Article:
Zhang, M, McDaid, A, Zhang, S et al. (2 more authors) (2019) Automated robot-assisted assessment for wrist active ranges of motion. Medical Engineering and Physics, 71. pp. 98-101. ISSN 1350-4533

https://doi.org/10.1016/j.medengphy.2019.07.003

Automated robot-assisted assessment for wrist active ranges of motion

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Abstract

The measurement of wrist active range of motion (ROM) is essential for determining the progress of hand functional recovery, which can provide insight into quantitative improvements and enable effective monitoring during hand rehabilitation. Compared with manual methods, which depend on therapists' experiences, the proposed robot-assisted assessment technique can measure active ROM of human wrists. The robot with a reconfigurable handle design allows for multiple wrist motions. Experiments were conducted with 11 human subjects to measure ROMs of human wrist flexion/extension and radial/ulnar deviation. Reliability analysis was conducted by calculating the intra-class correlation coefficients (ICC), standard error of measurement (SEM) and SEM%. Results showed high reliability ($ICC_{2,1} \geq 0.89$, SEM≤2.36°, SEM%≤6.81%). Future work will be focused on adaptive joint self-alignment design between human users and robots to further improve its assessment accuracy.

Keywords: Robot-assisted, assessment, wrist, active range of motion, admittance

NOMENCLATURE

ROM	Range of motion
ICC	Intraclass correlation coefficient
SEM	Standard error of measurement
F/E	Flexion/extension
RD/UD	Radial/ulnar deviation
SD	Standard deviation
SRD	Smallest real difference

1. Introduction

Examining joint range of motion (ROM) is part of the musculoskeletal functional assessment, and active ROM of human joints refers to their maximum voluntary movement without any external assistance [1, 2]. The measurement of human wrist active ROM is crucial in evaluating upper extremity functional recovery [2, 3]. Lang and Beebe [4] concluded that wrist active ROM is crucial to hand function through trails on people with chronic hemiparesis post stroke. Clinical data from stroke patients also support the use of wrist active ROM information in predicting upper extremity functions [5].

Conventional measurement techniques of human joint ROM generally involve the use of goniometry, which are carried out by raters manually [2, 6]. While the goniometric measurement of wrist active ROM has been clinically used in diagnosis [7], this kind of methods requires much labour from physical therapists. Furthermore, it cannot be combined with robot-assisted environments due to the lack of real-time measurements. The other concern of rater-dependent assessment techniques is the subjectivity, which can be accounted by that intra-rater reliability is higher than inter-rater reliability [7].

This study examines a new robot-assisted assessment technique for measuring active ROM of human wrists to reduce intra-inter-rater variability of manual methods. This is an extended work based on one of our previous studies where predefined interaction torque was used to automate passive ROM assessment of human wrists [8]. This study used an interaction control strategy based on the admittance control law, enabling the active ROM measurement of human wrists. Experiments were carried out in measuring wrist flexion/extension (F/E) and radial/ulnar deviation (RD/UD) with statistical reliability analysis on 11 human subjects.

2. Methods

2.1 Participants

Eleven healthy human subjects volunteered to participate in this study with ethical approval from the University of Auckland, Human Participants Ethics Committee (019707). Participants include six males with age 26.17±4.22 years, height 173.83±7.28 cm, weight 79.83±10.03 kg, and five females with age 26.40±5.98 years, height 164.20±3.49 cm, weight 55.30±5.72 kg. It should be noted that these data are described in the form of means and standard deviations (SDs), and the participants are same as those in [8].

2.2 Wrist robot and control strategy

The proposed measurement technique of human wrist active ROM mainly involves an admittance-based interaction control strategy implemented with the wrist robot, as illustrated by Figure 1. The robotic system can be reconfigured for wrist F/E, RD/UD and others by rotating the handle holder to certain positions, which has been previously reported as well as its mechanical and electrical design [8]. Wrist F/E is allowed by setting 0° of the handle (horizontal), and wrist RD/UD by adjusting the handle to 90° (vertical), as shown in Figure 1.

