Effects of Robotic Exoskeleton Dynamics on Joint Recruitment in a Neurorehabilitation Context

Justin Fong, Vincent Crocher, Denny Oetomo, Ying Tan and Iven Mareels
The Melbourne School of Engineering
The University of Melbourne
Melbourne, VIC 3010
Email: {fong.j, vcrocher, doetomo, yingt, i.mareels}@unimelb.edu.au

***Abstract*—Increasing research has been conducted into the use of robotic devices for neurorehabilitation. One advantage of these devices over traditional rehabilitation is the availability of measured data, which can be used to inform potential patient-specific protocol for recovery or simply to provide higher frequency feedback to the patients and therapists. It has previously been identified that such devices may have unplanned effects on the movement of patients. However, the exact nature of these effects are unknown, which makes the meaning of any measured data less clear. As such, this study investigates the effect of the mechanical dynamics of a robotic exoskeleton (ArmeoPower, Hocoma, Switzerland) on the movements of healthy subjects – particularly with respect to the movements of the shoulder, and joint utilisation. The study finds that the exoskeleton may encourage changes in shoulder movement in both magnitude and direction and changes in the joints recruited for the movement. Furthermore, the effects of the robot on joint utilisation are not consistent across reaching directions, however, the peak joint velocities are decreased across all joints and reaching directions.**

I. Introduction

The potential for robotics for use in neurorehabilitation is well-documented [1], [2]. The use of such devices may provide advantages over traditional rehabilitation, such as a reduced workload for therapists; increased session frequency and intensity; and systematic and high frequency assessment.

This assessment would potentially be made through measurements identifying specific weaknesses in patients' movement capabilities [3]. This information, can then be used to select or develop exercises targeting these identified weaknesses. However, care must be taken in this analysis. It is natural to attempt to compare the measured trajectories to well-studied, 'ideal' trajectories (for example, straight trajectories minimising jerk [4]), or models of ideal trajectories [5], [6]. However, if these robotic devices change the movement of the patient, such comparisons would be inaccurate. Furthermore, if the measurements from the robot are to be used for these comparisons, care should be taken to ensure that these measurements correspond to the appropriate anatomic values.

Few studies have approached this topic. Jarrassé et al. presented a pilot study [7] identifying that exoskeletons can affect movement, and suggested methods for quantifying them. [8] concluded that trajectories of the wrist in reaching motions can be adequately recorded by an exoskeleton. It was also observed that the mechanical properties of the robot had an effect on the wrist trajectory, likely to due to the uncompensated inertia of the robot device itself. The present study aims to extend the previous investigations onto changes of reaching trajectories using joint-level measurements, as they often considered in clinical assessments.

Specifically, this study utilises metrics measuring shoulder movement (quantity and direction); and joint utilisation and velocity. Shoulder movement is considered as excessive shoulder movement during reaching is a common compensatory technique for neuro-impaired patients [13], and thus may be considered an indicator of patient ability. In terms of joint metrics, joint recruitment is often abnormal for hemiparetic patients [9], and this is reflected in clinical measures, such as the Wolf Motor Function Test [10] and the Fugl Meyer Assessment [11]. Measurements of recruitment can be made through range of motion measurements. Furthemore, joint velocity reflects torque capabilities of patients [14], where a larger peak velocity indicates a larger joint torque can be produced. As such, peak joint velocity is also investigated.

A combination of these metrics are used to investigate on two fronts, (1) a comparison of movements of healthy subjects between movements within the exoskeleton, verses those without; and (2) a comparison of joint utilisation measurements between those reported by the exoskeleton with those reported by external sensors.

Within this study, we consider the ArmeoPower (Hocoma, Switzerland), a powered exoskeleton. Although the results reported in this study are specific to this exoskeleton, the study seeks to highlight areas of potential shortcoming of the measured data in all similar robotic devices designed for rehabilitation.

