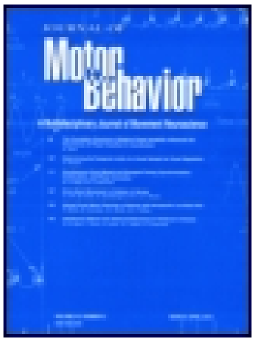

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RESEARCH ARTICLE

Does Object Height Affect the Dart Throwing Motion Angle during Seated Activities of Daily Living?

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ABSTRACT. Complex wrist motions are needed to complete various daily activities. Analyzing the multidimensional motion of the wrist is crucial for understanding our functional movement. Several studies have shown that numerous activities of daily livings (ADLs) are performed using an oblique plane of wrist motion from radial-extension to ulnar-flexion, named the Dart Throwing Motion (DTM) plane. To the best of our knowledge, the DTM plane angle performed during ADLs has not been compared between different heights (e.g. table, shoulder and head height), as is common when performing day-to-day tasks. In this study, we compared DTM plane angles when performing different ADLs at three different heights and examined the relationship between DTM plane angles and limb position. We found that height had a significant effect on the DTM plane angles - the mean DTM plane angle was greater at the lower level compared to the mid and higher levels. A significant effect of shoulder orientation on mean DTM plane angles was shown in the sagittal and coronal planes. Our findings support the importance of training daily tasks at different heights during rehabilitation following wrist injuries, in order to explore a large range of DTM angles, to accommodate needs of common ADLs.

Keywords: kinematics, upper extremity, dart throwing motion (DTM), seated activities of daily living (ADL), wrist rehabilitation, heights

INTRODUCTION

Upper limb movement consists of many degrees of freedom in numerous joints which move synchronously and produce a wide range of motion (ROM) while functioning (Gates, Walters, Cowley, Wilken, & Resnik, 2015). Complex wrist motions are needed to complete various daily activities. Analyzing the multidimensional motion of the wrist is crucial for understanding our functional movement (Rainbow, Wolff, Crisco, & Wolfe, 2016). One of the interesting findings regarding wrist biomechanics is that during motion on a path from wrist radial-extension to ulnar-flexion, most movement occurs at the midcarpal joint (Crisco et al., 2005; Edirisinghe, Troupis, Patel, Smith, & Crossett, 2014; Garcia-Elias, Alomar Serrallach, & Monill Serra, 2014; Moritomo et al., 2007; Werner, Green, Short, & Masaoka, 2004). This oblique plane of motion (i.e., not purely flexion-extension or radial-ulnar deviation) is referred to as the Dart Throwing Motion (DTM) (Moritomo et al., 2014; Werner et al., 2004). Most of the studies analyzing the DTM incorporated motions, such as throwing a dart or using a hammer, whereas more common Activities of Daily Living (ADL) were not explored (Rohde, Crisco, & Wolfe, 2010). In a recent study, we showed that for various ADLs, there was no difference in the DTM plane angles between the dominant and non-dominant hands (Kaufman-Cohen et al., 2018). However, the DTM plane angles differed between the various activities and between subjects. In both hands, most common daily tasks occurred in a DTM plane angle between 20° and 45° (Kaufman-Cohen et al., 2018). These findings should be incorporated during rehabilitation following wrist injuries. To date most exercises are performed in the sagittal plane, i.e., flexion and extension exercises. However, exercises in the DTM plane, might be considered more stable and controlled, i.e. less carpal bone displacements and rotations, since most of the motion occurs at the midcarpal joint, with the proximal carpal row of bones remaining relatively stable (Garcia-Elias et al., 2014). This stable condition might prove advantageous in rehabilitation after wrist fracture when the ligaments are intact (Garcia-Elias et al., 2014; Rainbow et al., 2016), as well as after wrist fracture in which the tissues around the proximal carpal row are repaired, because these tissues might not be disturbed during early DTM (Braidotti, Atzei, & Fairplay, 2015). One limitation of the aforementioned study was that all tasks were performed at table height. However, some ADLs are performed at different heights, e.g. taking a book off a high library shelf or hammering a nail close to the ceiling. These tasks may produce different DTM plane angles.

According to a Donders' like law, the straight arm when pointing is restricted to two degrees of its possible three degrees of freedom, as is also the case for the eye (Donders, 1847; Hore, Watts, & Vilis, 1992). Therefore, an articulated body part would reach a specific end posture, at a particular movement endpoint, regardless of its start position. Most of the variance in the final position of the arm (at the endpoint) is a result of the movement itself towards the endpoint, rather than the original posture of the upper limb for that specific movement (Liebermann, Biess, Friedman, Gielen, & Flash, 2006).