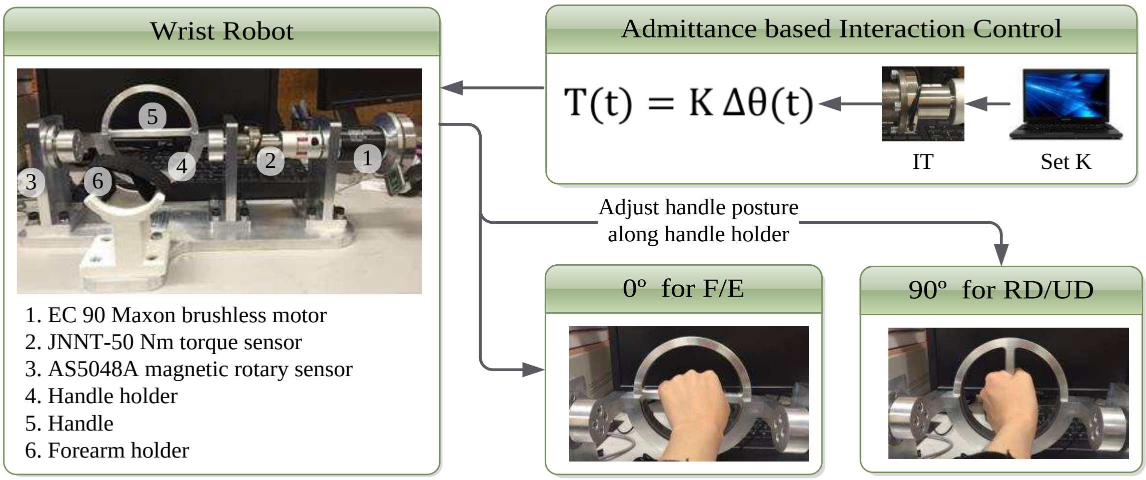

Figure 1. The wrist robot with an interaction control strategy based on the admittance law. (IT: Interaction torque, K: Control stiffness)

The proposed control strategy allows the robot's movements to be directed by real-time human-robot interaction based on an admittance law [9]. This law is presented in Equation (1), where $\theta_r(t)$ and $\theta_d(t)$ represent the reference trajectory and the desired trajectory, respectively, and $T(t)$ refers to human-robot interaction torque, parameters M, B and K respectively represent the inertia, damping, and stiffness coefficients of the robotic system. In this study, M and B are assumed to be zero due to the low-velocity movement environment. The reference trajectory $\theta_r(t)$ is considered as the robot's current position, hence a simplified control law can be derived as in Equation (2), where K represents the difficulty or resistance level of actively driving the robotic handle, and $\Delta\theta$ is the angle that the robot moves in a control loop. In this mode, the wrist robot deviates from its current position in the presence of real-time human-robot interaction but is otherwise stationary. To facilitate direct speed control of the robot, Equation (3) is obtained, where $k=K\Delta t$ and Δt is the time period of the control loop. In brief, human users can actively drive the robotic handle with different resistance levels controlled by parameters K or k.

$$T(t) = M(\ddot{\theta_d}(t) - \ddot{\theta_r}(t)) + B(\dot{\theta_d}(t) - \dot{\theta_r}(t)) + K(\theta_d(t) - \theta_r(t)) \quad (1)$$

$$T(t) = K\,\Delta\theta(t) \quad (2)$$

$$T(t) = kV(t) \quad (3)$$

2.3 Protocols and statistics

All participants were instructed to sit on a height-adjustable chair with their forearms strapped on the forearm holder and hands grasping the handle, as illustrated by Figure 1. The handle arm was determined and prototyped based on hand sizes of selected participants. For each participant, his or her wrist joint was visually adjusted to approximate the rotational axis of the robot. For the admittance control law, the coefficient k is set at 0.05 Nm*second/° with the time period Δt being 0.02 second, which was determined based on participants' feedback during the pilot trials.

There are two measures for test-retest reliability: wrist F/E test (0°) and wrist RD/UD test (90°). For each measure, each participant was required to conduct a three-minute warming up wrist exercise and followed by 12 cycles of maximum voluntary movement. During the whole process, participants were verbally encouraged to relax and drive the robotic handle stably. Data of wrist active ROM were collected from the magnetic rotary sensor. The intraclass correlation coefficient ($ICC_{2,1}$), standard error of measurement (SEM) and smallest real difference (SRD) with 95% confidence interval were analysed to examine the test-retest reliability, as in Equation (4) and (5). More specifically, each participant conducted 12 cycles of active assessment movements for each measure. To minimize the effects from random factors, such as external disturbances, each set of data finally includes 10 elements by removing the maximum and minimum values.

$$SEM = SD\sqrt{1 - ICC} \quad (4)$$

$$SRD = SEM * 1.96 * \sqrt{2} \quad (5)$$

3. Results

Table 1 presents the raw data from each participant. To facilitate data analysis in SPSS, Table 2 presents the means and SDs of measurements over all participants for each measure and each cycle. Table 3 summarizes the statistical results of the test-retest reliability of the two measures (wrist F/E test and wrist RD/UD test), where $ICC_{2,1}$ values are no less than 0.891 and SEM values are no greater than 2.36°. By using Munro's correlation description [10], the proposed robot-assisted assessment technique has a high reliability for measuring wrist active ROM. Other statistical parameters of SEM% and SRD% are also provided in Table 3.

Table 1. Means and SDs of measurements for each participant.

