Study of Gross Muscle Fatigue During Human-Robot Interactions

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***Abstract*—This study explores the utility of Electromyogram (EMG) signals in the context of upper-limb exercises during human-robot interaction considering muscle fatigue of the participant. We hypothesise that the Electromyogram features from muscles and kinematic measurements from the robotic sensors can be used as indicators of fatigue and there is a potential to identify the muscle contribution during the activity where the Electromyogram data is correlated with the kinematic data. Electromyogram measurements were taken from four upper limb muscles of 10 healthy individuals. HapticMaster robot in active assisted mode together with a virtual environment was used to guide the participants for moving the robotic arm in a prescribed path in a horizontal plane consisting of four segments. The experiments were conducted until the participants reached a state of fatigue or until a defined maximum number of 6 trials were reached. Comparing the first and last trials indicated that the muscle fatigue had caused an increase in the average power and a decrease in the median frequency of EMG, which was more visible in Trapezius (TRP) and Anterior Deltoid (DLT) muscles in most of the analysed cases compared to Biceps Brachii (BB) and Triceps Brachii (TB) muscles. As the muscles came to a state of fatigue, the kinematic position also showed an increase in tracking error between the first and last trials. The 'near-the-body' segment movements (S1 and S4 segments) were found to have less increase of tracking error compared to the 'away-from-body' movements (S2 and S3 segments). A further analysis on this proved that the tracking error observed was mainly due to fatigue building up over the number of trials when performing 'away-from-body' movements, and not a bi-product of perception errors. We identify that Deltoid and Trapezius muscles were fatigued more. These EMG fatigue indications can be mapped to kinematic indications of fatigue mainly in the segments S2 and S3, which required away from body movements because of the role of these two muscles in lifting the arm to the shoulder height in order to perform the activity. Our extracted features have shown the potential to identify the fatigued muscles as expected. The study also showed that the Electromyogram and kinematic features have a potential to be used to highlight the extent of muscle involvement.**

***Keywords*–Robotic Rehabilitation; Upper Limb Training; Fatigue Detection; Electromyogram; Kinematic Fatigue Indicators.**

I. INTRODUCTION

Stroke patients during physical therapies may easily come to a state of fatigue due to their reduced muscle and cognitive capabilities. Repetitions in training exercises are thought to impact on their neuro-plasticity that aids the recovery after stroke [1], but the repetitions often result in a faster occurrence of muscle fatigue. Robots can be used to help rehabilitation exercises due to their potential to deliver large number of repetitions. But the existing physical therapies are designed without sufficiently considering the implications (pain or state of fatigue) to the patient [2][3][4]. Hence, closed loop control and adaptability to individuals becomes important criteria for the acceptance of such rehabilitation solutions. Even though adaptive robotic interactions for upper limb rehabilitation have been studied before [2][5], a commercially accepted solution for robotic interaction considering muscle fatigue could not be found yet. Electromyogram (EMG) features from the involved muscles can be used to understand the current physical state and the effort exerted by the patient [2][3] and then to alter the intensity of the training. The study may be done initially on healthy control groups in various testing conditions and for different muscle combinations before applying the solution on real patients. Such a solution can also be used in a wide-range of human-machine or human-human interactions by providing insights into the state of individual's ability to actively contribute to the interaction.

This study is focused on exploring a practical solution for better therapeutic interaction by considering the muscle fatigue indicators. The study used HapticMaster (HM) as the robotic platform, which is an admittance controlled robot developed by MOOG BV, The Netherlands. Admittance control strategy is a force-in, and displacement-out system where the user's applied force is measured and the haptic device is controlled to move proportional to that force. The robot had been utilised in a stroke rehabilitation project, GENTLE/S where 3 different interaction modes namely passive, active-assisted and active where developed [6]. The active-assisted mode is utilised in this current study, where the robot automatically compensates for the lag or lead in subject arm's position with reference to an internal trajectory model by offering support to achieve the task in time. The current research studied the fatigue development in the upper limb muscles of 10 healthy individuals using EMG and kinematic features recorded during the experiment.