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In this functional mode, the central nervous system (CNS) would move the arm, for example, to the particular end posture matching the intended movement endpoint, regardless of the arm's starting position (Ewart, Hynes, Darling, & Capaday, 2016). According to these findings, what determines the selection of the DTM plane angle in the wrist? How much of it is due to a particular end posture of the upper limb, and how much is due to the activity demands of the functional task? We will explore these questions in this study. Additionally, to the best of our knowledge, the DTM plane angle performed during ADLs has not been compared between different heights. We therefore aimed to (A) compare the DTM plane angles when performing different ADLs between three different heights, and (B) examine the relationship between the DTM plane angles and the limb position, i.e. the angles of the shoulder and elbow, while performing different ADLs in a seated position. The hypotheses consequently were: (A) A difference will be found between the DTM plane angles when performing daily tasks at different heights, and (B) a correlation will be found between the upper extremity position (shoulder and elbow angles) and the DTM plane angles during the performed tasks. For this purpose, we measured the three-dimensional (3 D) angles of the shoulder, elbow and wrist during performance of ADLs completed at table height (low-level), shoulder height (mid-level) and head height.

METHODS

Population

Forty healthy right hand dominant subjects participated in this cross-sectional study design (4 males and 36 females, average and standard deviation (SD) of age was 22.3 ± 2.3 years). The mean and SD of hand span was 19.1 ± 1.4 cm. The DTM plane angle ranged between $43.7 \pm 7.7°$ in extension-radial deviation to $18.3 \pm 7.1°$ in flexion-ulnar deviation.

Individuals with orthopedic or neurological impairment of the upper limb or a cognitive impairment were excluded from the study. The subjects were recruited using a convenience sample, a snowball sample, and enrolled from the credit volunteer pool of the Psychology and Occupational Therapy departments at Tel-Aviv University. Overall, 40 subjects participated in this study. Ethical approval was obtained from the university ethics committee, and the participants signed an informed consent form before beginning the experiment.

Tools

A personal information questionnaire containing data on age and sex was completed. Right limb and hand span measurements were obtained. A manual goniometer was used to measure the active ROM of the upper right limb and to ensure that the subjects had no physical limitations.

A six-camera motion capture system (Qualisys, Sweden) tracked the coordinates of passive markers, placed on the torso and right upper extremity of each subject, using the Heidelberg (Upper Extremity) model (Rettig, Fradet, Kasten, Raiss, & Wolf, 2009), which has been shown to accurately represent clinical measurement of the shoulder and elbow. The 3 D angles of the shoulder, elbow and wrist joints were calculated using the motion of the distal segment in relation to the proximal one. The 3 D angle of the torso was calculated in relation to the lab coordinate system.

Nine daily tasks were chosen for this study involving full activation of the upper limb (Figure 1). Some of the tasks (hammering a nail, pouring the content of a container, turning a doorknob, pushing a small object) were selected based on preexisting studies on the dominant hand kinematics as tasks reflecting important daily activities of an individual (Aizawa et al., 2010; Engdahl & Gates, 2018; Garg et al., 2014; Murgia, Kyberd, Chappell, & Light, 2004; Ricci, Santiago, Zampar, Pinola, & Fonseca, 2015).

The nine tasks were as follows (Figure 1): (1) Pouring 300 g of beans from a cup with a side handle into a plastic container; (2) Hammering a 2.5 cm spring-stabilized nail into a vertical wooden board on a slope of 45° using a 300 gr. hammer; (3) Pressing a push button, with the thumb, was installed into a vertical wooden installation; (4) Taking a book out of a book holder; (5) Rotating a bulb into a light bulb socket fixed to a vertical wooden plank; (6) Screwing a screw with a screwdriver into a vertical wooden fixture with a bolted bolt house; (7) Pushing down a door handle attached to a vertical wooden device with a standard door cylinder; (8) Sliding a credit card through a simulated credit card slot; (9) Inserting a coin through a 2.5 cm slot in a tin box. All objects were placed 10 cm from the edge of the tray. These tasks were chosen as they are unilateral tasks representing daily tasks that might be performed at different heights, e.g., watering a table plant or one hanging over the front entrance door. Following our previous study, we expected to find DTM in the tasks of using a hammer and pouring contents of a container (Kaufman-Cohen et al., 2018). The other 7 tasks were not previously analyzed for DTM. We designed and built an adjustable device that allowed lifting/lowering and securing a round swivel tray with all nine tasks attached to it (Figure 1). The height of the tray could be adjusted for different size of participants.

The device was placed on a table with a steel frame and wooden plate with demarcations noting the placement of device. The tray was rotated after completing each task and the new task was set in front of the subject

