.21-0.86)*</i>	2.9	8.0
		2	0.84 (0.34-0.96)	0.7	2.0	0.84 (0.34-0.96)	0.9	2.6	<i>0.68 (-0.27-0.92)*</i>	2.2	6.2
		3	<i>0.01 (-2.98-0.76)*</i>	1.3	3.5	<i>0.62 (-0.55-0.90)*</i>	2.6	7.2	<i>0.73 (-0.07-0.93)</i>	3.4	9.4
	Peak angular velocity (degrees/sec)	1	<i>0.47 (-1.13-0.87)*</i>	7.7	21.3	<i>0.66 (-0.35-0.93)*</i>	4.8	13.4	<i>0.11 (-2.57-0.78)*</i>	6.1	16.8
		2	0.89 (0.55-0.97)	3.4	9.6	<i>0.60 (-0.62-0.90)*</i>	2.2	6.1	<b>0.90 (0.59-0.97)</b>	3.3	9.3
		3	<i>0.48 (-1.10-0.87)*</i>	5.2	14.5	<i>0.60 (-0.63-0.90)*</i>	4.3	11.9	<i>0.55 (-0.81-0.89)*</i>	7.2	20.0
Shoulder		Flexion/extension			Abduction/adduction			Internal/external rotation			
	Movement	ICC	SEM	MDC	ICC	SEM	MDC	ICC	SEM	MDC	
Shoulder	Peak angle (degrees)	1	0.80 (0.20-0.95)	6.6	18.2	<i>0.26 (-1.97-0.82)*</i>	3.9	10.9	0.75 (-0.02-0.94)	7.1	19.6
		2	<b>0.91 (0.64-0.98)</b>	5.5	15.3	<i>0.54 (-0.85-0.89)*</i>	5.8	16.1	<i>0.69 (-0.26-0.92)</i>	8.2	22.7
		3	<b>0.90 (0.60-0.98)</b>	5.8	16.0	<i>0.57 (-0.73-0.89)*</i>	5.4	15.1	<i>0.45 (-1.21-0.86)*</i>	7.7	21.4
	Range of motion (degrees)	1	<b>0.96 (0.85-0.99)</b>	3.3	9.2	0.86 (0.44-0.97)	3.7	10.1	<b>0.95 (0.80-0.99)</b>	3.6	10.0
		2	<b>0.97 (0.88-0.99)</b>	2.8	7.8	0.79 (0.16-0.95)	5.9	16.3	0.78 (0.13-0.95)	5.9	16.5
		3	<b>0.93 (0.74-0.98)</b>	4.4	12.1	<i>0.10 (-2.64-0.78)*</i>	8.9	24.5	<b>0.92 (0.68-0.98)</b>	3.9	10.7
	Peak angular velocity (degrees/sec)	1	<b>0.95 (0.79-0.99)</b>	14.5	40.2	0.83 (0.32-0.96)	12.0	33.1	0.82 (0.28-0.96)	17.2	47.7
		2	<b>0.97 (0.89-0.99)</b>	9.3	25.9	0.84 (0.35-0.96)	16.9	46.8	<i>0.53 (-0.87-0.88)*</i>	16.4	45.5
		3	<b>0.95 (0.80-0.99)</b>	12.1	33.6	<i>0.69 (-0.27-0.92)</i>	17.0	47.0	<i>0.71 (-0.18-0.93)</i>	21.6	59.9
Elbow/Forearm		Flexion/extension			Pronation/supination						
	Movement	ICC	SEM	MDC	ICC	SEM	MDC				
Elbow/Forearm	Peak angle (degrees)	1	0.83 (0.32-0.96)	5.2	14.3	<i>0.70 (-0.2-0.93)</i>	12.3	34.2			
		2	0.85 (0.41-0.96)	6.1	16.9	<i>0.60 (-0.62-0.90)*</i>	11.9	32.9			
		3	0.79 (0.14-0.95)	6.2	17.2	<i>0.66 (-0.36-0.92)*</i>	10.6	29.3			
	Range of motion (degrees)	1	0.77 (0.06-0.94)	5.7	15.8	<b>0.92 (0.68-0.98)</b>	8.2	22.6			
		2	<b>0.92 (0.67-0.98)</b>	3.6	10.1	<b>0.95 (0.79-0.99)</b>	5.9	16.3			
		3	<b>0.91 (0.62-0.98)</b>	4.9	13.7	0.89 (0.57-0.97)	5.2	14.5			
	Peak angular velocity (degrees/sec)	1	0.85 (0.39-0.96)	24.0	66.5	0.88 (0.51-0.97)	36.9	102.2			
		2	<b>0.95 (0.80-0.99)</b>	14.6	40.4	<b>0.90 (0.60-0.98)</b>	21.8	60.4			
		3	<b>0.96 (0.85-0.99)</b>	11.7	32.5	<i>0.67 (-0.33-0.92)*</i>	27.6	76.5			
Wrist		Flexion/extension			Radial/ulnar deviation						
	Movement	ICC	SEM	MDC	ICC	SEM	MDC				
Wrist	Peak angle (degrees)	1	<i>0.45 (-1.21-0.86)*</i>	8.7	24.2	<i>-0.43 (-4.77-0.64)*</i>	7.3	20.1			
		2	<i>0.65 (-0.39-0.91)*</i>	7.8	21.5	<i>-0.77 (-6.12-0.56)*</i>	7.3	20.2			
		3	<i>0.69 (-0.26-0.92)*</i>	6.6	18.3	<i>0.25 (-2.01-0.81)*</i>	6.8	18.7			
	Range of motion (degrees)	1	0.89 (0.57-0.97)	2.9	8.0	<i>-0.27 (-3.90-0.70)*</i>	4.2	11.7			
		2	0.89 (0.54-0.97)	4.0	11.1	<i>0.69 (-0.24-0.92)</i>	3.9	10.7			
		3	<i>0.67 (-0.33-0.92)*</i>	5.0	13.9	<i>0.50 (-1.01-0.88)*</i>	2.6	7.3			
	Peak angular velocity (degrees/sec)	1	<b>0.94 (0.74-0.98)</b>	13.5	37.4	<b>0.90 (0.61-0.98)</b>	15.9	44.1			
		2	0.79 (0.16-0.95)	16.2	44.8	<i>0.25 (-2.03-0.81)*</i>	16.8	46.5			
		3	0.85 (0.39-0.96)	12.2	33.8	<b>0.91 (0.63-0.98)</b>	13.3	37.0			