Particpant No.	F/E Test		RD/UD Test	
	E (°)	F (°)	RD (°)	UD (°)
1	49.62±2.27	-65.13±2.41	31.23±1.84	-53.07±2.11
2	46.46±1.64	--66.53±2.14	24.55±1.17	-45.70±2.22
3	39.53±1.29	-69.83±0.88	27.08±0.87	-63.52±1.26
4	31.04±1.05	-44.67±1.45	20.26±0.57	-38.27±1.22
5	42.52±4.74	-51.51±2.33	15.65±0.86	-41.61±1.71
6	38.87±1.98	-50.09±2.59	29.75±1.07	-42.65±2.15
7	47.26±3.60	-81.59±3.11	41.05±3.55	-70.24±2.28
8	40.50±1.91	-62.66±2.63	24.90±2.28	-43.54±1.93
9	40.41±1.50	-60.69±3.50	20.91±1.56	-39.88±1.90
10	36.95±1.75	-69.79±1.51	21.06±0.72	-48.70±0.57
11	26.31±1.97	-64.47±1.15	17.06±1.79	-45.16±1.00

Table 2. Means and SDs of measurements over all participants.

Cycle No.	F/E Test		RD/UD Test	
	E (°)	F (°)	RD (°)	UD (°)
1	40.70±7.08	-62.99±11.54	24.69±6.66	-48.61±9.80
2	40.53±7.49	-63.13±11.44	24.82±6.65	-47.50±9.66
3	40.32±8.57	-61.82±10.54	24.38±6.94	-47.74±10.25
4	39.09±5.84	-62.20±10.24	24.28±7.41	-47.99±9.64
5	40.96±9.05	-62.94±9.09	25.94±8.44	-48.25±9.81
6	40.29±6.46	-62.04±10.75	24.77±8.04	-48.45±9.65
7	39.70±6.95	-62.09±9.76	24.84±8.12	-48.40±10.63
8	39.42±7.33	-62.71±10.93	25.21±8.34	-48.80±10.76
9	39.09±5.57	-62.33±12.21	25.03±6.95	-48.68±11.48
10	39.41±7.31	-62.25±10.11	24.68±6.62	-49.52±10.65

Table 3. Statistical results of the test-retest reliability of the selected two measures.

Indices		**ICC$_{2,1}$**	**MofMs (°)**	**MofSDs (°)**	**SEM (°)**	**SEM %**	**SRD (°)**	**SRD %**
F/E Test	E	0.891	39.95	7.16	2.36	5.92	6.55	16.40
	F	0.954	-62.45	10.66	2.29	-3.66	6.34	-10.15
RD/UD Test	RD	0.948	24.86	7.42	1.69	6.81	4.69	18.86
	UD	0.971	-48.39	10.23	1.74	-3.60	4.83	-9.98
Note: MofMs: Mean of means of all measurements, MofSDs: Mean of SDs of all measurements.								

4. Discussion

In general, the proposed robotic technique has two major features in measuring joint active ROM of human wrists. One is that it does not depend on the manual operation by human raters, which helps to reduce the influences of subjective factors from raters and save their efforts. The other is the use of multiple measurements to minimize the influences of external disturbances, and it has analogous assessment reliability when compared with manual techniques. A comparison with the study by Horger [7] analysed the assessment reliability of goniometric measurements of active ROMs of wrist F/E and RD/UD, with ICC values all greater than 0.90 for intra-rater reliability and no less than 0.783 for inter-rater reliability. In contrast, the proposed robot-assisted assessment method in this study has ICC values ranging from 0.891 to 0.971, which is even better than those of inter-rater reliability (0.783 to 0.905) reported in [7]. As this comparison may be subject to the assessment protocol and the sample size, more direct comparisons should be conducted.

While the relevance of the proposed robot-assisted assessment method to therapy has been discussed [8], it is essential to state again that the proposed robot-assisted assessment method can help to facilitate automatic control of robot-assisted therapy. One major advantage of this robot-assisted technique is its objectivity without the issue of inter-rater differences. However, this study still suffers from three limitations. One limitation is the determination of the predefined k value that decides the difficulty level of actively driving the robotic handle and a more objective method should be proposed instead of pilot trials or therapists' experiences. A potential way is to use machine learning to allow adaptive tuning of the k value. The second limitation is the issue of joint mis-alignment between humans and robots that can have an obvious effect on measurement accuracy [11]. An adaptive mechanism of joint self-alignment is highly recommended to further improve the assessment validity and reliability. The last limitation is the robotic handle posture setting that should be made anatomically consistent with active wrist movements.

This study examined a new robot-assisted assessment technique for measuring active ROM of human wrists using an admittance control strategy. Experimental data demonstrated its high reliability in measuring wrist F/E and RD/UD. Future work will be focused on integrating adaptive joint self-alignment function into the current robotic system, for enhanced assessment validity and reliability.

Competing interests: None declared

Funding: The University of Auckland, Faculty of Engineering Research Development Fund 3625057.

Ethical approval: The study was approved by the University of Auckland, Human Participants Ethics Committee (019707).

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