Upper limb discomfort profile due to intermittent isometric pronation torque at different postural combinations of the shoulder-arm system

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Relevance of Findings:

Industrial jobs involving deviated upper arm postures are typical in industry but have a strong association with injury. Data from this study enables better understanding of the effects of deviated upper arm postures on Musculoskeletal Disorders and can also be used to identify and control high-risk tasks in industry.

Keywords

Pronation, elbow flexion, musculoskeletal disorders, discomfort

Abstract

Twenty-seven right-handed male university students participated in this study which comprised a full factorial model consisting of three forearm rotation angles (60% prone and supine, and neutral range of motion), three elbow angles ($45,^0$ 90^0 and 135^0), three upper arm angles (45^0flexion/extension, and neutral), one exertion frequency (15 per minute) and one level of pronation torque (20% MVC relative to MVC at each articulation). Discomfort rating after the end of each five minute treatment was recorded on a visual analogue scale. Results of a repeated measures ANCOVA on discomfort score, with torque endurance time as covariate, indicated that none of the factors were significant including torque endurance time (p=0.153). An initial data collection phase preceded the main experiment in order to ensure that participants exerted exactly 20% MVC of the particular articulation. In this phase MVC pronation torque was measured at each articulation and the data revealed a significant forearm rotation angle effect (p=0.001) and participant effect (p=0.001). Of the two-way interactions, elbow*participant (p=0.004), forearm*participant (p=0.001) and upper arm*participant (p=0.005) were the significant factors. Electromyographic activity of the Pronator Teres (PT) and Biceps Brachii (BB) muscles revealed no significant change in muscle activity in most of the articulations.

Key words: upper arm, flexion, extension, pronation torque, pronation, supination

1. Introduction

Any force exertion, repetition of activities or adoption of one particular posture for prolonged periods, imposes stress on the human physical system. This leads to a mismatch between the task and person leading to different types of Work Related Musculoskeletal Disorders (WMSDs) injury and accidents at the work place (Kumar, 2001).

Anderson (1971) reported that among assembly line workers the shoulder complex and upper limbs were the centres of 21.1% of complaints of musculoskeletal pain. Maeda (1975) found that in the Japanese manufacturing industry pain was reported in the shoulders, arms and hands of nearly 21% of the factory workers studied, with all the symptoms mainly due to poor workplace design. Bjelle et al. (1979) reported that 68.8% of the patients in an occupational health clinic suffering from shoulder pain worked with their hands at or above shoulder level. Wiker et al. (1989) inferred that sustained work with awkward or biomechanically stressful postures increased the risk of encountering musculoskeletal pain and discomfort.

There are many industries where work needs to be performed with awkward postures. Hagberg and Wegman (1987) reported a high prevalence of neck and shoulder disorders among dentists, meat carriers and miners. In the electronics industry working conditions often demand working with raised arms (Kilbom and Persson 1987). In garment, automotive trim sewing, metal parts assembly, packaging etc. awkward postures affect the shoulder and upper limbs in general and can lead to musculoskeletal disorders in the long run (Ranney et al. 1995). Herbert et al. (2001) reported that sewing machine operators had a very high incidence of upper arm and shoulder related musculoskeletal symptoms. In the shoulder joint the movements found to be frequent and awkward in workplaces were abduction and upper arm flexion (Hagberg and Wegman 1987).

Work activities performed by industrial workers involve handling objects such as tools, products etc. which necessitate upper arm flexion, abduction and adduction (Gill Coury et al. 1998a). In another study carried out in Brazilian industry (Gill Coury et al. 1998b) very short work cycle time (about 10 secs) involving compression and frequent adduction movement was reported. Lutz et al. (2001) reported that many occupations in industry required upper arm flexion and some deviation from neutral neck and shoulder positions. These jobs included inspection, assembly, and prolonged work at a video display unit (VDU). Kilbom and Persson (1987) in a study on an electronics manufacturing industry revealed forward flexion of the neck along with shoulder elevation. Anton et al. (2001) reported that construction workers, sheet metal workers etc., have to work with hands overhead to manipulate drills or pliers.