differing shelf heights or object locations in relation to the edge of a counter, as in a standard kitchen, highly influences the joint range needed to complete activities of daily living.

Elbow flexion/extension displayed some of the largest angular velocities among all DOFs for both tasks. Angular velocity, a predictor of an individual’s muscle power [25], is valuable when studying populations with impairments as it gives insight into the adequate functioning and force production of muscles [16,26]. Mackey et al. found that angular velocities were reduced in children with cerebral palsy [27], indicating muscle fatigue or weakness could be present with upper limb deficits. Forearm pronation/supination RoM during the Pasta Box Task displayed the largest amount of between- and within-participant

variability during transport (Table 1). The task standardized the movement requirements by setting a specific starting position for the hand and defining precise pick-up and drop-off locations for the objects; however, the orientation in which the box of pasta was grasped, carried, and placed was not enforced, allowing individual grasp strategies. The tilt of the box of pasta during the transport phase would in turn change the angle of pronation or supination of the forearm, thereby explaining the larger between-participant variability observed in this task.

Clear differences, based on task requirements, were observed in wrist angular joint trajectories. Throughout the Pasta Box Task, interacting with the box of pasta forced the wrist into an extended position. For the

**Table 4**

For each Cup Transfer Task movement, repeatability analysis was performed on peak angle, range of motion, and peak angular velocity for trunk flexion/extension, lateral bending, and axial rotation; shoulder flexion/extension, abduction/adduction, and internal/external rotation; elbow flexion/extension and forearm pronation/supination; and wrist flexion/extension and radial/ulnar deviation. Repeatability measures include intra-class correlation (ICC) with corresponding 95% confidence intervals, standard error of measurement (SEM), and minimal detectable change (MDC). ICC values above 0.90 are presented in bold. ICC values below 0.75 are presented in italics. ICC values that failed the F-test ( $p > 0.05$ ) are presented with an asterisk (\*), indicating the validity of the ICC may be compromised for this result.