The rest of the paper is organized as follows. In Section II, the past researches in this area and current gaps are briefly discussed. Section III explains the materials and methods used in the study. In Section IV, the results of the data analysis are discussed and further discussion on the results is done in Section V. Finally in Section VI, the conclusions, limitations and possible future work are presented.

II. LITERATURE REVIEW

Muscle or physical fatigue is defined as the decline in the ability of muscles to generate force or power during a physical task. Fatigue usually results in a feeling of tiredness because of the lack of strength and it develops gradually during a physical activity and is typically temporary in duration [7]. Fatigue analysis based on EMG data during upper limb exercises have been studied in the past in different contexts and it was identified that the fatigue affects the movement duration, position sense and task performance. Few researchers in the past had investigated the effect of repetitive tasks and muscle fatigue on upper limb tasks during rehabilitation training [8][9][10]. The subjects were found to get easily fatigued mentally and physically when the tasks were of long duration and of high precision [9]. The results suggested that muscle fatigue need to be considered as an important parameter during the treatment of musculoskeletal injuries as well as athletic/rehabilitation training [8][11].

EMG was used in some of the robot-assisted rehabilitation studies for detection of user's intention. For example, a robot-assisted stroke rehabilitation training system with an interactive training game was controlled through an EMG based detection of user's intention [3]. Another study detected user's intention to move based on EMG measurements, but without interactive games [4]. Even though few of them had actually tried to address the adaptability of rehabilitation training in different ways, the participant's state of fatigue is an overlooked area, which can potentially benefit the adaptation algorithms.

The HapticMaster robot was used in the past to assist (through anti-gravity compensation) in improving the difficulty in reaching away movements by chronic stroke survivors during shoulder abduction tasks [12]. An increase in the upper limb reach area was achieved through robot assisted progressive shoulder abduction loading exercises, which reduced the abnormal coupling of shoulder abduction with elbow flexion. As possible expansion of this study, robotic assistance in combination with muscle EMG studies were also proposed. A further research had experimented HapticMaster based upper limb rehabilitation training in a virtual learning environment [13]. The effects of intensive robot-assisted training were studied in multiple sclerosis (MS) patients. The hand path ratio was used as an indicator for the variation from the optimal trajectory between the start position of the hand and the target position. However, the idea of the paper was not to develop a solution that can directly read the physiological state of the patient say for example, using the muscle EMG. The user's state of fatigue and the possibility of using EMG features as fatigue indicators were not explored in either of these studies. The study had also indicated that other interfacing technologies for example, lightweight sensor-based technologies, may be a more appropriate solution [13].

HapticMaster robot and adaptive games were also used for the rehabilitation training of multiple sclerosis (MS) patients based on EMG data from shoulder muscles (Deltoid and Trapezius) [2]. The EMG data were used only for detecting whether or not the muscle fatigue develops in the patients. Only low frequency (0.8-2.5Hz) mean EMG amplitudes were used as fatigue indicators and no spectral/frequency domain features of EMG were studied. Also no kinematic study was conducted, which could help to understand the corresponding kinematic implications of muscle fatigue. The main upper limb movement involved in the training game was lifting and holding tasks. All the game movements were parallel to the frontal plane (either Left/Right or Top/Bottom) and the game did not involve any movements parallel to the sagittal plane. The HapticMaster robot in this study was used just as a haptic input/output device and no robotic assistance was used during the exercise. Hence, the EMG fatigue indicators were statistically significant in all the participants for Deltoid (DLT) and Trapezius (TRP) muscles. In presence of robotic assistance/guidance the impact of fatigue could be improved and the fatigue indicators would indicate lesser fatigue, and this was not covered in this study.