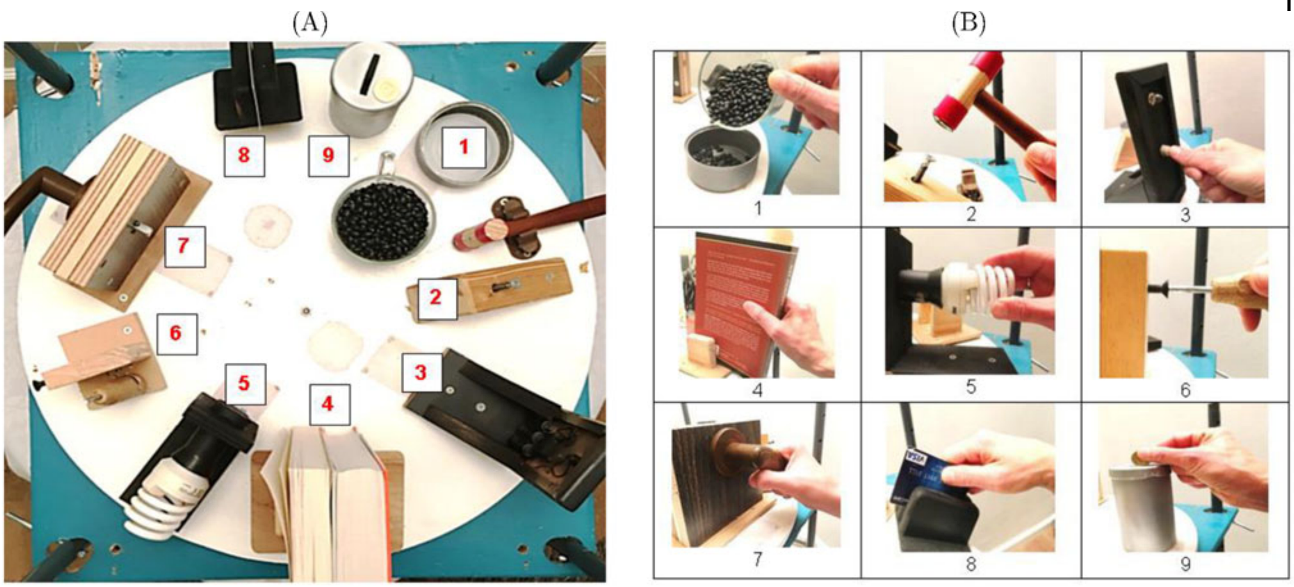

FIGURE 1. (A) The 9 tasks placed on a round swivel device (Lazy Susan). 1. Pouring beans; 2. Hammering; 3. Pressing a push button; 4. Taking a book out of a book holder; 5. Bulb; 6. Screwdriver; 7. Door handle; 8. Credit card; 9. Coin. (B) A Matrix of each of the nine tasks, following the same order as in (A).

using a permanent mark on the base of the rotating tray to maintain uniformity of the tasks relative to the subject at each height (Figure 1). Two tasks: screwing a screw and sliding a credit card were located at a 45° angle to the right of subject's body center line. A chair without armrests, but with a backrest was positioned in front of the table.

Protocol

All subjects read and signed an informed consent form, completed a personal information form and their upper limb ROM and anthropometric dimensions were measured by an occupational therapist. Then, 14 reflective markers were positioned in specific anatomical locations on the torso and right upper limb, according to the Heidelberg (Upper Extremity) model.

Each subject was seated in front of the table with his or her trunk touching the backrest of the chair and with right hand situated on the right thigh. The subject was shown how to complete each task and then performed each task once, to get acquainted with it. Then, each subject performed each of the 9 tasks 3 times, at the three heights, in a counter-balanced order (so that 20 subjects began the trial with the tray at the low level and 20 subjects began the trial with the try at the high level), and in a random order to prevent an order effect (Figure 2). The three repetitions were performed without a rest in between, with the held object lowered to thigh level between repetitions.

Post Processing and Statistical Analysis

Kinematic data were collected at a frequency of 100 Hz, processed in Visual 3 D (C-Motion, USA) Software. The joint angles were expressed as Euler angle decompositions of the relative orientation of the distal segment relative to a proximal segment. A LabView (National Instruments, USA) program was written to calculate the joint angles of each subject in each task, at each height. The sagittal angle of the shoulder was visualized on a graph. The three repetitions of the movement were thus clearly visualized, since shoulder flexion was used for the reaching, but the shoulder remained mostly immobile while the hand was manipulating the held object. The code visualized the location where the first derivative of the sagittal shoulder angle was below a value, set by the analyst, at a range between 0.5°/s and 0.9°/s. This was manually chosen in order to remove the reaching movement, best registered by the angular velocity of the shoulder in the sagittal plane, and focus only on the task execution. Three files were produced, one for each of the 3 repetitions performed for each task at each height, where the object manipulation was isolated, so that the reaching movement itself was not included in the analysis. The ROM of the shoulder (flexion-extension, abduction-adduction, and internal-external rotation), the elbow (flexion-extension and supination-pronation), and the wrist (flexion-extension and radial-ulnar deviation) were calculated during the object manipulation phase. Also, the DTM plane angle was calculated as the