II. Methods

This study utilises the results of an experiment in which healthy subjects ($n = 9, 26.7 \pm 3.9$ years old) performed reaching tasks with their dominant arm (right $n = 8$, left $n = 1$) under two conditions - reaching within a robotic exoskeleton ('Robot Reaching') and outside the exoskeleton ('Free Reaching'), see Figure 1. Within the 'Robot Reaching' condition, the robot was set to actively compensate for its own friction and weight, resulting in as close to a 'transparent' environment as possible. In the 'Free Reaching' condition, the subject wore only lightweight straps, and thus it was assumed that the natural reaching motion of the subjects was captured. The study was approved by the University of Melbourne Engineering Ethics Advisory Group under the ethics identification number #1442734.

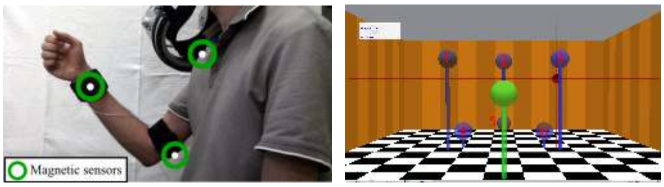


Fig. 1. Experimental Setup with sensors location in 'Free Reaching' (left) and Virtual Environment (right) with the six different targets (blue), home position target (green) and cursor (red). Six targets shown for reference only, targets were never displayed simultaneously.

A. Protocol

Subjects completed 7 sessions - the first and last were under 'Free Reaching' conditions, with all others in 'Robot Reaching' conditions. Each session consisted of 2 blocks, and each consisting of 10 consecutive attempts at the reaching task (trials) to each target (Figure 2). Sessions 1 and 2, and 6 and 7 were completed on the same days, however, other sessions were separated by between 1 and 5 days. To reduce the effects of fatigue, subjects were instructed to rest as much as desired between each trial, and longer breaks were enforced every 10 trials, and a longer break of at least 10 minutes was also enforced between sessions 1 and 2, and 6 and 7. In this study, only results from sessions 1, 2, 6 and 7 are reported, and as such, for clarity, will be referred to as 'Free 1' (Session 1), 'Robot 1' (2), 'Robot 2' (6) and 'Free 2' (7). The intermediate sessions (3-5) were included in the protocol for a future study into the learning behaviour of the subject. This intermediate data is not reported here.

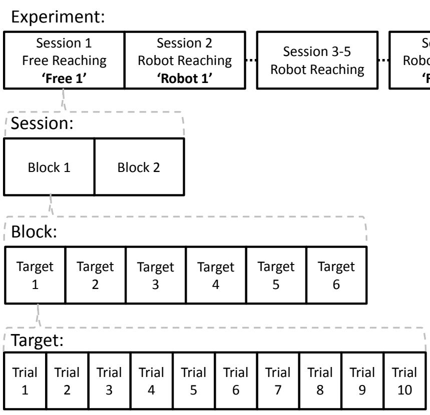


Fig. 2. Experimental Protocol. Only results from Sessions 1, 2, 6 and 7 are reported in this study.

B. Sensors

Data was primarily recorded using 'Magnetic Sensors' – the 3D Guidance trakSTAR system (Ascension Technology Corporation, USA), which provides 3D position and 3D orientation information. Three sensors were attached to the subject - one on the acromion, aligned with the coronal plane, pointed away from the body; one near the distal end of the humerus, aligned with the humerus, pointed away from the body; and one on the wrist, aligned with the forearm (ulna), pointed towards the hand. These sensors recorded at approximately 30 Hz. The humerus and wrist sensors were attached using straps 50 mm wide, aligning the sensor with the corresponding limb segment (see Figure 1).

In 'Robot Reaching' trials, data from the ArmeoPower was also recorded, providing an indication of the data available under non-experimental operating conditions. This data ('Robot Data') included the joint angles at each robotic joint of the robot, and the position of the elbow, wrist and hand. This data was recorded at approximately 60 Hz. In these trials, the data was synchronised with the magnetic sensor data at the post-processing stage.

C. Reaching Task

A 3D virtual environment was presented to the subject (see Figure 1). The position of the cursor (red) was mapped to the position of the wrist sensor. Subjects were asked to reach from home (green) to a target (blue) within one second. The movement was to commence when an audible tone was played at the end of a countdown. On completion of a successful movement (when the subject had reached the target and stayed there for 0.4 seconds), an affirmative tone was played, and a cumulative score was incremented. If the attempt was unsuccessful, a negative tone was played, and the score not incremented.

