Importance of Wrist Movement Direction in Performing Activities of Daily Living Efficiently

Nicholas Moser, Marcia K. O'Malley, and Andrew Erwin

Abstract— **The wrist is an essential component in performing the activities of daily living (ADLs) associated with a high quality of life. After a neurological disorder, motor function of the hand and wrist can be affected, reducing quality of life. Many experiments have illustrated that more wrist flexion/extension is required than radial/ulnar deviation when performing ADLs; however, how this result translates to efficiency in performing ADLs has not been investigated. Motivated by clinical assessment during neurorehabilitation, in this paper we investigate with able-bodied participants how performing tasks representative of the Jebsen-Taylor Hand Function Test are impacted when a splint constrains the user to a single rotational degree of freedom of the wrist. Twenty participants enrolled in the study, performing five tasks under five conditions, including constraint to pure flexion/extension and radial/ulnar deviation. The importance of wrist movement direction in performing ADLs efficiently found in this study could shape clinical wrist rehabilitation paradigms and wrist rehabilitation robot designs.**

I. Introduction

Neurological disorders such as stroke and spinal cord injury (SCI) can have devastating social and economic impacts on an individual. A common outcome of a neurological disorder is loss of motor function leading to lower quality of life through loss of independent care [1], [2]. In the United States alone, 795,000 individuals suffer a stroke [3] and 12,000 suffer an SCI annually [4]. The financial burdens associated with these injuries is immense, with the costs associated with stroke exceeding $30 billion [3] and the costs of SCI exceeding $10 billion [5]. A component of these costs is the high-intensity rehabilitation required after injury to promote recovery of reduced motor function [3], [4].

To assist in performing the high-intensity rehabilitation required after neurological injury, robots that can measure and assist the patient's movements have been created [6], [7]. It is generally accepted that task-specific training is a critical component for recovery [8], [9]; however, designing devices for task-specific training can be challenging since task-specific movements generally require many degrees of freedom (DOF). Since the cost and design of a robot are directly related to the number of degrees of freedom, it would be beneficial to be able to perform task-specific training while limiting controlled DOFs.

The wrist is a candidate joint for reducing the DOFs during robotic design and rehabilitation while still maintaining task-specific training. Most wrist rehabilitation robots focus on the two largest movements of the wrist, i.e., flexion/extension (FE) and radial/ulnar deviation (RUD) [10], [11]; however, creating these wrist robots is nontrivial since the axes of these two rotational movements are modeled as intersecting.

Although the wrist is typically modeled as two rotational movements with intersecting axes, some studies state that the most functional wrist movement direction is along the axis of the dart thrower's motion (DTM), an oblique motion from radial/extension to ulnar/flexion [12]. Determining the importance of wrist movement direction could have important implications for therapy. If task-specific training can be accomplished with only one rotational DOF of the wrist, robotic design complexity could be decreased and task-specific rehabilitation intensity increased.

In this study, the impact of limiting movements of the wrist during ADLs through the custom-made splint shown in Fig. 1 is investigated. We quantify the reduction in function that would be realized if an individual only experienced recovery of movement along a single wrist movement direction, possibly as a result of single DOF rehabilitation, using four tasks inspired by the Jebsen-Taylor Hand Function Test (JTHFT) and one representative ADL. The JTHFT is a clinical test administered throughout rehabilitation after neurological injury [13]. This test assesses the performance of hand function in performing representative ADLs, consisting of tasks such as writing, card flipping, and moving objects. The tests are timed with a stopwatch, and improvements are associated with decreased completion time. In this work, we recruited able-bodied participants to perform tasks inspired

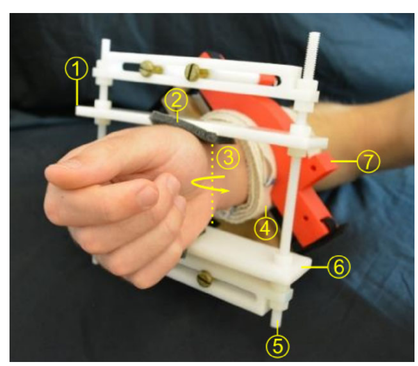

Fig. 1. Custom-designed and prototyped wrist splint designed for the experiment that can be rotated to constrain the user to any rotational direction of the wrist. 1) Top pressure bar for constraint, 2) foam padding for comfort, 3) FE rotational DOF allowed in shown splint condition, 4) compression wrap for donning the splint, 5) threaded rod for controlling pressure bars, 6) bottom pressure bar, and 7) base attachment to the forearm.