In another similiar study [5], the Root Mean Square (RMS) amplitude and median frequency of EMG signals from the Deltoid muscles (the prime mover in the task) were studied to compare the muscle fatigue in 16 MS patients and 16 healthy individuals, during a robot mediated upper limb training exercise using HapticMaster robot and a virtual game. Only vertical movements (e.g., lifting tasks) were involved and no movements parallel to sagittal plane were defined in this experiment. The study showed that the game performance was not affected by fatigue possibly due to the contribution from other compensatory muscles and there was no relation between the subjective and objective fatigue indicators for the MS patients. Even though the experiment involved movements with dynamic muscle contraction, the EMG used for fatigue study was collected during another 30 seconds isometric muscle contraction task with 90 degree shoulder anteflexion after each training bout. The maximum voluntary contraction (MVC) force was also measured at this position using HapticMaster. The changes in median frequency and RMS amplitude during fatigue were less in the MS patients than in the healthy individuals possibly due to the different weights used or the difference in muscle physiology between the two groups. However, kinematic trajectory (position) parameters were not under the scope of this study. Also the interaction was not guided by the robot and hence, the experiment rythm was not fixed. The patients should have exercised longer time to get the same amount of repetitions or use a higher weight for the exercise. As a result, the comparison of results between the MS patients and healthy participants could not give a clear picture on the usage of EMG fatigue indicators.

The HapticMaster robot was also used in another rehabilitation project, GENTLE/S for upper limb training of stroke survivors [6][14]. As an extension of these studies, [15] had tried to identify the contribution of the participants and the robot during different human-robot interaction modes and to identify who was leading (robot or the person) this interaction. The actual performance of the participant was compared with the minimum jerk model used by the robot. An adaptive algorithm was developed based on altering the movement duration and resistance parameter of the robot to change the task difficulty level. The adaptability of the system using the robot was tested against the performance of the user. But the study did not consider the muscle fatigue state of the participant during the exercise and no EMG studies were employed.

III. Materials and Methods

This section describes the experimental setup and protocol used in the study. Additionally, the signal processing methodologies for EMG and kinematic feature extraction are briefly explained here. The muscle fatigue indicators used in the analysis are also mentioned.

A. Experiment Setup

Biometrics Ltd DataLINK hardware was used for EMG data acquisition. HapticMaster robot was configured to run in active assisted mode [15]. The Virtual Reality (VR) environment and the graphical user interface (GUI) was configured to follow a rectangular path as shown in Figure 1 and Figure 3.

B. Experiment Protocol

An experiment was designed as shown in Figure 2 and ethics approval was obtained from the University of Hertfordshire under approval reference: COM/PGT/UH/02002. Ten healthy individuals took part in this explorative study. EMG

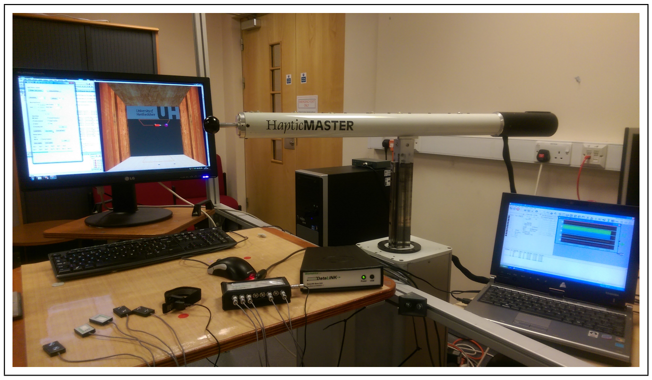

Figure 1. HapticMaster, EMG Device and Virtual Reality Environment

measurements were taken from four upper limb muscles; Trapezius (TRP), Anterior Deltoid (DLT), Biceps Brachii (BB) and Triceps Brachii (TB) muscles. The experiment involved interaction with the HapticMaster robot in active assisted mode where the robot and human participant both contributed to activities and the corresponding position of the robot end-effector was measured during interaction. In the exercise, participants moved the robotic arm in a prescribed path in a two dimensional horizontal plane consisting of four segments S1, S2, S3 and S4. The experiment consisted of 6 trials, and each trials included 10 repetitions of the rectangular motions as shown in Figure 3. The experiments would stop if a total of 6 trials were completed, or if a participant reported fatigue.