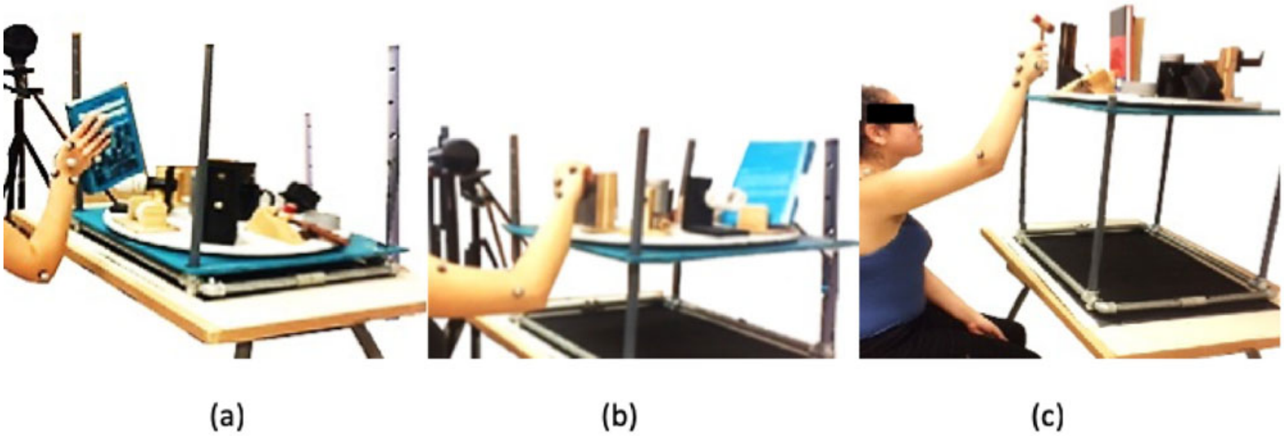

FIGURE 2. Daily tasks performed at 3 different heights; (A) Low-level; (B) Mid-level; (C) High-level.

angle between the best linear fit for a scatter plot of flexion-extension versus radial-ulnar deviation angles and the axis of flexion-extension (Kaufman-Cohen et al., 2018). Negative values of the DTM plane angle represent the motion plane for ulnar extension with radial flexion. Tasks with mean values of R^2 of the linear fit below 0.5 were discarded from further analyses, since these tasks involved out of plane motions, i.e. circumduction.

The analysis of the data included descriptive statistics. Differences between the group of subjects who started at low-level and the group that started at high-level were calculated using the Mann-Whitney U test to make sure that there was no effect of fatigue or learning. Differences of the DTM plane angle between at the three heights for each task were calculated using a repeated measure ANOVA. Normality of the distributions was assessed using the Shapiro–Wilk test (Shapiro & Wilk, 1965). While most values were not normally distributed (14 out of 18), due to the relatively large sample size ($N = 40$), we still used an ANOVA due to its robustness to deviations to normality in relatively large sample sizes (Lantz, 2013). We used the Huynh-Feldt correction when the assumption of sphericity was violated. For post-hoc t-tests, we used the Bonferroni correction. Statistical analyses were performed using IBM SPSS software, v25 (IBM, Armonk, NY).

For the second research question, a multilevel model was used to analyze the correlations between the angles of the shoulder and elbow and the DTM plane angle during performance of ADL tasks at low, mid and high height levels in a seated position. This model was chosen since we expect that the relationship between joint angles and DTM plane angles will differ across subjects, due to different body sizes and strategies. In order to analyze the relationship in a subject-specific way between the limb positions and the DTM plane angles at three different heights, a nested data structure was required.

The significance level was set to $p < 0.05$. The multilevel modeling was performed using Matlab (version 2017 b).

RESULTS

There were no significant differences between the DTM plane angles, at each level, between subjects who started at the low levels versus those that started at the high levels (P-values ranged from .105-1.000). These findings indicate that there was no effect of fatigue or learning effect.

The mean and SD of the R^2 values of the linear fit of the DTM plane, derived from data of wrist motion in the sagittal versus coronal plane are presented in Table 1.

The height had a significant effect on the DTM plane angles, as shown by a main effect of height ($F_{(1.828,72)}=4.979$, $p = 0.009$). Post-hoc t-tests showed that the mean DTM plane angle was greater at the low level (mean ± SEM; 35.4°±2.0) compared to the mid-level (29.9°±1.7; $p = 0.04$) and high level (27.4°±2.8; $p = 0.03$).

There were no significant differences in the mean DTM plane angles between the mid and high level (Table 2). In addition, the task significantly affected the DTM plane angle, as shown by a main effect of task ($F_{(4.658,180)}=32.719$, $p < 0.001$). As differences in DTM plane angle due to task were expected (Kaufman-Cohen et al., 2018), we will not further examine these differences. Finally, the DTM plane angle for the tasks also differed depending on the height, as shown by a significant interaction of height and task ($F_{(7.052,\ 360)}=26.347$, $p < 0.001$). The full results are shown in Table 2. Table 3 details the ROM averages during task performance at the three different heights.

The results of the multi-level model analyses, i.e. the direction of relationship between each joint angle and the DTM plane angle, are presented in Table 4. Significant relationships were observed for the slopes of the sagittal (b=-0.22°, p = 0.02) and coronal (b = 0.41°, p = 0.02) angles of the shoulder. In the sagittal plane a significant negative relationship was observed, i.e. the greater the shoulder flexion, the smaller the DTM plane angle in the wrist. In the coronal plane a significant positive relationship was observed, i.e. the greater the shoulder abduction, the larger the DTM plane angle in the wrist.

Figure 3 depicts the significant regression coefficients presented in Table 4. The effect of the shoulder position in the sagittal and coronal planes on the mean DTM plane angles for the 6 chosen tasks is demonstrated by the different sizes in the graph. The differences (apart from the handle task) in the DTM plane angles (i.e. shape size) display the minor but significant effect (-0.22 and 0.41 for sagittal and coronal angles, respectively), meaning that a 10° change in shoulder angle leads to a -2.2° or 4.1° change in DTM plane angle. As generally the sagittal and coronal angles increased together as the object location became higher, the positive and negative effects tended to cancel out.