This work was supported in part by the National Science Foundation Graduate Research Fellowship Program under grant number 1450681. This work was carried out at the Mechatronics and Haptic Interfaces Laboratory, Department of Mechanical Engineering, Rice University, Houston, TX 77005. Corresponding author: omalleym@rice.edu.

978-1-7281-1990-8/20/$31.00 ©2020 IEEE

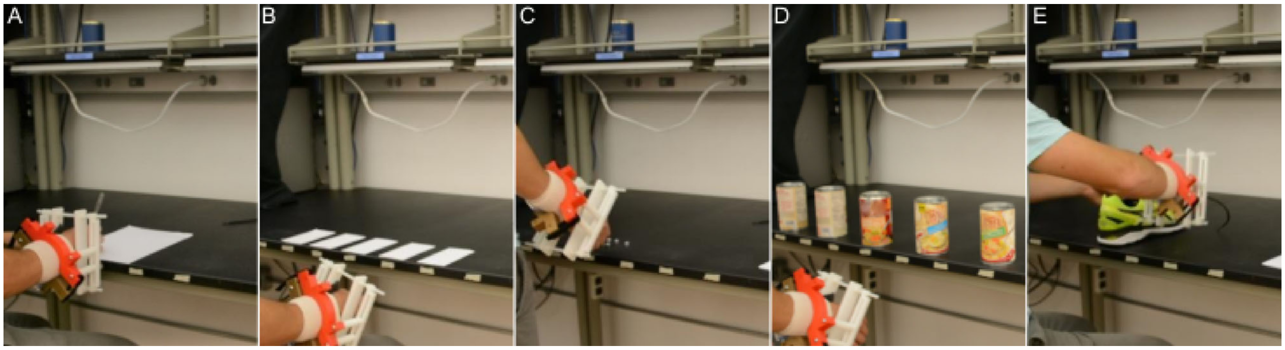

Fig. 2. A user wore the wrist splint while performing all five tasks presented in the experiment. A) Writing a sentence, B) flipping over light objects (cards), C) moving light objects (mechanical nuts) to a shelf, D) flipping over heavy objects (cans), and E) tying a shoe with a double knot.

by the JTHFT to test the possibility that tasks are completed less efficiently when constrained to RUD.

II. Materials and Methods

Participants were asked to perform five tasks under five different conditions of wrist constraint. Wrist constraint was accomplished through the use of the custom wrist splint shown in Fig. 1, which partially restricted normal wrist motion through two pressure bars. The time taken to perform each task was recorded with a 10 ms resolution stopwatch, and the same experimenter administered all experiments.

A. Participants

Twenty individuals (15 male, 5 female) with an age range of 20-31 years, mean of 23 years, and standard deviation of 3.0 years participated in the experiment. All participants were right-hand dominant. Note that 21 participants had to be recruited since one was unable to complete the experiment. Approval for the experiment was obtained through the appropriate institutional review board.

B. Wrist Splint

The objective in the splint design was to be able to easily adjust the constrained wrist axis for a variety of wrist sizes and to minimize its weight. The splint consists of two forearm mounts 3D printed from acrylonitrile butadiene styrene (ABS) plastic, as well as two pressure bars, two slotted bars, and four connecting rods machined from Delrin.

To don the splint, the experimenter would wrap the participant's right forearm with compression wrap, then securely, but comfortably, fasten the two mounts to either side of the forearm using Velcro. The experimenter would then position the pressure bars, with foam between the Delrin and skin for user comfort, to provide pressure against the participant's hand at a point 1-2 cm distal of the wrist joint. Thus positioned, the pressure bars create a channel that limits the wearer's hand motion to the plane of motion defined by this channel. The user can freely rotate their wrist such that the hand moves parallel between the pressure bars, but any other wrist motion would be constrained by the pressure bars.

While hand maneuverability outside of the channel decreases the closer the bars are to the hand, completely removing motion outside of the channel would be excessively uncomfortable for the user. As a result, the splint only partially constrains motion out of the channel while applying a comfortable amount of pressure. A maximum bound on the amount of play possible with the splint is 35° in FE when constrained to RUD and 25° in RUD when constrained to FE. Note that the user would still experience resistance when attempting to move in the restricted direction, so the only truly free direction is the one set by the channel.

C. Experimental Procedure

The experimental procedure consisted of the participant performing five tasks in each of five constraint conditions. One of the constraint conditions was to perform the experiment without any restraint to evaluate the impact of wearing the splint on performance, while in the other four constraint conditions, the participant wore the custom wrist splint. To help familiarize themselves with the splint prior to each of the four splint conditions, the participant spent approximately one minute performing a representative task. The practice session was followed by the five tasks, each of which was performed twice. After completing the tasks, the experiment proceeded to the next condition. For each participant, the order of the tasks and conditions was randomized to balance any learning effects. Completion of the entire experiment took approximately 40 minutes.