The position of the 6 targets used are listed in Table I and shown in Figure 1. The home position was located in the coronal plane aligned with the shoulder of the reaching arm, at a position requiring approximately 45° shoulder flexion, and 90° elbow flexion. All movements required forward motion, to the up-left, directly up, up-right, down-left, directly down and down-right from the home position. The locations of these targets were chosen such that they were of significant distance from the home position; reachable when the subject was both in and out of the exoskeleton; and provided appropriate coverage of the workspace within the exoskeleton.

TABLE I
TARGET POSITION (VIRTUAL COORDINATES)

Target	x	y	z	**Target**	x	y	z
Home	0.5	0.5	0.0	-	-	-	-
1	0.3	0.8	0.45	4	0.35	0.15	0.5
2	0.5	0.8	0.55	5	0.5	0.15	0.85
3	0.7	0.8	0.45	6	0.65	0.15	0.5

Axes are as follows: x - left/right, y - up/down, z - forward/back. Origin is located at the bottom-left corner of the reachable space, in the vertical plane of home position.

D. Magnetic Sensor Angle Computation

The joint angles of Shoulder Plane of Elevation (α), Shoulder Elevation (β) and Shoulder Axial Rotation (γ) were calculated in accordance to section 2.4.7 in the ISB recommendations for joint angle coordinate systems [12], based on two assumptions: (1) the wrist and elbow sensors were aligned with the forearm and humerus respectively, and the shoulder sensor lay in the Z-Y plane of the Thorax Frame; and (2) the Y axis in the Thorax Frame was assumed to be vertical - i.e. that the subject started their movement while upright, and maintained an upright posture during the entirety of the movement.

Thus the Thorax Frame has Y_t directly up, Z_t positive in the plane of the shoulder sensor orientation and parallel to the ground, and X_t such that the frame is right-handed. The Humerus Frame has Y_h parallel to the elbow sensor in the opposite direction, X_h in the plane of the direction between the elbow sensor and the wrist sensor, but perpendicular to Y_h, and Z_h resolved for a right-handed frame.

Elbow Flexion/Extension (θ) was calculated as the angle between Y_h and the direction of the wrist sensor.

E. Metrics of Comparison

Five metrics were chosen for this study: three related to shoulder movements, and two utilising joint angles. These metrics were chosen for their relevance as measures in rehabilitation, their capabilities to characterise the effects of the robot dynamics on the movements, and their capability to reflect inaccuracies in the reported data. In this section, definitions for each metric are given.

1) Shoulder Movement: Three shoulder movement metrics are presented in this study – the Cumulative Shoulder Movement ($D_{s,cum}$), the Net Shoulder Movement ($D_{s,net}$) and the Shoulder Movement in Reach Direction (S_w).

The Cumulative Shoulder Movement was calculated as the cumulative movement of the shoulder during the task. This was calculated using the shoulder sensor as the sum of the distance (Euclidean Norm) between each successive sample within a trial:

$$D_{s,cum} = \sum_{i=1}^{N-1} ||\mathbf{x}_{s,i+1} - \mathbf{x}_{s,i}|| \tag{1}$$

where $\mathbf{x}_{s,i}$ is the position of the shoulder sensor in a global coordinate frame at the i^{th} discrete measurement in a trial, and N is the total number of measurements in that trial.

The Net Shoulder Movement demonstrates the resultant displacement of the subject's shoulder. It was calculated as the distance between the position of the shoulder at the start of the movement ($t_0 = 0$) to its position at the end ($t_f = 1$):

$$D_{s,net} = ||\mathbf{x}_s(t_f) - \mathbf{x}_s(t_0)|| \tag{2}$$

The Shoulder Movement in Reach Direction is the fraction of net shoulder movement in the same direction as the wrist movement. It was calculated as the dot product of the normalised net shoulder movement vector against the normalised net wrist movement vector, and expressed as a percentage.

$$S_r = \frac{\mathbf{x}_s(t_f) - \mathbf{x}_s(t_0)}{||\mathbf{x}_s(t_f) - \mathbf{x}_s(t_0)||} \cdot \frac{\mathbf{x}_w(t_f) - \mathbf{x}_w(t_0)}{||\mathbf{x}_w(t_f) - \mathbf{x}_w(t_0)||} \cdot 100\% \tag{3}$$

Where $\mathbf{x}_w(t)$ corresponds to the position of the wrist at time t.