TABLE 1. Average and standard deviation of R^2 values of the linear fit of the Dart-Throw Motion (DTM) plane, derived from data of wrist motion in the sagittal versus coronal plane. Values are displayed for each task (N = 40).

Task	R^2
Hammer	0.80 ± 0.18
Card	0.73 ± 0.30
Coin	0.68 ± 0.32
Screwdriver	0.60 ± 0.33
Book	0.55 ± 0.33
Door handle	0.51 ± 0.32
Pouring beans§	0.43 ± 0.29
Button§	0.43 ± 0.30
Bulb§	0.35 ± 0.30

§The R^2 value is below 0.5. This task was therefore discarded.

DISCUSSION

The goal of this study was to compare the DTM plane angles observed while performing ADL tasks at three different heights in a seated position and to examine the relationship between these DTM plane angles and the limb positions. Both height and task had a significant effect on the DTM plane angles, although the effect differed between tasks. In addition, the shoulder sagittal and coronal angles predicted a significant amount of the variance of the DTM plane angles in the wrist.

Difference in DTM Plane Angles Between Heights

The DTM planes angles at the low level height in 3 out of 6 tasks significantly differed from the angles at the mid and high levels (Table 2). There was a great diversity between tasks in this finding, e.g., between the low and mid-levels there was a decrease of DTM plane angle in one task (door), increase in other two tasks (coin and card) and no change in the DTM plane angle for the remaining three tasks (hammer, book and screw). The chosen tasks for this study cover a wide range of common daily upper limb actions. Accordingly, as demonstrated by our previous work, different tasks showed different DTM plane angles (Kaufman-Cohen, et. al., 2018). These differences are inherently caused by the characteristics of these tasks. Four tasks were characterized as an open kinetic chain (OKC) activity (hammer, card, coin and book tasks) and two were considered a closed kinetic chain (CKC) activity (door handle and screw tasks) (Lephart & Henry, 1996). Also, the tasks differed in their kinematics, as well as in kinetic requirements.

TABLE 2. Differences in the mean DTM plane angles at low level, mid level and high levels (N = 40). Values are means ± SEM. Superscripts indicate post-hoc tests show the value is significantly different from: 1= Low level; 2 = Mid-level; 3 = High level.

Task	Low level	Mid level	High level	F-value	P-Value
Hammer	31.8°±3.4	43.5°±2.9	42.3°±6.2	$F(1.26,49.24) = 2.128$	.114
Card	31.0°±3.8^{2,3}	48.8°±2.6^{1}	50.1°±4.6^{1}	$F(1.75,68.18)=10.173$	**<.001**
Coin	26.9°±3.3^{2}	46.4°±3.2^{1}	39.8°±6.4	$F(1.50,58.34)=6.079$	**.008**
Screw	35.1°±5.6	28.5°±5.8	39.9°±5.5	F(2,76)=1.477	.235
Book	30.6°±3.7	31.2°±3.4	28.9°±5.8	$F(1.51,56.03)=0.084$	.869
Door handle	57.0°±2.4^{2,3}	−19.0°±8.1^{1}	−36.7°±3.8^{1}	$F(1.56,60.68)=88.08$	**<.001**

TABLE 3. Averages and standard deviations of all upper right limb range of motion during task performance at three different heights (N = 40).

Task	Joint Height	Wrist range (°)		Elbow range (°)		Shoulder range (°)		
		FE	RUD	FE	Pro-Sup	FE	Abd-Add	Rotation
Hammer	High	19.6 ± 9.4	29.5 ± 10.6	27.9 ± 10.2	12.0 ± 7.9	17.4 ± 8.8	6.6 ± 3.6	21.4 ± 8.6
	Mid	22.6 ± 9.2	23.2 ± 9.7	23.4 ± 8.0	9.9 ± 9.9	16.7 ± 9.3	5.4 ± 2.9	16.4 ± 8.1
	Low	25.2 ± 11.0	18.9 ± 8.7	20.9 ± 9.4	10.4 ± 12.2	11.9 ± 5.0	5.0 ± 2.1	13.2 ± 10.4
Card	High	12.1 ± 7.1	20.8 ± 9.1	48.5 ± 14.7	19.6 ± 13.1	27.1 ± 13.1	14.0 ± 5.8	25.7 ± 11.2
	Mid	13.5 ± 8.5	16.9 ± 9.0	38.4 ± 14.1	16.8 ± 11.7	31.8 ± 14.9	8.1 ± 3.5	21.1 ± 9.3
	Low	11.9 ± 10.0	11.1 ± 8.6	25.1 ± 10.5	12.2 ± 10.8	22.5 ± 9.2	4.8 ± 2.6	12.8 ± 7.7
Coin	High	12.5 ± 7.7	21.2 ± 8.5	31.2 ± 12.0	19.0 ± 32.6	15.8 ± 7.2	7.3 ± 3.4	18.9 ± 6.4
	Mid	13.6 ± 7.6	17.9 ± 8.1	24.6 ± 13.1	11.7 ± 9.0	16.2 ± 9.7	4.1 ± 2.3	13.6 ± 6.5
	Low	22.4 ± 13.1	18.2 ± 12.6	21.3 ± 9.1	12.0 ± 14.3	16.8 ± 8.3	5.1 ± 3.1	11.1 ± 8.8
Screw	High	29.4 ± 15.3	40.5 ± 13.1	39.8 ± 15.2	35.5 ± 35.5	36.9 ± 15.4	12.2 ± 6.1	47.6 ± 27.4
	Mid	30.0 ± 12.2	38.0 ± 13.6	28.2 ± 13.6	29.6 ± 28.9	36.9 ± 16.5	14.6 ± 7.8	38.6 ± 23.0
	Low	26.4 ± 9.5	38.0 ± 13.8	21.2 ± 13.1	31.2 ± 21.8	18.1 ± 9.9	10.8 ± 6.1	27.3 ± 40.5
Book	High	13.5 ± 8.3	17.8 ± 7.7	54.7 ± 18.2	21.5 ± 13.6	23.9 ± 15.4	9.8 ± 4.4	19.5 ± 9.2
	Mid	17.4 ± 10.7	15 ± 7.1	50.5 ± 15.8	19.8 ± 15.0	24.5 ± 12.5	9.9 ± 5.5	14.3 ± 7.3
	Low	16.8 ± 7.7	15.3 ± 7.3	38 ± 13.9	15.6 ± 12.2	15.7 ± 8.5	9.6 ± 4.2	9.9 ± 7.8
Door handle	High	18.3 ± 6.6	25.7 ± 7.7	28.0 ± 11.5	12.2 ± 7.1	22.3 ± 6.8	19.8 ± 7.9	31.5 ± 13.3
	Mid	11.9 ± 3.9	27.1 ± 6.2	23.2 ± 10.6	14.8 ± 11.9	22.5 ± 9.4	18.9 ± 6.1	23.3 ± 11.8
	Low	18.3 ± 8.4	31.4 ± 10.0	28.4 ± 8.5	18.6 ± 8.7	20.2 ± 7.7	13.8 ± 5.1	17.2 ± 8.2