1) Tasks: Participants performed a series of five different tasks illustrated in Fig. 2 and described below. Four of the tasks were inspired by the JTHFT, while the fifth (tying a shoe) was selected as an ADL.

- Writing a Sentence: The participant was presented with a sentence and asked to write the sentence as quickly and legibly as possible on a piece of paper using his or her dominant hand. Participants were seated in a standardized position that limited the impact of the splint's bulk, and no instruction was given to participants on whether to use print or cursive.
- Flipping over Light Objects: Five index cards were laid out in a row on the table in front of the participant. The participant was asked to flip over each card as quickly as possible using only their dominant hand.

- Moving Objects to a Shelf: Five metal nuts were placed close together on the table in front of the participant. The participant was asked to, using only their dominant hand, move the nuts one at a time into a small cup on a shelf above their head as quickly as possible.
- Flipping over Heavy Objects: Five full soup cans were placed in a row on the table in front of the participant. The participant was asked to flip over each can as quickly as possible using only their dominant hand.
- Tying a Shoe: A shoe was placed on the table in front of the participant. The participant was asked to tie the shoe as quickly as possible using a double knot.

2) Conditions: The participants performed each of the above tasks under the five different constraint conditions described below. In all splint conditions, the participant wore the splint on his or her dominant hand.

- Free (FR): The participant did not wear the splint, but still wore the compression wrap.
- No Constraint (NC): The participant wore the splint with the bars applying no pressure and positioned away from the hand so that full wrist ROM was possible without making contact with the splint.
- FE: The participant wore the splint in a configuration to constrain motion to FE.
- Linear Combination (LC): The participant wore the splint in a configuration to constrain motion to approximately midway between FE and RUD so that the wrist could only freely move from extension and radial deviation to flexion and ulnar deviation.
- RUD: The participant wore the splint in a configuration to constrain motion to RUD.

D. Data Analysis

Participants performed each task for a given condition twice (one after the other), and the fastest time of the two was used for subsequent analysis. This method reduced the likelihood of outliers as a result of an unrepresentative trial, while not fatiguing the participant due to excessive trials. The primary measure of performance in this study was the execution time between participants for a given task and total experiment time across splint conditions.

Since the FR condition was included only to quantify the impact of the splint compared with being completely free, for the primary statistical analyses, only the NC, FE, RUD, and LC conditions were compared. Since all participants performed each condition, a repeated measure analysis of variance (ANOVA) was used to evaluate if there was a significant difference in task completion times across the four splint conditions for a given task using a threshold of $\alpha = 0.05$ for statistical significance. For significant effects found in the repeated measure ANOVAs, post-hoc pairwise comparisons with Bonferroni corrections were performed to determine statistically significant differences in means between conditions for a given task. Additionally, to determine if the splint weight and shape impacted performance between the two baseline conditions, t-tests were performed between FR and NC for the five tasks and completion time.

III. Results

Mean completion time for all tasks and conditions is shown in a bar plot in Fig. 3. A repeated measure ANOVA of the mean completion time for all tasks across the splint conditions showed statistically significant differences as shown in Table I. Post-hoc pairwise comparisons with Bonferroni corrections were performed for all tasks across a given condition. The impact of the splint on free motion was evaluated by comparing FR and NC for all tasks and total experiment time through t-tests with Bonferroni corrections.

Significant effects were found in writing a sentence between NC and LC ($p < 0.03$); moving objects to a shelf between NC and LC ($p = 0.04$); flipping over cans between FE and RUD ($p < 0.01$) as well as NC and RUD ($p < 0.02$); and total experiment time between FE and RUD ($p < 0.02$), NC and LC ($p < 0.03$), and NC and RUD ($p < 0.01$). For the case of total experiment time, the mean values were 36.8, 39.0, 40.5, and 41.5 s for NC, FE, LC, and RUD respectively. Additionally, other than the pairwise comparison with tying a shoe (not significant), the other five comparisons between FR and NC were significant with $p < 0.01$.

IV. Discussion

Statistically significant differences ($p < 0.05$) were found between NC and LC (sentence, shelf, and total experiment time), NC and RUD (cans and total experiment time), and FE and RUD (cans and total experiment time). When constrained to movements in the FE direction, users performed all of the tasks more quickly than when constrained to only movements in LC and RUD. The results from this work on wrist performance as a measure of wrist function with respect to wrist motion axis provides complimentary support to the literature on wrist ROM during ADLs, suggesting that RUD might be less functional than wrist FE or the DTM. It is worth noting that FR compared with NC was statistically different for all comparisons except for tying a shoe, indicating that in general wearing the splint affected user performance, and so in the future the splint design should be improved to reduce its impact in the NC condition.