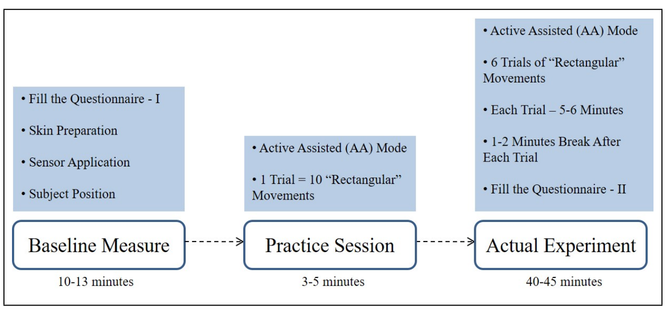

Figure 2. Experiment Protocol

The sitting position and upper limb position of participants during the experiment were as shown in Figure 3

C. Methodology

1) EMG Features: Signal processing algorithms for pre-processing and feature extraction were developed in MATLAB. The EMG signals were band pass filtered in the frequency band of 20-450 Hz using Chebyshev Type II filter [16][17][18]. A narrow notch filter was used (50Hz) to remove the power line interferences [16]. The EMG average power and median frequency were calculated for each segment and each trial.

2) Kinematic Features: The kinematic data like position and segment parameters were logged from the HapticMaster robot and the kinematic features were calculated. Minimum Jerk Trajectory (MJT) position coefficients were calculated from the actual position parameters as described by [6]. The Root Mean Square Error (RMSE) between the actual and MJT position vectors was calculated and used to assess the tracking error in position. It was believed that tracking error will increase as the muscles fatigue.

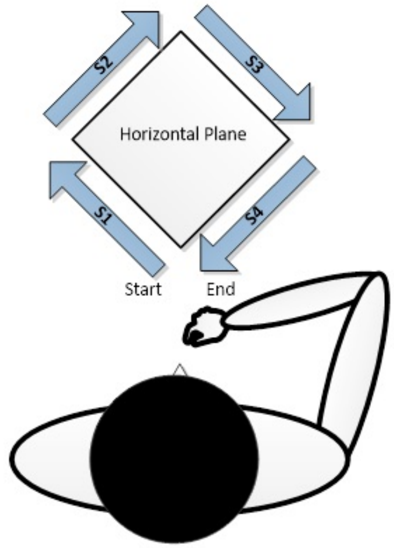

Figure 3. Sitting Position of Participants During the Experiment - Top View

3) Muscle Fatigue Detection: Kinematic (root mean square error (RMSE) in position) and EMG (Average power and median frequency) features corresponding to different trials and segments were analyzed. The change in EMG and kinematic features were studied to understand the development of fatigue in the upper limb muscles in different trials. As the muscle fatigue develops the frequency spectrum and hence, the median frequency will start shifting to lower frequency side and the EMG amplitude will start increasing [16][10][9]. Some studies had also used kinematic position parameters to indicate the performance of participants during robotic interactions [6][14][15] .

IV. Results

This section explains the different results obtained during the analysis of EMG and kinematic data. IBM SPSS version 22 was used for the statistical analysis of the results.

A. EMG Fatigue Indicators

Box plots of the features were generated for each segment to identify trends in median values of EMG features as the trials progressed. The box plots for average power and median frequency as the trials progressed for a typical subject for Trapezius muscle and 1st segment are shown in Figure 4 and Figure 5. A decrease of median frequency and an increase of average power could be noted as the trials progressed [10][5].