FE = Flexion-Extension; RUD = Radial-Ulnar deviation; Pro-Sup = Pronation-Supination; Abd-Add = Abduction-Adduction.

TABLE 4. Regression coefficients between shoulder and elbow joint angles and the DTM plane angle (*N* = 40).

Parameter	Estimate	t(711) =	p=
Intercept	33.09 ± 10.42	3.17	<0.001
Shoulder.Sagittal	−0.22 ± 0.09	−2.42	**0.02**
Shoulder.Coronal	0.41 ± 0.17	2.41	**0.02**
Shoulder.Transverse	0.13 ± 0.08	1.66	0.10
Elbow. Sagittal	−0.03 ± 0.10	−0.33	0.74
Elbow.Transverse	0.07 ± 0.11	0.66	0.51

In this study, the hammering task was unique in that it was the only task that required both force and precision. The swing phase of hammering included "snapping" of the wrist from radial extension to ulnar flexion to generate high driving forces (Leventhal, Moore, Akelman, Wolfe, & Crisco, 2010). Hammering is known as the gold standard representation of many occupational activities involving the DTM arc of motion (Garcia-Elias et al., 2014; Garg et al., 2014; Kaufman-Cohen, et.al., 2018; Lees, 2013; Leventhal et al., 2010; Moritomo, et. al., 2014; Palmer et. al., 1985; Rohde et al., 2010). Our study strengthened this convention, as we found high R^2 (0.8) calculated in this task compared to other tasks' R^2s, i.e. most of the motion occurred in the DTM plane. Additionally, compared to the other tasks in this study, hammering required rotational manipulation of an object that has high inertial torque in order to produce force (Schoenmarklin & Marras, 1989). The need to produce high force with high precision might explain the constrained pattern of wrist movement of the subjects, regardless of the height of the object.

The two tasks that required precise manipulation of small objects without the need for high force were the card and coin tasks. The wrist movement in both tasks mostly remained in the DTM plane, i.e., having high R^2 valves (Table 1). In both these tasks, the DTM plane angle was higher in mid-level compared with the low level (Table 2). This might be explained by the high demands for accuracy of the end effector in these two tasks. The accuracy was optimally controlled by the distal joint, i.e. the wrist, so that different wrist angles were applied at different heights. It was formerly shown that precise control of the wrist is important for achieving accuracy (Koshland, Galloway, & Nevoret-Bell, 2000). Aside from the difference in DTM angles, it seems that at the low level, the sagittal ROM of the wrist was higher for the coin task. This might be explained by the positioning of the objects. The card slot was positioned in a 45° angle to the right of the body center line of the subjects, while the coin slot was positioned directly in front of the subject. Tilting of the card slot to this angle