Prior to the experiment, we suspected that motions for LC would be similar if not faster than in FE given its relative similarity to the DTM. In the functional tasks studied here, we did not observe any statistically significant differences between the FE and LC conditions. It should be noted that the DTM plane resides approximately 20-45° from pure FE [14], in contrast to the approximately 45° used in this study. However, recent studies have shown that the wrist appears to use a variety of DTM planes for different ADLs, and so the 45° in this work has some merit [15], [16]. Additionally, over 5 experimental tasks, the mean difference

TABLE I
Repeated Measures ANOVA between NC, FE, LC, and RUD

	Sentence	Cards	Shelf	Cans	Shoe	Total
$F(3,57)$	4.85	3.15	4.35	8.64	3.17	8.24
p	.0045*	.03*	.0079*	.00008*	.03*	.00012*

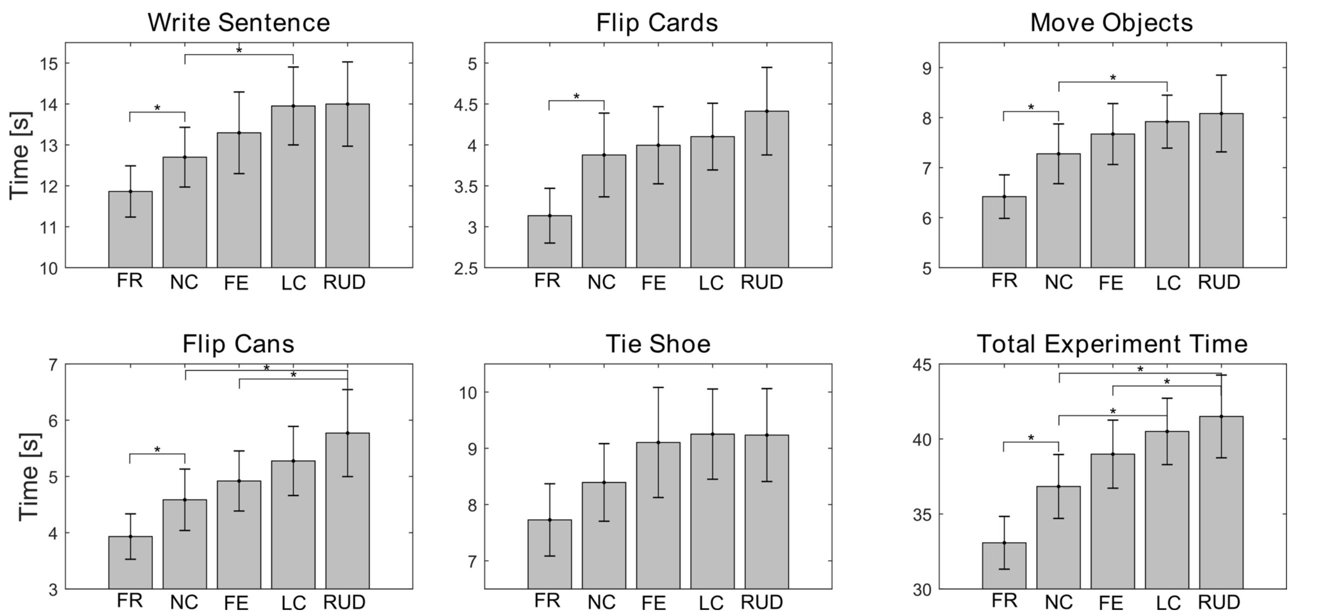

Fig. 3. Bar plot of mean completion time over all participants for a given task under all conditions (FR: free, NC: no constraint, FE: wrist flexion/extension, LC: linear combination of FE and RUD in the direction of the DTM, and RUD: wrist radial/ulnar deviation). Total experiment time is the sum of the five tasks for a given condition. Note that each bar represents 20 data points—one for each of the 20 participants who performed the experiment. The error bars in the plot represent the 95% confidence intervals. Pairwise comparisons with Bonferroni corrections were performed between the NC, FE, RUD, and LC conditions, as well as between FR and NC. Statistical significance of a pairwise comparison is indicated by *.

in time for 20 participants between FE and LC was only 1.5 s (3.8% difference) and between FE and RUD was 2.5 s (6.2% difference). While the comparison of FE and RUD was statistically significant, further research is needed to determine the clinical relevance of this difference in time.