Summary tables were created based on the variation of different EMG features across trials as shown in Table I and Table II. Since the EMG features were normally distributed, the mean value of features in each trial for each segment was used to make decisions on the state of fatigue. The mean values between the initial and final trials were compared. The hypothesis for fatigue detection using average power parameter was that, the mean value of average power in the first trial will be smaller that the last trial [10][9]. A "1" in the corresponding cell indicates that the hypothesis is true; meaning that there is an increase in the average power as the trials progresses. A "0" indicates that there is no increase or there is a decrease in its mean value between trials. The table highlights that for the majority of cases, the average power of EMG displays an increasing trend as the trials progressed. As seen in Table I,

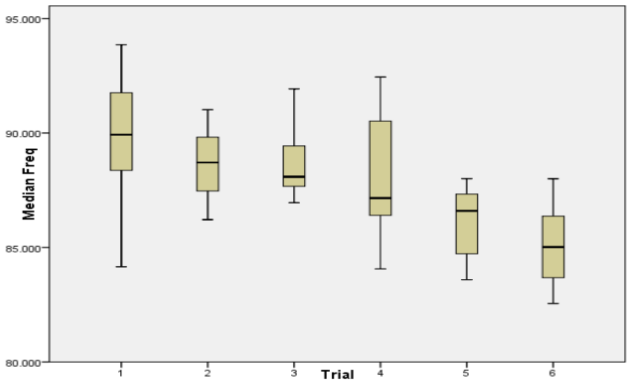

Figure 4. Box Plots for Median Frequency in Trapezius Muscle and Segment 1

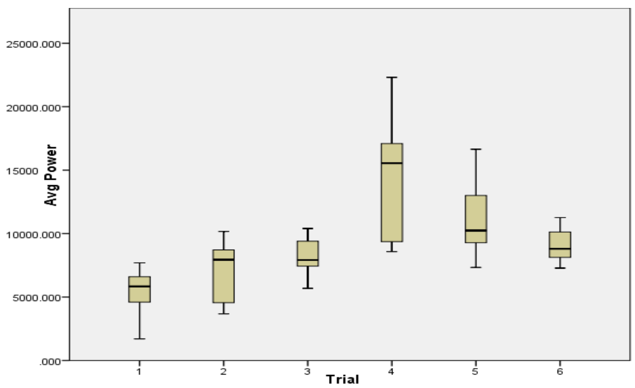

Figure 5. Box Plots for Average Power in Trapezius Muscle and Segment 1

a majority of the analysed cases in Trapezius and Deltoid muscles show an increasing trend (60% and 70% respectively) compared to Biceps and Triceps muscles (37.5% and 40% respectively).

TABLE I. SUMMARY TABLE FOR EMG AVERAGE POWER

Feature ->	EMG Average Power															
Hypothesis ->	The mean value of EMG Average Power in the first trial is smaller than that of the last trial (1 = TRUE, 0 = FALSE, NA = Not Known)															
Methodology ->	Compare the mean values of the parameter between 1st and last trials to see if there is an increase. Each trial includes 10 iterations.															
Muscles ->	TRP				DLT				BB				TB			
Segments ->	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4
Subject 1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1
Subject 2	1	1	1	1	1	1	1	1	1	0	0	0	0	0	1	0
Subject 3	0	0	0	0	0	1	1	0	0	1	1	1	1	1	1	1
Subject 4	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0
Subject 5	0	0	0	0	1	1	1	1	0	0	1	0	1	1	1	1
Subject 6	1	1	1	0	0	1	1	1	0	0	1	0	0	0	0	0
Subject 7	1	1	0	0	1	1	0	1	0	0	0	0	0	0	0	0
Subject 8	1	1	1	1	1	0	0	1	0	0	1	1	0	0	0	0
Subject 9	1	1	1	1	0	1	1	1	0	0	0	0	0	0	0	0
Subject 10	0	1	1	1	1	1	1	1	0	0	1	1	1	0	1	0
TOTAL	6	7	6	5	6	8	7	7	2	2	7	4	5	3	5	3
Fatigue Score	24				28				15				16			
Percentage %	60				70				37.5				40			