Trunk		Flexion/extension			Lateral bending			Axial rotation		
	Movement	ICC	SEM	MDC	ICC	SEM	MDC	ICC	SEM	MDC
Peak angle (degrees)	1	<i>-0.10 (-3.07-0.75)*</i>	2.8	7.9	0.82 (0.28-0.96)	1.1	3.0	<i>0.25 (-2.02-0.81)*</i>	3.6	9.9
	2	<i>0.38 (-1.49-0.85)*</i>	2.8	7.8	<b>0.91 (0.64-0.98)</b>	1.6	4.6	<i>0.70 (-0.20-0.93)</i>	3.6	10.0
	3	<i>0.62 (-0.52-0.91)*</i>	2.3	6.4	<b>0.93 (0.73-0.98)</b>	1.0	2.8	<i>0.72 (-0.14-0.93)</i>	3.6	9.9
	4	<i>0.63 (-0.48-0.91)*</i>	2.5	7.1	0.89 (0.54-0.97)	1.2	3.4	<i>0.51 (-0.97-0.88)*</i>	3.5	9.7
Range of motion (degrees)	1	<i>0.39 (-1.44-0.85)*</i>	1.1	2.9	<i>0.70 (-0.22-0.93)</i>	1.2	3.2	<b>0.90 (0.61-0.98)</b>	1.4	4.0
	2	<i>0.73 (-0.08-0.93)</i>	1.9	5.3	<b>0.94 (0.76-0.99)</b>	1.0	2.9	<b>0.91 (0.65-0.98)</b>	1.2	3.4
	3	<i>0.48 (-1.08-0.87)*</i>	2.2	6.0	<i>0.52 (-0.95-0.88)*</i>	1.7	4.8	<b>0.95 (0.80-0.99)</b>	2.0	5.7
	4	<i>0.58 (-0.68-0.90)*</i>	1.4	3.8	<i>0.60 (-0.60-0.90)*</i>	1.0	2.8	<b>0.91 (0.63-0.98)</b>	1.2	3.2
Peak angular velocity (degrees/sec)	1	0.89 (0.55-0.97)	2.2	6.0	0.81 (0.22-0.95)	1.4	3.9	0.89 (0.57-0.97)	2.7	7.6
	2	<i>0.58 (-0.70-0.90)*</i>	5.6	15.7	<b>0.94 (0.77-0.99)</b>	1.9	5.2	<b>0.91 (0.63-0.98)</b>	3.1	8.6
	3	<i>0.71 (-0.18-0.93)</i>	5.4	15.0	<i>0.24 (-2.07-0.81)*</i>	2.5	6.9	<b>0.94 (0.77-0.99)</b>	3.0	8.2
	4	0.79 (0.14-0.95)	1.7	4.8	<i>0.06 (-2.77-0.77)*</i>	2.2	6.0	0.89 (0.55-0.97)	3.3	9.3
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Shoulder		Flexion/extension			Abduction/adduction			Internal/external rotation		
	Movement	ICC	SEM	MDC	ICC	SEM	MDC	ICC	SEM	MDC
Peak angle (degrees)	1	<b>0.95 (0.79-0.99)</b>	5.9	16.3	<i>0.64 (-0.46-0.91)*</i>	3.7	10.3	0.80 (0.19-0.95)	8.9	24.6
	2	<b>0.90 (0.58-0.97)</b>	6.1	16.9	<i>0.42 (-1.35-0.86)*</i>	5.0	14.0	0.78 (0.13-0.95)	8.4	23.3
	3	<b>0.91 (0.66-0.98)</b>	6.0	16.5	<i>0.34 (-1.67-0.84)*</i>	5.5	15.2	<i>0.57 (-0.73-0.89)*</i>	9.4	26.1
	4	<b>0.97 (0.86-0.99)</b>	5.3	14.7	<i>0.56 (-0.76-0.89)*</i>	5.0	13.8	<i>0.74 (-0.06-0.94)</i>	9.7	26.9
Range of motion (degrees)	1	<b>0.98 (0.92-1.00)</b>	3.4	9.4	0.85 (0.41-0.96)	4.1	11.3	<b>0.95 (0.80-0.99)</b>	5.5	15.1
	2	0.75 (0.01-0.94)	3.6	9.9	<b>0.94 (0.75-0.98)</b>	2.4	6.7	0.84 (0.33-0.96)	4.5	12.5
	3	<b>0.95 (0.79-0.99)</b>	4.1	11.4	0.89 (0.58-0.97)	4.2	11.5	0.84 (0.37-0.96)	7.5	20.7
	4	0.86 (0.43-0.97)	5.5	15.2	<b>0.90 (0.60-0.98)</b>	2.7	7.6	0.86 (0.42-0.96)	5.4	15.0
Peak angular velocity (degrees/sec)	1	<b>0.97 (0.87-0.99)</b>	11.6	32.1	<b>0.97 (0.89-0.99)</b>	5.9	16.2	<b>0.96 (0.83-0.99)</b>	19.0	52.7