This work has presented evidence to suggest that when partially constrained to a single wrist movement direction, performance by able-bodied individuals differed in a few representative functional tasks from the JTHFT and an actual ADL. Constraining the user to move in RUD or LC resulted in slower performance than when constrained to FE. These results indicate that when performing a variety of representative tasks with the hand and wrist, movement direction might impact efficiency in completing the task. In this experiment, it was found that being constrained to FE still allowed comparable performance of the tasks relative to not being constrained, and was significantly faster than being constrained to RUD. Thus, we have further quantified what aspects of wrist kinematics are important in completing daily tasks. By furthering our understanding on how the wrist functions, clinicians can be better informed while determining rehabilitation strategies after neurological injury.

REFERENCES

[1] G. J. Snoek, M. J. IJzerman, H. J. Hermens, D. Maxwell, and F. Biering-Sorensen, "Survey of the needs of patients with spinal cord injury: Impact and priority for improvement in hand function in tetraplegics," *Spinal Cord*, vol. 42, no. 9, pp. 526–532, 2004.

[2] G. Kwakkel, B. J. Kollen, and H. I. Krebs, "Effects of robot-assisted therapy on upper limb recovery after stroke: A systematic review," *Neurorehab. Neural Repair*, vol. 22, no. 2, pp. 111–121, 2008.

[3] D. Mozaffarian, *et al.*, "Heart disease and stroke statistics–2016 update: A report from the American Heart Association," *Circulation*, vol. 133, no. 4, pp. 1–324, 2016.

[4] "Spinal cord injury (SCI) facts and figures at a glance," National Spinal Cord Injury Statistical Center, 2016.

[5] M. Berkowitz, *Spinal cord injury: An analysis of medical and social costs*. Demos Med. Pub., 1998.

[6] H. I. Krebs, N. Hogan, M. L. Aisen, and B. T. Volpe, "Robot-aided neurorehabilitation," *IEEE Trans. Rehab. Eng.*, vol. 6, pp. 75–87, 1998.

[7] A. Gupta, M. K. O'Malley, V. Patoglu, and C. Burgar, "Design, control and performance of RiceWrist: A force feedback wrist exoskeleton for rehabilitation and training," *Int. J. Robot. Res.*, vol. 27, no. 2, pp. 233–251, 2008.

[8] R. J. Nudo, B. M. Wise, F. SiFuentes, and G. W. Milliken, "Neural substrates for the effects of rehabilitative training on motor recovery after ischemic infarct," *Sci.*, vol. 272, no. 5269, pp. 1791–1794, 1996.

[9] N. A. Bayona, J. Bitensky, K. Salter, and R. Teasell, "The role of task-specific training in rehabilitation therapies," *Top. Stroke Rehab.*, vol. 12, no. 3, pp. 58–65, 2015.

[10] H. I. Krebs, *et al.*, "Robot-aided neurorehabilitation: A robot for wrist rehabilitation," *IEEE Trans. Neural Syst. Rehab. Eng.*, vol. 15, no. 3, pp. 327–335, 2007.

[11] V. Squeri, L. Masia, P. Giannoni, G. Sandini, and P. Morasso, "Wrist rehabilitation in chronic stroke patients by means of adaptive, progressive robot-aided therapy," *IEEE Trans. Neural Syst. Rehab. Eng.*, vol. 22, no. 2, pp. 312–325, 2014.

[12] H. Moritomo, E. P. Apergis, G. Herzberg, F. W. Werner, S. W. Wolfe, and M. Garcia-Elias, "2007 IFSSH committee report of wrist biomechanics committee: Biomechanics of the so-called dart-throwing motion of the wrist," *J. Hand Surg.*, vol. 32, no. 9, pp. 1447–1453, 2007.

[13] R. H. Jebsen, "An objective and standardized test of hand function," *Arch. Phys. Med. Rehabil.*, vol. 50, pp. 311–319, 1969.

[14] A. L. Pando, H. Lee, W. B. Drake, N. Hogan, and S. K. Charles, "Position-dependent characterization of passive wrist stiffness," *IEEE Trans. Biomed. Eng.*, vol. 61, no. 8, pp. 2235–2244, 2014.

[15] R. Garg, *et al.*, "Wrist kinematic coupling and performance during functional tasks: Effects of constrained motion," *J. Hand Surg.*, vol. 39, no. 4, pp. 634–642, 2014.

[16] Y. Kaufman-Cohen, J. Friedman, Y. Levanon, G. Jacobi, N. Doron, and S. Portnoy, "Wrist plane of motion and range during daily activities," *Am. J. Occup. Ther.*, vol. 72, no. 6, pp. 7 206 205 080p1–7 206 205 080p10, 2018.