2) Joint Metrics: Two metrics are calculated using the joint angles – Peak Joint Velocity and Joint Utilisation.

The joint velocities were calculated using a first order finite difference approximation. The Peak Joint Velocities ($\dot{\alpha}_{max}, \dot{\beta}_{max}, \dot{\gamma}_{max}, \dot{\theta}_{max}$) were then calculated as the maximum of each of these values throughout each trial.

$$\dot{\alpha}_{max} = \max_{t\in[t_0,t_f]} \{\dot{\alpha}(t)\}, \text{ similarly for } \dot{\beta}_{max}, \dot{\gamma}_{max}, \dot{\theta}_{max} \tag{4}$$

The Joint Utilisations ($\alpha_{rom}, \beta_{rom}, \gamma_{rom}, \theta_{rom}$) are calculated as the difference between the maximum and minimum of each of the calculated joint angles:

$$\alpha_{rom} = \alpha_{max} - \alpha_{min}, \text{ similarly for } \beta_{rom}, \gamma_{rom}, \theta_{rom} \tag{5}$$

Where α_{max} and α_{min} correspond to the maximum and minimum values of the Shoulder Plane of Elevation Angle throughout the entirety of the trajectory of each trial.

F. Metrics Comparison and Statistical Analysis

It was noted that during each Target set (set of 10 reaches), subjects performed with higher variance during the first few reaches, due to difficulty in perception within the 3D virtual environment. To demonstrate the effects of only the robot, only attempts 3 to 10 of each Target (see Figure 2) are utilised in the analysis.

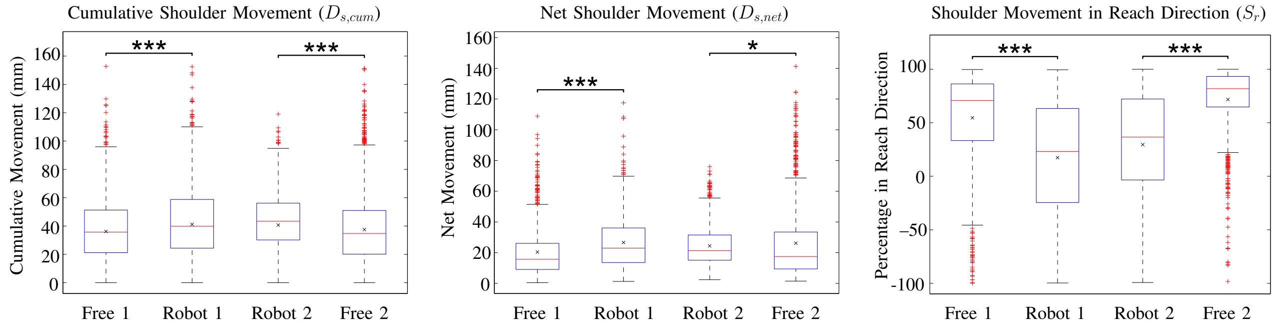
Statistical differences between metrics in Free and Robot conditions are tested using the paired Wilcoxon Signed Rank Test [15].

III. Results

Results are presented for each metric class in this section.

A. Shoulder Movement

Boxplots showing the Cumulative Shoulder Movement, Net Shoulder Movement and the Fraction of Shoulder Movement in Reach Direction are shown in Figure 3. Between each pair of sessions, a significant difference was observed under the paired Wilcoxon Signed Rank Test in all metrics ($p < 0.05$). Additionally, the Cumulative Shoulder Movement is higher in the Robot Sessions (means of 50.4mm and 49.7mm) compared with the Free Sessions (42.7mm and 45.7mm). Furthermore, the Shoulder Movement in Direction of Reach is also affected, with means of 17% and 30% compared to 55% and 72%. Changes in Net Shoulder Movement do not have a trend between the sessions.