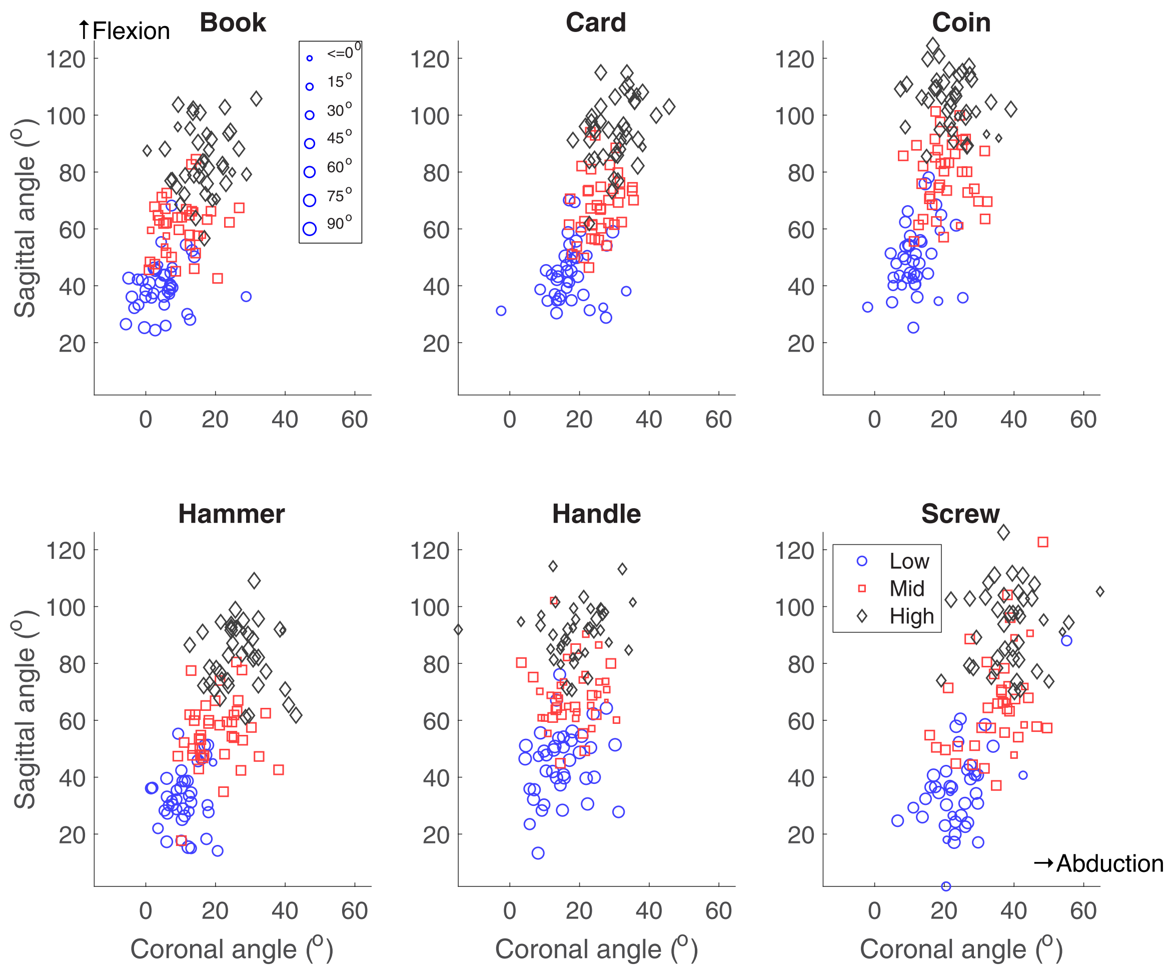

FIGURE 3. The relationships between the mean Dart Throw Motion (DTM) plane angles and the shoulder angles in the sagittal and coronal planes for the 6 chosen tasks. Data are shown for all subjects (N = 40). The color/shape indicates the height of the object, while the size of the object indicates the DTM angle.

may have enabled a more natural positioning of the subjects, i.e., a positioning which they would have chosen themselves when performing the task outside of the laboratory settings. Consequently, the entire upper limb, starting with the shoulder, flexed and abducted in the scapular plane, resulted in smaller FE movement of the wrist.

The final three tasks of pushing down a door handle, taking a book off a shelf, and using a screwdriver, require force with minimal precision. Compared to the tasks of hammering, inserting a coin and sliding a card, these three tasks were more out-of-plane, as shown by a lower R^2 (Table 1). Also, there were no differences in the DTM plane angles between heights while taking a book off a shelf. This task was mainly controlled by FE of the elbow. Therefore, we do not expect variation in the wrist pattern while performing this task in the different heights. On the other hand, the other two tasks (door handle and screwdriver) were CKC tasks, so they involved greater wrist movements, and less elbow movement. In the door handle task, significant differences in the DTM plane angle between heights were observed, although not for the screwdriver task. We assume that the negative DTM plane angle, found in some of the trials, mostly in the mid and high-level heights, resulted from the position of the door handle, which was not rotated to 45° as for the screwdriver task. This position of the door handle produced constrained elbow movement, so that the handle was mostly manipulated by the shoulder and wrist. Negative DTM plane angles were registered in a previous study mostly during bimanual tasks, performed when each hand constrained the other, as in a CKC task, leading to a controlled form of object manipulation, as for the door handle task (Kaufman-Cohen, et. al., 2018). These insights could be applicable for both kinds of ADLs trained in the clinic after wrist injuries: Basic ADLs, especially self-care tasks, and instrumental ADLs including heavy weights or handling larger instruments. Self-care daily activities such as grooming activities are usually performed closer to the body, with minimal force but require dynamic fine motor coordination (such as buttoning a shirt or washing one's face). According to these outcomes, we should expect larger DTM plane angles for basic ADLs (depending on arm position, height and task characteristics). On the other hand, instrumental activities could be performed at changing heights, through further trajectories from the body and with heavier instruments. These might require more static, proximal upper extremity force and grip strength in order to stabilize the object, usually with minimal precision. In the discussed cases, smaller DTM plane angles are to be expected at the wrist.