Similarly, the hypothesis for fatigue detection using median frequency parameter was that, the mean value of the feature in the first trial will be larger that of the last trial [19][20]. A "1" in the corresponding cell indicated that the hypothesis was true, which meant that there was a decrease in the median frequency as the trials progressed. A "0" meant that there was no decrease or there was an increase in its mean value. As seen in Table II, the median frequency of EMG displayed a decreasing trend as the trials progressed in Trapezius and Deltoid muscles in majority of the analyzed cases (57.5% and 62.5% respectively) compared to Biceps and Triceps muscles (37.5% and 27.7% respectively). This might be probably due to the increased fatigue state of TRP and DLT muscles compared to BB and TB muscles.

TABLE II. SUMMARY TABLE FOR EMG MEDIAN FREQUENCY

Feature ->	EMG Median Frequency															
Hypothesis ->	The mean value of EMG Median Frequency in the first trial is higher than that of the last trial (1 = TRUE, 0 = FALSE, NA = Not Known)															
Methodology ->	Compare the mean values of the parameter between 1st and last trials to see if there is a decrease. Each trial includes 10 iterations.															
Muscles ->	TRP				DLT				BB				TB			
Segments ->	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4
Subject 1	1	1	1	1	1	1	1	1	0	1	1	1	0	0	0	1
Subject 2	1	1	1	1	0	1	0	0	0	0	0	1	0	0	0	1
Subject 3	1	1	0	0	1	1	0	0	0	0	0	1	1	0	0	0
Subject 4	1	1	0	0	1	1	1	1	1	0	1	0	1	0	1	0
Subject 5	0	0	1	1	0	1	1	1	0	1	1	0	0	0	0	1
Subject 6	1	0	0	1	1	1	1	1	1	0	1	0	0	1	1	1
Subject 7	1	1	0	1	0	0	0	1	0	0	0	1	0	0	0	0
Subject 8	1	1	1	1	1	1	1	0	0	1	1	0	0	0	1	1
Subject 9	0	0	0	0	0	0	1	1	0	0	1	0	0	0	0	0
Subject 10	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
TOTAL	7	6	4	6	5	7	7	6	2	3	6	4	2	1	3	5
Fatigue Score	23				25				15				11			
Percentage %	57.5				62.5				37.5				27.5			

B. *Kinematic Fatigue Indicators*

The RMSE feature was studied using SPSS box plots and MATLAB plots and summary tables were generated by comparing the median values of first and last trials. An increase of RMSE error was noted between the first and last trials. In the summary table (Table III), a value of 1 means that there was an increase in the error between first and last trials. A value of 0 means there was no increase or there was a decrease in the error. The hypothesis was that there will be an increase of RMSE error between first and last trials when the muscles come to a state of fatigue. 70% and 60% of the subjects displayed an increase of RMSE for the S2 and S3 segments respectively, whereas S1 and S4 segments had the least percentage(40% for both). The RMSE fatigue indication was hence, more during S2 and S3 segments than during the S1 and S4 segments. This might be possibly due to the fatigue developed during the trials in association with the 'away-from-body' movements involved in S2 and S3 segments.

V. DISCUSSION

This section presents further discussion on the results, the possible inference from the results and their linkage to similar studies in the past.

A. *Discussion on EMG Analysis*

It was noticed that most of the participants were challenged especially on the DLT and TRP muscles due to the horizontal position of the upper limb. It was observed that none of the participants were able to hold their upper limb in the horizontal position continuously (as it was supposed to be). This was due to the intentionally complex movement requirements [12]. Subjects could only complete the trials by lowering their upper limb below the shoulder level (hence, by not following the preferred position in the experiment design).