(a) Cumulative Shoulder Movement (b) Net Shoulder Movement (c) Shoulder Movement in Reach Direction

Fig. 3. Shoulder Movement (all subjects to all targets combined) in each of the reported sessions. '×' indicates the mean. Box plots indicate first and third quartiles, and medians in respective sessions. The level of significant difference is given by the label, * : $p < 0.05$, ** : $p < 0.01$, *** : $p < 10^{-3}$

B. Joint Metrics

The average Peak Joint Velocities to each target are shown in Figure 4. On this metric, the effect of the robot is similar over all targets and over all joints — the peak velocity is decreased. The relative magnitude of the decrease is most significant in the Shoulder Elevation, with an average decrease of 38 % and 26 % between the first and second set of sessions respectively.

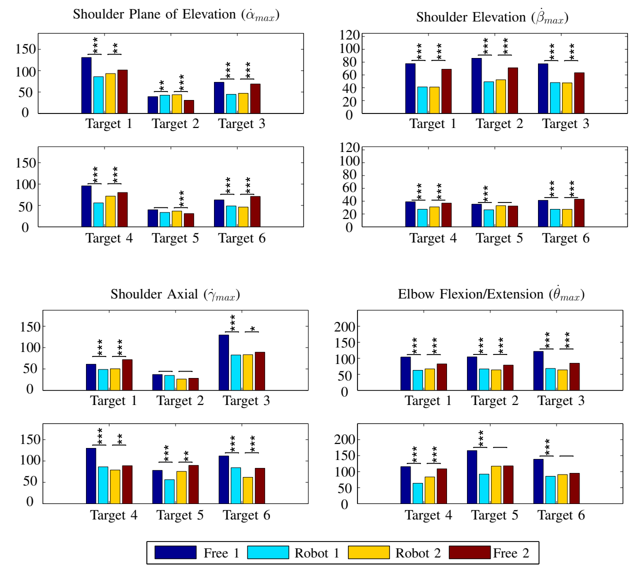


Fig. 4. Mean Peak Joint Velocity for Each Target (°/s). The level of significant difference is given by the label, * : $p < 0.05$, ** : $p < 0.01$, *** : $p < 10^{-3}$

The Joint Utilisation Metric suggests a difference in joint recruitment between the 'Free Reaching' and 'Robot Reaching' conditions. Figure 5 shows the mean Joint Utilisation for each angle, over all subjects for each target. Over all the targets, it is worth noting that the Shoulder Elevation Angle (β_{rom}) has a smaller range in the Robot (means of 12.7° and 13.3°) compared to the Free Condition (17.1° and 15.9°). It can also be seen that the effects of the robot also appear to be similar between vertically aligned targets (i.e. 1 and 4, 2 and 5, and 3 and 6), as opposed to horizontally-aligned targets.

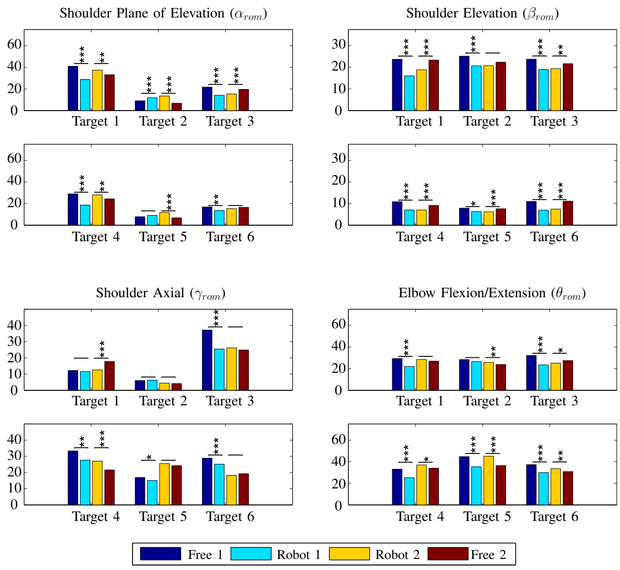


Fig. 5. Mean Joint Utilisation for Each Target (°). The level of significant difference is given by the label, * : $p < 0.05$, ** : $p < 0.01$, *** : $p < 10^{-3}$

A comparison was also made between Joint Utilisations as calculated by the exoskeleton, and those reported by the magnetic sensors. This data only exists in the 'Robot Reaching' sessions, and the comparison is shown in Table II. It can be seen that the robot reported lower utilisations of the Shoulder Plane of Elevation and Axial Rotation, but higher ultilisations for the Shoulder Elevation and Elbow Flexion/Extension over the range of movements tested. The most significant change in both absolute magnitude and relative magnitude is the reported Shoulder Axial Rotation.

