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Effects of wearing an upper extremity exoskeleton on measuring joint kinematics during standardized clinical assessment tasks

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***Abstract*— Evaluating upper extremity (UE) motor impairment post-stroke commonly relies on established clinical assessments, which suffer from inherent subjectivity due to human visual inspection. The sensing capabilities of robotics can facilitate the objective assessment of motor impairment. The robotic device needs to not only precisely measure movement characteristics but also minimally interfere with natural movement to assess motor impairment effectively. However, the effect of wearing an exoskeleton on the performance of motor impairment assessment tasks has yet to be evaluated. Thus, this study aimed to evaluate whether the joint kinematics recorded during Fugl-Meyer Assessment (FMA) tasks performance are comparable between two conditions: 1) while wearing the exoskeleton and 2) without wearing the exoskeleton. Six healthy participants performed six single-degree-of-freedom sub-tasks of the upper extremity subscale of the Fugl-Meyer Assessment (FMA-UE), one of the standardized clinical assessments. We estimated joint angle trajectories in both conditions using the exoskeleton and a motion capture system, respectively. The coefficient of multiple correlation (CMC) was used to evaluate the similarity of joint kinematic trajectories between the two conditions. The range of motion (RoM) between the two conditions was also compared. The calculated CMC indicated a good-to-excellent level of agreement across all tasks between the wearing and non-wearing conditions (CMC > 0.90). The RoMs of all tasks in the two conditions except for shoulder flexion to 180° were not significantly different ($p > 0.05$). These results revealed the minimal effect of wearing the exoskeleton on joint kinematics during FMA subtask performance. In addition, these results imply that each exoskeleton segment was well-aligned and attached to the corresponding anatomical body segment within the exoskeleton measurement system. Overall, we conclude that the HARMONY exoskeleton can be a feasible measurement tool for clinical assessment tasks.**

Keywords— Exoskeleton, Joint kinematics, robotic assessment, clinical assessment, motor impairment

I. INTRODUCTION

Stroke stands as a leading cause of long-term disability in the United States, with a significant number of stroke survivors experiencing chronic motor impairments in their upper extremities [1]. Despite the presence of acute medical treatment and rehabilitation, approximately 60% of patients still experience upper extremity (UE) impairment six months after a stroke [2]. This lingering impairment not only contributes to increased financial burdens but also diminishes the quality of life for stroke survivors.

The evaluation of UE motor impairment post-stroke commonly relies on established clinical assessments, such as the upper extremity subscale of the Fugl-Meyer Assessment (FMA-UE) [3]. However, these assessments face limitations in capturing the nuanced quality of sensorimotor performance due to their use of ordinal scales [4]. Despite the intention of traditional assessments to be repeatable (intra-operator) and objective (inter-operator), the inherent subjectivity in visual inspection introduces an unavoidable degree of uncertainty. Consequently, there is considerable interest in developing automated, computer-aided systems to facilitate objective and quantitative motor impairment assessments [5-7].

The sensing capabilities of the robotics make it a robust assessment tool, measuring kinematic and kinetic features of UE movement throughout the post-stroke recovery process [8]. It requires less preparation time and involves fewer post-processing steps than conventional measuring systems, such as optical motion capture systems. Additionally, robotics could provide real-time assessment results to both the patient and therapist, offering detailed and interpretable information, which might help to enhance the translation of assessment outcomes into practical rehabilitation practices.

When considering robotics as an assessment tool, it is crucial to assess how accurate the robotic measurements are and how the robotic device affects the natural movement during assessment tasks [8]. In a previous study, the joint kinematics measured by the robotic device HARMONY exoskeleton showed good agreement with measurements from an optical motion capture system [9]. However, the effect of wearing the HARMONY exoskeleton on performing motor tasks of standardized clinical assessments has not been assessed yet.

Thus, this study aimed to determine whether the joint kinematics in wearing the HARMONY exoskeleton are comparable to those without wearing it during FMA-UE tasks, an example of well-accepted traditional clinical scales. We hypothesized that the joint kinematics during FMA-UE tasks would be comparable between the two conditions. As the first step, we tested the hypothesis in healthy individuals who usually have a larger range of motion (RoM) in terms of joint kinematics compared to that post-stroke to evaluate the effect in a full RoM necessary for performing the FMA-UE tasks.