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TABLE III. SUMMARY TABLE FOR RMSE ERROR IN POSITION CONSIDERING FIRST AND LAST TRIALS

Feature ->	Root Mean Square Error (RMSE) between Actual Position Vector on MJT Position Vector			
Hypothesis ->	The median value of RMSE parameter in the FIRST trial is smaller than that of the LAST trial (1 = TRUE, 0 = FALSE, NA = Not Known)			
Methodology ->	Compare the median values of the parameter between 1st and last trials to see if there is an increase of error. Each trial includes 10 iterations.			
Segments ->	S1	S2	S3	S4
Subject 1	0	0	0	0
Subject 2	0	0	0	0
Subject 3	0	1	1	1
Subject 4	0	1	1	0
Subject 5	1	1	1	1
Subject 6	0	1	0	0
Subject 7	1	1	1	1
Subject 8	1	1	1	1
Subject 9	1	1	1	0
Subject 10	0	0	0	0
TOTAL	4	7	6	4
Percentage	40%	70%	60%	40%

TABLE IV. SUMMARY TABLE FOR RMSE ERROR IN POSITION CONSIDERING 1ST AND 2ND TRIALS

Feature ->	Root Mean Square Error (RMSE) between Actual Position Vector on MJT Position Vector			
Hypothesis ->	The median value of RMSE parameter in the FIRST trial is smaller than that of the SECOND trial (1 = TRUE, 0 = FALSE, NA = Not Known)			
Methodology ->	Compare the median values of the parameter between 1st and 2nd trials to see if there is an increase of error. Each trial includes 10 iterations.			
Segments ->	S1	S2	S3	S4
Subject 1	0	0	0	0
Subject 2	0	0	0	0
Subject 3	0	0	1	1
Subject 4	0	0	0	0
Subject 5	1	1	1	1
Subject 6	0	1	0	0
Subject 7	1	1	1	1
Subject 8	1	0	1	1
Subject 9	0	1	1	0
Subject 10	0	0	0	0
TOTAL	3	4	5	4
Percentage	30%	40%	50%	40%

During the analysis of EMG signals, the expectation was that there will be an increasing trend for the average power and a decreasing trend in median frequency as the trials progressed. The results had indicated that both the parameters displayed such a trend as explained by the summary tables Table I and Table II. However, the average power seems to be a better indicator of fatigue compared to median frequency due to the higher percentage scores achieved. In the current experiment, the fatigue was mainly caused by the horizontal position of upper limb hence, the fatigue had affected mainly the DLT and TRP muscles. Comparison of mean values of EMG features across trials displayed higher percentage fatigue scores for Trapezius and Deltoid muscles in majority of the analyzed cases (60% and 70% respectively) compared to Biceps Brachii and Triceps Brachii muscles (37.5% and 40% respectively).

B. Discussion on Kinematic Data Analysis

The study of the kinematic features showed that there was an increase of RMSE error more visible in S2 and S3 segments than in S1 and S4 segments. This could be because S2 and S3 were the most difficult segments, which were away from the body and hence, tracking error was more visible in them. To ascertain if the increase of RMSE error between first and last trial is due to fatigue or perception error, we compared the error between the first and second trial. Another summary table was formed by comparing the median values of RMSE error between the first and second trials as in Table IV. The fatigue percentage for S2 and S3 segments were found to be 40% and 50% respectively in this case compared to the case considering the first and last trials (70% for S2 and 60% for S3). This indicated that the RMSE error due to fatigue was not as visible in the second trial as was the case in the last trial in majority of the analysed cases. This study implied that the increased fatigue score during S2 and S3 segments was not attributed to the perception error in locating the 3 dimensional reach points but was due to the development of fatigue as the trials progressed.