IV. Discussion

Three main topics are highlighted in this discussion. First, we discuss the how reaching actions are changed when movements are made from within the robotic device, compared to those made under 'free' conditions. Second, a discussion is presented on the evidence suggesting that the anatomical axes move with respect to the robot's joint axes,

TABLE II
ROBOT AND MAGNETIC DATA - JOINT UTILISATION

Joint	Robot Session 1		Robot Session 2	
	%	Absolute (°)	%	Absolute (°)
Plane of Elevation	-17%	-2.5	-22 %	-4.4
Elevation	11%	1.3	17%	2.0
Axial Rotation	-56%	-10.2	-54%	-10.2
Elbow	14%	4.0	14%	4.6

*change calculated as Robot Data relative to Magnetic Data

and the possible consequences of this. Finally, we present and acknowledge some of the limitations of this study. It is noted that this discussion addresses these points from a rehabilitation perspective.

A. *Movement Patterns*

The results of this experiment suggest that the subjects make significant changes in their movement patterns when reaching within the exoskeleton, observable both through changes in the movement of the shoulder position, as well as the movements of the shoulder and elbow joints.

Within this study, the cumulative movement of the shoulder ($D_{s,cum}$) is clearly significantly higher in the robot. This suggests that this exoskeleton does not limit the movement of the subjects, and, in fact, may encourage movement. Furthermore, the Shoulder Movement in Reach Direction (S_r) metric show that the *type* of movement changes. In 'Free Reaching' conditions, net movement of the shoulder is primarily in the wrist movement direction, whereas this value while in 'Robot Reaching' conditions is much lower. There is also a much larger variation in S_r values for the 'Robot' trials. This change in shoulder movement magnitude and direction may be traced to the intention of this movement — particularly, that the movement may be produced to counteract uncompensated dynamics of the robotic device. This suggests that robot inertia should be considered for rehabilitation applications either through more lightweight designs or through inertia compensation methods.

Changes in movements are also observed in the joint angles. Figure 4 shows that the means of the Peak Velocities for all joints ($\dot{\alpha}_{max}, \dot{\beta}_{max}, \dot{\gamma}_{max}, \dot{\theta}_{max}$) are decreased within the exoskeleton. The exoskeleton discouraged movement, which is observable in movements made towards all targets, and in all the joints. This observation may be explained again by the presence of uncompensated inertia. Furthermore, the most significantly affected joint was that of Shoulder Elevation ($\dot{\beta}_{max}$), which was lower on average by 38 % in 'Robot 1' compared to 'Free 1'; and 26 % , in 'Robot 2' compared to 'Free 2'. This effect was on average greater in the targets which required more elevation (Targets 1, 2 and 3), indicating a limitation in upwards movements. This suggests that either the weight of the exoskeleton is not completely compensated for by the robotic device, or the limitations of the posterior muscles required for elevation are more rapidly encountered. This therefore may have implications for the design of robotic devices, in that the shoulder elevation may need to be considered more carefully than other joints. Figure 5 indicates changes also occur in Joint Utilisation ($\alpha_{rom}, \beta_{rom}, \gamma_{rom}, \theta_{rom}$) between the 'Robot Reaching' and 'Free Reaching' sessions. In contrast to the Peak Joint Velocities, the sign of these changes varies between each joint and also between target locations, with the exception of Shoulder Elevation. This suggests a non-uniform effect of the robot, which should be considered if an attempt to characterise this effect was made.