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II. METHODS

A. Participants

Six young, healthy adult participants (age, 29.3 ± 6.9 years (mean ± SD); five males and one female) with no known upper extremity injury were recruited and performed the experimental protocol in this study. All participants signed an informed consent form approved by the University of Houston Institutional Review Board in accordance with the Declaration of Helsinki.

B. Equipment

HARMONY exoskeleton (Harmonic Bionics, Austin, TX, Fig. 1) was used to record the joint angle while performing sub-tasks of the FMA-UE. The HARMONY is a bilateral UE exoskeleton with 7 degrees of freedom on each side of the arm, including shoulder protraction-retraction, elevation-depression, flexion-extension, abduction-adduction, internal-external rotation, elbow flexion, and wrist pronation-supination which can provide wide RoM. In addition, the exoskeleton implements a baseline control that allows users to move the robot with minimal force [10].

Figure 1. Exemplary illustration of HARMONY exoskeleton

C. Experimental Protocol

This experiment evaluated the effect of wearing the exoskeleton on joint trajectories during six single-degree-of-freedom (DoF) sub-tasks of the FMA-UE. Joint trajectories were compared between wearing exoskeleton and non-wearing exoskeleton conditions quantified by the exoskeleton's sensor (HARMONY, Harmonic Bionics, Austin, TX) and the motion capture system (Qualisys, Gothenburg, Sweden), respectively. The subtasks consisted of 1) shoulder flexion to 90° (Sh_FE90), 2) wrist pronation-supination during fixed elbow flexion (90°) and shoulder flexion (0°) (PS_E90), 3) shoulder abduction to 90° (Sh_AB90), 4) shoulder flexion 90-180° (SH_FE180), 5) wrist pronation-supination during fixed elbow flexion (0°) and shoulder flexion (30°-90°) (PS_E0), and 6) elbow full flexion (E_FE). We included the single-DoF movement of the elbow joint to see the effect of the exoskeleton on elbow joint movement even though it is not the FMA-UE task. Since we did not simultaneously record the movement in two different conditions, physical starting and finishing points were provided to ensure tasks were identical between the two conditions. Participants completed six subtasks for five trials each, where the experimental operator provided appropriate instructions (e.g., auditory cue).

D. Data Acquisition and Analysis

For the non-wearing condition, six cameras with a sampling rate of 100 Hz were used to track the reflective markers attached to the acromion, incisura jugularis, 7th cervical vertebra, 10th thoracic vertebra, lateral and medial epicondyle, and radial and ulnar styloid to estimate the coordination system of the trunk, clavicle, humerus, and forearm body segment. Marker trajectory data were filtered using a fourth-order low-pass Butterworth filter with a cut-off frequency of 3 Hz. The filtered marker trajectories were then used to estimate the coordinate system of each body segment. We adopted the definition of a coordinate system from previous studies [11]. To calculate the joint kinematics, we used the rotation sequence recommended by the International Society of Biomechanics [12], except for the shoulder joint. For the shoulder joint, we used two different sequences, the YXY` sequence and the XZY sequence, for the shoulder flexion-extension and abduction-adduction, respectively, to ensure the amplitude coherence of each movement [13].

For the wearing condition, the built-in rotary encoder recorded the exoskeleton's joint angle with a sampling rate of 200 Hz during movement. The sensor data were filtered using a fourth-order low-pass Butterworth filter with a cut-off frequency of 10 Hz. Using filtered data and Denavit-Hartenberg parameters, we obtained a coordinate system of the exoskeleton's each segment using forward kinematics. Since the exoskeleton's coordinate system was not identical to that of the motion capture system used in this study, we redefined the coordinate system based on the same methodology used for the motion capture system to conduct a fair comparison between the two measurement modalities.

We subtracted the joint angle of the initial posture at each task (i.e., presented the angle in SH_FE180 as a relative angle from 90°, which is the initial posture angle) from the estimated joint angle trajectory and trimmed it from movement onset to offset. Movement onset or offset was determined by where the movement velocity exceeded or fell below 10% of maximum velocity at each task. Trimmed datasets were then normalized from 0 to 100%.