Our results concerning the first hypothesis highlight the variability of the measured DTM plane angles, not just between different ADLs, but also for the same ADL, under different height conditions. Consequently, the rationale for exercising an injured wrist mainly in the sagittal plane, as is performed today in most clinics, is disputed. We use complex wrist manipulation to perform various tasks under various conditions. We therefore believe that the return to healthy and functional wrist activities following injury should not be confined to one plane of motion. In summary, performing daily tasks at different heights has an impact on the DTM plane angles of the wrist. Both height and task influenced the DTM plane angles in diverse functional tasks, although this influence was different between tasks. These findings support the importance of training daily tasks at different heights during the rehabilitation following injury of the wrist.

Prediction of DTM Plane Angles by Limb Posture

Sagittal and coronal shoulder angles predicted a significant amount of the DTM plane angles in the wrist (Table 4). A change in shoulder angle (greater extension or abduction) led to a greater DTM angle (on average). Due to the opposite effects of shoulder flexion and abduction on the DTM plane angle, these tend to cancel each other out during real time task performance, as most tasks showed an increase of flexion and abduction as the height changed. Thus, not much change in the DTM plane angles of the wrist was observed. The graphs presented in Figure 3 support this effect of the shoulder position (in the sagittal and coronal planes) on the mean DTM plane angles. For the door handle task it is noticeable that most of the DTM plane angles for the higher level were lesser then those observed for mid and low levels (as discussed for the results of the first hypothesis) – this is likely because of the limited coronal plane range of motion for this task.

The particular end postures of the shoulder in the sagittal and coronal planes resulted in different DTM planes, whereas rotational movements in the shoulder and elbow postures did not predict the DTM plane angle, when examined on a subject-by-subject basis. This finding is similar to the observations of a Donders' like law for the arm, which finds that the internal-external rotation of the arm can be predicted based on the sagittal and coronal angles (Liebermann et al., 2006). Ewart et al. (2016) hypothesized that reaching to grasp and lift a cylinder from different starting locations would demonstrate low variability in final arm posture, because the hand orientation required grasping the object in a particular way so should be adjusted to it. In this study, both task requirements and object location dictated the arm posture at its end point. When the object was positioned at the high level, the shoulder joint flexed to reach it and as result, in general, less DTM plane angle was observed. Conversely, when extending the arm position towards a task closer to the body, this endpoint could enable, in general, a larger DTM plane angle. However, unlike the aforementioned Donder's law for the arm, the task to be performed also has a large impact on the DTM angle selected, and not only the shoulder posture.

To summarize this section, a general tendency of elevating the shoulder to an end position of flexion or flexion and adduction predicted a reduction in DTM plane angle. An inferior end position in the shoulder joint, as well as extending and/or extending and abducting the shoulder, resulted in a greater DTM plane angle in the wrist. These findings support the conclusions of the previous hypothesis for height differences.

Limitations

This study had some limitations. First, we must note that all of our subjects were novices at using working tools such as the hammer and screwdriver: none of them had worked at jobs or had hobbies involving considerable use of the hammer or screwdriver. This likely explains the task performance variation among subjects. It is possible that the DTM plane angle motion for more experienced labor workers would differ from what we reported. Moreover, we controlled how tasks were to be performed by the constraints of the mechanism, but some variation in motion requirements was expected. Similarly, the measurement approach, including the precise location of the markers, marker occlusion (especially as for the medial epicondyle marker of the elbow), and incorrect tracking of markers can contribute to measurement error. We expected these to be random measurement errors (i.e., not biased). To reduce these errors, we used reflective markers and manual correction of tracking where these were poorly captured and automatic tracking was lost. Moreover, the experiment setup was likely to fix the position of the subject to perform tasks that typically allow flexibility in how they are performed, e.g. changing the start position.

Second, our study participants were relatively young (22.3 years old; SD ± 2.3) and had no upper limb pathology. The study outcomes may not apply to individuals outside this age or physical health range; however, the primary objective of this study was to compare the DTM plane angles while performing different tasks at different heights, and the relationship between the DTM plane angles and the angles of the shoulder and elbow while performing different tasks in a seated position. The study findings provide a baseline and inform future studies that might include expanding research also to calculating the impact of gravity and muscular activity while performing the tasks such as when hammering or opening a door. Placing markers on the task objects and analyzing their manipulated usage could possibly shed light on these results as well.

CONCLUSIONS

This study analyzed DTM plane angles performed at different heights and examined the relationships between the DTM plane angles and the limb position, while performing different ADL tasks. Differences in the DTM plane angles were significant across task performance in different heights and the shoulder posture predicted a significant amount of the variance of the DTM plane angles in the wrist. The use of activities of daily living to investigate upper limbs kinematics provides a more detailed and real picture of the subject's capabilities. The clinical application of these findings can highlight the importance of training daily tasks at different heights while taking into to account the effect of the shoulder postures on the DTM angle in the wrist during rehabilitation period after injured wrist.

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