These changes in movement patterns may have implications on the use of the robot on patients. If 'unnatural' movements are encouraged, rehabilitation within such a robot may involve training of non-natural synergies or compensatory strategies. The consequences (positive or negative) of this on patients' rehabilitation are not investigated in this study, but may be a future avenue of research.

B. *Robot-Subject Alignment*

This experiment also suggests that during the movements of the subjects, the anatomic axes of the subject are not always aligned with the joint axes of the exoskeleton. As such, a movement in one of these joints does not necessarily correspond to a movement in the other. Two observations support this. First, the movement of the shoulder, and second, a comparison between the joint angles reported by the exoskeleton and those generated by the magnetic sensors.

Figure 3 indicates the shoulder does move in 'Robot Reaching' conditions. Thus, the assumption that the shoulder is fixed during movements within the robot does not hold. As the joint axes of the exoskeleton do not translate, movement of the shoulder indicates that the joint axes of the shoulder cannot be aligned with the corresponding joint axes of the exoskeleton during the entire reach.

From Table II, it is apparent the robotic device reported, on average, lower changes in Shoulder Angle of Elevation, and Axial Rotation; and higher changes in Elevation and Elbow extension. Differences in these values suggest that the range reported by the exoskeleton may not necessarily reflect the actual range achieved by the subject.

Joint misalignment may have two consequences. First, it is possible that such a misalignment can cause undesired forces on the subjects [16], [17], which may, in turn, encourage the unnatural movement discussed in Section IV-A. Secondly, and importantly for the use of robotic devices as measurement devices, misalignment may also have an impact on the reported values for the joint angles. This suggests that measurements from exoskeleton devices should be use with care and that particular attention should be paid to the subject-exoskeleton alignment in the design of exoskeletons [18] and/or that auxiliary measurement systems or estimation strategies should be used when accurate joint measures are required [19].

C. Limitations

The authors note three main caveats when considering the conclusions drawn within this investigation.

First, this study utilised the ArmeoPower for all data collection, and therefore any conclusions drawn apply specifically to this exoskeleton. However, it is noted that this study seeks to highlight possible limitations in the data collection in all robotic devices used for rehabilitation. The analysis presented also serves as potential framework for eliminating the bias introduced by the effects of this robot into tools for patient assessment.

Secondly, the task was intentionally designed to be challenging to healthy subjects. Importantly, this required movements faster than those achievable for a typical hemiparetic patient, who are the intended users of the ArmeoPower. It is noted that many of the effects on the movement in 'Robot Reaching' conditions might be explained by the effects of uncompensated inertia of the robot, which are greater with faster movements. However, the effect is present, and should be considered in this and other robotic devices.

Thirdly, the calculations made for the joint angles using the magnetic sensors are based on a number of assumptions. Although the authors are confident in the reported conclusions in this study, and care was taken to minimise the effects of any uncertainties, it is prudent to identify that the joint angles do not represent a ground truth. However, comparisons made between movements inside and outside the robot utilise the same method of estimating the joint angles, and do indicate that there is a significant change.

V. Conclusion

This study utilised an experimental protocol to investigate the nature of the changes in reaching actions when reaching tasks are performed within a robotic exoskeleton, compared to without, particularly addressing metrics considered in a rehabilitation context.

In a previous study [8], we concluded that reaching within an exoskeleton changed the hand trajectory, which may affect the use of the exoskeleton as an assessment device. The present analysis indicated two main new conclusions directly related to neurorehabilitation. First, the movements patterns of the subjects changed whilst within the exoskeleton at the joint level. Second, the joints of the robotic exoskeleton do not necessarily align with the anatomic joints of the subject. However, it is possible that these effects be mitigated through the use of auxiliary devices, either through additional feedback to the patient discouraging the changes in movements, or to provide additional data to improve these measures. These conclusions apply only to this robotic exoskeleton, and the experimental results presented here deliberately accentuate potential issues. However, it our intention to highlight and qualify some of the possible effects of uncompensated robotic inertia and joint misalignment in all robotics intended for use in neurorehabilitation, especially in relation to joint recruitment and shoulder compensation.

Acknowledgment

This work was supported by the Australian Research Council Discovery Project DP130100849.