To evaluate the effect of the exoskeleton on joint kinematics during FMA-UE sub-tasks, we compared joint kinematics patterns between wearing and non-wearing conditions using the coefficient of multiple correlation (CMC) adopted from a previous study [14]. The CMC is a metric quantifying the similarity between two waveforms on a scale from zero to one. We interpreted values as excellent ($0.95 < CMC < 1$), very good ($0.85 < CMC < 0.95$), good

(0.75 < CMC < 0.85), moderate (0.65 < CMC < 0.75), and poor (0 < CMC < 0.65) [15]. Additionally, we compared the RoM between two conditions.

E. Statistical Analysis

We employed the Paired t-test with a significance level of 5 % to the statistical difference in RoM between the two conditions. Pearson correlation analysis was also used to determine whether the RoM difference between the two conditions and the CMC value showed a statistically significant relationship.

III. RESULTS

A. Joint Trajectory Similarity

The result of the current study demonstrated the performance during selected FMA-UE tasks comparable between the exoskeleton-wearing and non-wearing conditions, except for shoulder flexion to 180°. The joint trajectories were substantially overlapped between the two conditions, except for shoulder flexion to 180° (Fig. 2A).

The result of CMC indicated a good-to-excellent level of agreement across all tasks between the wearing and non-wearing conditions (Sh_FE90, CMC = 0.98 [IQR 0.98 - 0.99]; PS_E90, CMC = 0.98 [0.93 - 0.99]; Sh_AB90, CMC = 0.93 [0.88 - 0.98]; Sh_FE180, CMC = 0.90 [0.82 - 0.94]; PS_E0, CMC = 0.98 [0.96 - 0.99]; E_FE, CMC = 0.99 [0.98 - 0.99], Fig. 2B).

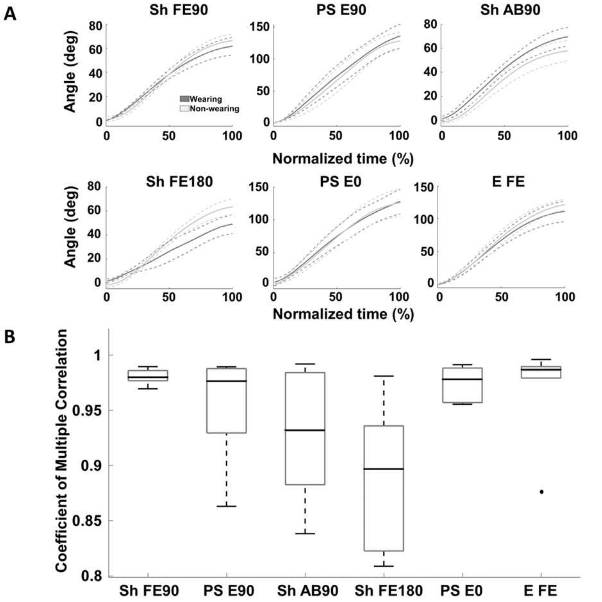

Figure 2. The mean and standard deviation of the joint trajectory (A) and the Box plot of CMC values for each of the six tasks (B): shoulder flexion to 90° (Sh_FE90), wrist pronation-supination during fixed elbow flexion (90°) and shoulder flexion (0°) (PS_E90), shoulder abduction to 90° (Sh_AB90), shoulder flexion 90-180° (SH_FE180), wrist pronation-supination during fixed elbow flexion (0°) and shoulder flexion (30°-90°) (PS_E0), and elbow fully flexion (E_FE). Solid and dashed lines represent the mean and standard deviation across participants.

B. Range of Motion

A notable difference was observed in the RoM of shoulder flexion to 180° between the wearing (47 ± 8.2°) and non-wearing conditions (65.1 ± 6.0°) ($p < 0.01$, Fig. 3), while RoMs of other tasks were not significantly different between two conditions ($p > 0.05$, Fig. 2). Furthermore, this difference in RoM exhibited a significant correlation with CMC values across participants ($r^2 = 0.91$, $p < 0.01$, Fig. 4).