The S2 and S3 segments for majority of the subjects involved too much variations at the reaching point of the segment possibly due to the difficulty in accurately judging the end position of the segments. It seems that this inaccuracy increased when the subjects got fatigued as the trials progressed. This might have resulted in an increased RMSE in the final trials of S2 and S3 segments compared to the initial trials as implied by the higher percentage scores. On the other hand, the smaller percentage for the S1 and S4 segments (40%) might be because, they involved movements in space where the upper limb was closer to the body. This might make the movements easier than the other segments. This might mean that the subjects were in a more comfortable upper limb position during S1 and S4 movements or it was more easy to follow the robot in these segments. These results can be related to the findings of [15], which stated that the 'reaching away' movements were longer than the 'returning towards' movements. However, there could be a further explanation for the error in movements away from the body. The perception errors when trying to reach virtual objects away from the body could cause larger tracking errors due to overestimation of the distance to peripheral targets, which might lead to overshooting reaching movements [21][22].

The results of EMG fatigue analysis had indicated that the DLT and TRP muscles were fatigued more. Similarly, the results from the analysis of RMSE error had indicated that S2 and S3 segments displayed more error and variation in position compared to S1 and S4 segments. Hence, it can be inferred that the indication of fatigue by EMG signals (mainly from TRP and DLT muscles) were kinematically correlated with the errors and variations in position mainly in the segments, which were difficult to execute (S2 and S3) as shown by the summary tables of kinematic and EMG features.

VI. CONCLUSION AND FUTURE WORK

The research studied quantitatively which muscles where involved and fatigued in a robot assisted exercise in a 3 dimensional space in presence of a virtual environment. The EMG analysis indicated that Trapezius (TRP) and Anterior Deltoid (DLT) muscles were more in a state of fatigue compared to Biceps Brachii (BB) and Triceps Brachii (TB) muscles. The study also looked into how the kinematic features from the robot represented the muscular fatigue. The variation in tracking error during the robot assisted upper limb interactions were found to indicate physical fatigue in the muscles involved. Similar to the study by [12], we identify that DLT and TRP muscles were fatigued more. This is because of the role of the two muscles in lifting the arm to the shoulder height in order to perform the activity. The higher fatigue indication in Trapezius and Deltoid muscles can be mapped to kinematic indications of fatigue mainly in the segments S2 and S3 which were away from body, because these muscles were actively contributing to keep the horizontal position of the upper limb.

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Our extracted features have shown the potential to identify the fatigued muscles as expected. The study also showed that the EMG and kinematic features have a potential to be used to highlight the extent of muscle involvement, as the positioning of the segments and the required articulations for performing those segments relate to the EMG observations. For example, the increase of RMSE error was the least in S1 and S4 segments, which were comfortable 'near-the-body' movements and considering musculoskeletal physiology, Biceps Brachii and Triceps Brachii muscles play the major roles in these segments. The summary tables for tracking error also implied that the increased fatigue score during S2 and S3 segments was not attributed to the perception error in locating the 3 dimensional reach points but due to the development of fatigue by the end of the experiment.

In the experiment, the HapticMaster robot was configured in the Active Assisted mode and all the participants in the experiment were healthy individuals. The robot was providing some assistance/guidance to the participant when there was less effort from the participant to move the end-effector along the different segments. A limitation of this study was that, the robotic assistance resulted in a reduced the muscle fatigue to the participant. However, it was also noticed that the indications of fatigue were observed even with this robotic assistance. Additionally, the experiment protocol had also defined 1-2 minutes of break period between each trial. This period was introduced in order not to harm the participant's muscles due to over challenging. However, this break period could result in a recovery from the state of muscle fatigue developed during the trial (short term fatigue) before they started the next trial. Hence, the continuity of any trend in the features used as fatigue indicators were partly lost. Hence, the experiments could have been be made a bit more difficult and the break period could be avoided so that the muscles are sufficiently tired to produce better indications of fatigue. Probably due to this reason, at the end of the experiments all the participants stated (through a questionnaire) that they were only slightly fatigued. A further study is hence planned to address these aspects.

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