References

[1] G Prange, M Jannink, C Groothuis-Oudshoorn, H Hermens, M IJzerman, et al. Systematic review of the effect of robot-aided therapy on recovery of the hemiparetic arm after stroke. *Journal of Rehabilitation Research and Development*, 43(2):171–184, 2006.

[2] A Basteris, S Nijenhuis, A Stienen, J Buurke, G Prange, and F Amirabdollahian. Training modalities in robot-mediated upper limb rehabilitation in stroke: a framework for classification based on a systematic review. *Journal of NeuroEngineering and Rehabilitation*, 11(1):111, 2014.

[3] VS Huang and JW Krakauer. Robotic neurorehabilitation: a computational motor learning perspective. *Journal of NeuroEngineering and Rehabilitation*, 6:5, 2009.

[4] T Flash and N Hogan. The coordination of arm movements: an experimentally confirmed mathematical model. *The Journal of Neuroscience*, 5(7):1688–1703, 1985.

[5] E Guigon, P Baraduc, and M Desmurget. Computational motor control: redundancy and invariance. *Journal of Neurophysiology*, 97(1):331–347, 2007.

[6] T Kang, JP He, and SIH Tillery. Determining natural arm configuration along a reaching trajectory. *Experimental Brain Research*, 167(3):352–361, 2005.

[7] N Jarrassé, M Tagliabue, JVG Robertson, A Maiza, V Crocher, A Roby-Brami, and G Morel. A methodology to quantify alterations in human upper limb movement during co-manipulation with an exoskeleton. volume 18, pages 389–397. IEEE, 2010.

[8] J Fong, V Crocher, D Oetomo, and Y Tan. An investigation into the reliability of upper-limb robotic exoskeleton measurements for clinical evaluation in neurorehabilitation. In *Proceedings of the 7th International IEEE EMBS Neural Engineering Conference*, 2015. In Press.

[9] MF Levin. Interjoint coordination during pointing movements is disrupted in spastic hemiparesis. *Brain*, 119(1):281–293, 1996.

[10] SL Wolf, DE Lecraw, LA Barton, and BB Jann. Forced use of hemiplegic upper extremities to reverse the effect of learned nonuse among chronic stroke and head-injured patients. *Experimental Neurology*, 104(2):125–132, 1989.

[11] AR Fugl-Meyer, L Jääskö, I Leyman, S Olsson, and S Steglind. The post-stroke hemiplegic patient. 1. a method for evaluation of physical performance. *Scandinavian Journal of Rehabilitation Medicine*, 7(1):13–31, 1974.

[12] G Wu, FCT Van der Helm, HEJ Veeger, M Makhsous, P Van Roy, C Anglin, J Nagels, AR Karduna, K McQuade, XG Wang, et al. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motionpart ii: shoulder, elbow, wrist and hand. *Journal of Biomechanics*, 38(5):981–992, 2005.

[13] MC Cirstea and MF Levin. Compensatory strategies for reaching in stroke. *Brain*, 123(5):940–953, 2000.

[14] A de los Reyes-Guzmán, I Dimbwadyo-Terrer, F Trincado-Alonso, F Monasterio-Huelin, D Torricelli, and A Gil-Agudo. Quantitative assessment based on kinematic measures of functional impairments during upper extremity movements: A review. *Clinical Biomechanics*, 29(7):719–727, 2014.

[15] F Wilcoxon. Individual comparisons by ranking methods. *Biometrics Bulletin*, pages 80–83, 1945.

[16] A Schiele and FCT van der Helm. Kinematic design to improve ergonomics in human machine interaction. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 14(4):456–469, 2006.

[17] N Jarrassé and G Morel. Connecting a human limb to an exoskeleton. *IEEE Transactions on Robotics*, 28(3):697–709, 2012.

[18] N Jarrassé and G Morel. On the kinematic design of exoskeletons and their fixations with a human member. In *Robotics: Science and Systems*. Citeseer, 2010.

[19] C Cortés, A Ardanza, F Molina-Rueda, A Cuesta-Gomez, L Unzueta, G Epelde, OE Ruiz, A De Mauro, and J Florez. Upper limb posture estimation in robotic and virtual reality-based rehabilitation. *BioMed Research International*, 2014, 2014.