	2	<b>0.90 (0.58-0.97)</b>	12.1	33.4	<b>0.94 (0.76-0.99)</b>	7.0	19.3	<b>0.93 (0.71-0.98)</b>	17.2	47.7
	3	<b>0.93 (0.71-0.98)</b>	27.0	75.0	<b>0.94 (0.74-0.98)</b>	13.1	36.3	0.85 (0.38-0.96)	37.7	104.6
	4	0.84 (0.36-0.96)	16.1	44.5	0.83 (0.30-0.96)	11.4	31.7	0.85 (0.39-0.96)	22.3	61.8
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Elbow/Forearm		Flexion/extension			Pronation/supination					
	Movement	ICC	SEM	MDC	ICC	SEM	MDC			
Peak angle (degrees)	1	<i>-0.13 (-3.55-0.72)*</i>		7.9	21.8	<i>0.40 (-1.40-0.85)*</i>	14.6	40.4		
	2	<i>0.40 (-1.42-0.85)*</i>		7.4	20.6	0.82 (0.26-0.95)	10.7	29.8		
	3	<i>0.55 (-0.80-0.89)*</i>		7.0	19.5	<i>0.59 (-0.67-0.90)*</i>	11.7	32.5		
	4	<i>0.67 (-0.31-0.92)*</i>		8.0	22.3	0.75 (0.00-0.94)	11.3	31.4		
Range of motion (degrees)	1	<i>0.65 (-0.41-0.91)*</i>		5.8	16.1	<i>0.53 (-0.89-0.88)*</i>	8.7	24.2		
	2	<i>0.64 (-0.46-0.91)*</i>		4.2	11.6	<i>0.54 (-0.86-0.89)*</i>	9.4	26.2		
	3	0.84 (0.36-0.96)		4.1	11.4	<i>0.24 (-2.06-0.81)*</i>	11.4	31.7		
	4	<i>0.68 (-0.29-0.92)*</i>		4.0	11.1	<i>0.74 (-0.06-0.94)</i>	5.0	13.8		
Peak angular velocity (degrees/sec)	1	0.84 (0.34-0.96)		21.4	59.4	<i>0.74 (-0.04-0.94)</i>	24.3	67.4		
	2	<b>0.92 (0.67-0.98)</b>		19.6	54.3	<i>0.64 (-0.46-0.91)*</i>	20.0	55.3		
	3	0.89 (0.55-0.97)		25.1	69.5	0.81 (0.25-0.95)	28.2	78.1		
	4	<b>0.97 (0.87-0.99)</b>		15.0	41.4	0.83 (0.30-0.96)	25.9	71.8		
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Wrist		Flexion/extension			Radial/ulnar deviation					
	Movement	ICC	SEM	MDC	ICC	SEM	MDC			
Peak angle (degrees)	1	<i>0.44 (-1.26-0.86)*</i>	8.5	23.5	<i>0.51 (-0.96-0.88)*</i>	9.2	25.6			
	2	<i>0.32 (-1.75-0.83)*</i>	9.1	25.4	<i>0.36 (-1.57-0.84)*</i>	8.9	24.8			
	3	<i>0.72 (-0.12-0.93)</i>	9.4	26.2	<i>0.53 (-0.88-0.88)*</i>	6.1	17.0			
	4	<i>0.40 (-1.43-0.85)*</i>	10.2	28.2	<i>0.48 (-1.08-0.87)*</i>	9.4	26.1			
Range of motion (degrees)	1	<b>0.97 (0.87-0.99)</b>	3.7	10.3	<i>0.74 (-0.05-0.94)</i>	6.7	18.6			
	2	0.83 (0.31-0.96)	2.9	7.9	0.77 (0.09-0.94)	5.1	14.0			
	3	<i>0.74 (-0.06-0.94)</i>	6.5	18.1	0.87 (0.45-0.97)	3.3	9.2			
	4	<i>0.72 (-0.13-0.93)</i>	6.2	17.3	<i>0.62 (-0.55-0.91)*</i>	4.6	12.8			
Peak angular velocity (degrees/sec)	1	<b>0.98 (0.91-1.00)</b>	16.1	44.6	<i>0.52 (-0.93-0.88)*</i>	31.3	86.8			
	2	<b>0.92 (0.67-0.98)</b>	25.3	70.0	<i>0.57 (-0.72-0.89)*</i>	28.2	78.3			
	3	<i>0.50 (-1.00-0.88)*</i>	44.3	122.7	<b>0.92 (0.67-0.98)</b>	14.0	38.9			
	4	<b>0.90 (0.58-0.97)</b>	32.9	91.3	<i>0.73 (-0.08-0.93)</i>	22.7	62.9			