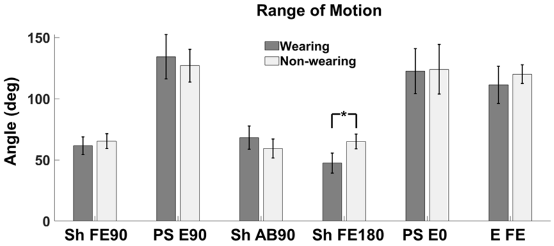

*Figure 3. The mean and standard deviation of a range of motion at each task. shoulder flexion to 90° (Sh_FE90), wrist pronation-supination during fixed elbow flexion (90°) and shoulder flexion (0°) (PS_E90), shoulder abduction to 90° (Sh_AB90), shoulder flexion 90-180° (SH_FE180), wrist pronation-supination during fixed elbow flexion (0°) and shoulder flexion (30°-90°) (PS_E0), and elbow fully flexion (E_FE). (paired t-test; *, p<0.05)*

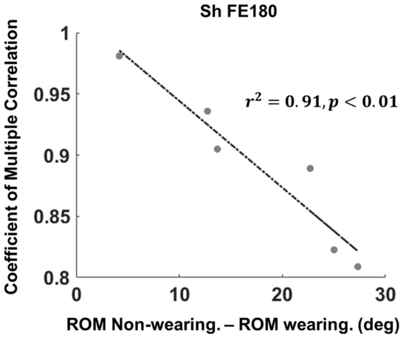

Figure 4. The correlation between coefficient of multiple correlation and range of motion difference between wearing and non-wearing conditions. Each circle represents the data collected from each of six individuals and its linear regression line with Pearson correlation coefficient.

IV. DISCUSSION

When evaluating motor performance, it is crucial for a measurement system to accurately capture movement without impeding natural motion. In a previous study, the joint kinematics recorded by an exoskeleton measurement system demonstrated strong agreement with those measured by the standard optical motion capture system when the exoskeleton was worn [9]. This current study extends these findings by revealing that the effect of wearing the exoskeleton on joint kinematics is minimal, particularly in tasks involving single-degree-of-freedom movements, except when the movement extends beyond the exoskeleton's ROM constraint.

The previous study addressed the importance of transforming kinematics from a robot's functional frame to the anatomical frame for the clinical interpretation of robotic measures [8]. This study showed a good-to-excellent degree of agreement between the joint kinematics calculated within the exoskeleton's frame and those based on the anatomical frame using the motion capture system, even though we did not simultaneously record the movement using two measurement modalities. These results imply effective alignment and attachment of each exoskeleton segment to the corresponding anatomical body segment within the exoskeleton measurement system.

The limited range of motion of the exoskeleton might cause the ceiling effect if we assess movement requiring an excessive range of motion. In this study, a significant RoM difference between the two conditions was observed during the shoulder flexion to 180° task. This difference resulted in dissimilarity in the joint kinematic pattern when wearing an exoskeleton compared to the natural movement (Fig. 3 and Fig. 4). A previous study also revealed that mechanical RoM constraint can lead to a saturation effect [16]. However, the ceiling effect might not be critical to assess motor impairment because shoulder flexion necessary for daily activities was up to 130.5 [17, 18], below the exoskeleton's constraint. Also, the previous study showed that the exoskeleton's workspace covers almost a full range of daily activities [10].

The current study primarily focused on evaluating single DoF movements. As interjoint coordination and compensatory movement during multiple DoF movements are important for assessing motor impairment, further investigation will be needed to evaluate the effect of the exoskeleton on multiple DoF movements.

V. CONCLUSION

The current study evaluates the effect of the HARMONY Exoskeleton on joint kinematics during single DoF sub-tasks of the FMA-UE. We found that joint kinematics pattern and RoM were not significantly different between wearing exoskeleton and without wearing it. The results imply that the effect of HARMONY exoskeleton on joint kinematics was minimal in healthy participants. Future research targeting stroke populations and encompassing multi-DoF movements will be needed to confirm the HARMONY exoskeleton as an effective measurement tool for clinical assessment.

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