Cup Transfer Task, the top grasp required the wrist to be in a flexed position and the side grasp in a slightly extended position. This clear distinction of wrist movement between different grasp patterns is an example of how 3D kinematic analyses, along with these specific tasks, are capable of quantifying small changes in movement strategies. This level of sensitivity might be useful when assessing novel prosthetic technologies incorporating wrist movement as subtle shifts in wrist position would be expected to influence proximal joint motion. Current clinical assessments for prosthetic technologies are typically not sensitive enough to quantitatively detect subtleties in wrist movement [7,24,28].

#### 4.2. Intra-rater reliability

Overall, for both tasks, just over half of the measures presented good reliability and about a quarter of the measures presented excellent reliability. For the Pasta Box Task, measures for the shoulder and elbow DOFs in the sagittal plane were the most reliable. Trunk, forearm, and wrist DOFs were not as reliable, possibly due to the lack of standardization regarding the exact position where the participant had to stand and the orientation in which the participants had to hold the box of pasta. If the participant selected different end-point movement strategies to complete the task, this would increase trial-to-trial variability and decrease reliability [29]. In addition, trunk movement was minimal for the presented tasks, exhibiting small RoM and standard deviations, which would lead to lower ICC values [21]. This is consistent with previous literature, where Engdahl and Gates as well as Jaspers et al. indicated lower reliability at trunk and wrist DOFs [17,30]. For the Cup Transfer Task, the shoulder DOFs displayed the best reliability. Overall, the Cup Transfer Task presented slightly higher reliability than the Pasta Box Task, potentially due to its more constricted movements. SEM and MDC values for peak angle and RoM were in accordance with previous studies examining peak angles and RoM at the upper body. In comparison to the present study where SEM values were below 11 degrees, Engdahl and Gates and Jaspers et al. reported SEM values below 9 degrees [17,30]. The present MDC values for trunk DOFs were less than 10 degrees, which is consistent with Engdahl and Gates. Overall, for shoulder, elbow, and wrist DOFs, the present MDC values were 5 degrees greater than those presented by Engdahl and Gates [17]. It should be noted that the slightly higher SEM and MDC values in the present study can be explained by the inclusion of all upper body DOFs, compared to studies that exclude many elbow and wrist DOFs exhibiting inconsistent results across participants [17].

#### 4.3. Limitations

The cluster-based marker set used here for calculating angular joint kinematics relies on a specific anatomical pose that does not require the identification of anatomical landmarks [19], making the marker set relatively easy to use. However, due to its calibration technique, there are potential offsets when comparing against a traditional anatomical marker set [14,15,23], especially for trunk flexion/extension, elbow and wrist DOFs. As a consequence, literature to directly compare our peak angle results against is limited. Despite this limitation, the marker set by Boser et al. presented low variability and good intra-rater reliability [19], making it a viable clinical tool for assessing kinematics in impaired populations. Another limitation may be that we did not normalize task setup relative to body height, potentially contributing to higher between-participant variability in our results. This choice was, however, driven by our goal to ecologically represent the natural variability in real-world activities, as would be encountered at a “standard” counter height.

#### 5. Conclusion

This study reported on the 3D angular joint kinematics of the upper body required to complete two standardized functional tasks.

Differences in trunk kinematics were observed based on the requirements of the specific movements. Participants converged on similar shoulder and elbow movement strategies, which exhibited smaller variability bands and higher intra-rater reliability. Forearm and wrist DOFs, which are to a greater degree responsible for specific end-point movement, showed larger variability and lower intra-rater reliability. Overall, this study provides a comprehensive upper body kinematic dataset that can be used for comparing populations with impairments and quantitatively assessing movement compensations.

#### Ethical approval

The study was approved by the University of Alberta Health Research Ethics Board (Pro00054011), the Department of the Navy Human Research Protection Program (DON-HRPP), and the SSC-Pacific Human Research Protection Office (SSCPAC HRPO).

#### Conflict of Interest

There are no conflicts of interest for the authors of this study.

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#### Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <https://doi.org/10.1016/j.gaitpost.2019.01.037>.

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