The disorders linked to shoulder movements are thoracic outlet syndrome and rotator cuff tendonitis (Muggleton et al. 1999). It was reported by Muggleton et al. that rotator cuff tendonitis is closely associated with upper arm abduction and forward flexion. It has been shown that with arms raised or abducted the blood vessels supplying the tendons on the supraspinatus muscles were compressed (Grieco et al. 1998), thus altering blood circulation. Such postures render the shoulder-arm system vulnerable to WMSD.

In the upper arm it is becoming accepted that certain types of physical stressors affect muscle tissue in general (Ranney et al. 1995). Gill Coury et al. (1998a) reported a significant drop in upper arm adduction strength with the upper arm flexed to 90^0 and more. Torque exertion was however not investigated. Kattel et al. (1996), in a study on the effects of upper extremity posture on grip strength reported a fall in grip strength with upper arm abduction. Upper arm flexion /extension were not looked into. Salter and Darcus (1952) in a study on Maximum Voluntary Contraction (MVC) torque at different articulations of the arm in adduction reported inconsistency in MVC torque data. They however did not look into pronation torque or into upper arm flexion /extension. Acosta et al. (2002) studied MVC supination torque with upper arm flexed at different angle, however upper arm extension, with pronation torque was not looked into. In a similar experiment the torque was defined as 20% relative to the MVC torque of the participant (O'Sullivan and Gallwey 2005) to reduce the effects of inter-individual differences. Kilbom and Persson (1987) reported that electronic manufacturing work has many common characteristics such as sitting with forward flexion of the neck and raised arms. Their study on an actual working group indicated that the percentage of work cycle time which had upper arm extension, was a strong indicator of shoulder and upper limb disorders. The same group reported that there was a natural tendency among some workers to support their arms as much as possible.

There are basically two ways in which work related musculoskeletal disorders can be identified. One is from epidemiological findings and looking for the relationship between WMSD and work conditions (Kumar 2001). The other is through experimental procedures in a controlled environment (Gill Coury et al. 1998b) by systematic variation of the levels of factors. In the latter, some studies measure short-term effects such as level of perceived bodily discomfort as the dependent variable. The warning provided by body discomforts can be used as valuable indicators of mismatches between the job and the human operator (Corlett and Bishop 1976). Thus the discomfort score of the participants has been used by various researchers (Bousenna et al. 1982, Briggs and Closs 1999, Carey and Gallwey 2002, O'Sullivan and Gallwey 2005) for predicting musculoskeletal injury. The problem of using discomfort scores to draw inferences is that there are inter-individual differences in pain tolerances. Such differences might confuse the results from the experiments when trying to draw general conclusions. Thus a covariate needs to be incorporated in the experiment to get a measure of pain tolerance.

This review reveals that there is a lack of quantitative data on the effects of upper arm flexion and extension angles combined with pronation torques as happen typically in industry. This study extends other work by some of the authors including effects of wrist posture (Carey and Gallwey, 2005) and forearm rotation (O' Sullivan and Gallwey, 2005) on upper limb discomfort. More recent studies extended this to include effects of posture combinations of the forearm, elbow and upper arm. Mukhopadhyay et al. 2007a reported discomfort profiles for forearm and elbow posture effects combined with two levels of force and forearm pronation torque frequency, while Mukhopadhyay et al. 2007b included effects of upper arm rotation and upper arm flexion. It was necessary to extend this work to include forearm rotation, upper arm flexion and elbow flexion effects simultaneously so as to cover a more complete set of postures as is typical in industry.

2. Method

2.1 Approach

The general approach involved using a jig that enabled combined setting of forearm rotation, elbow and upper arm flexion postures while the participant applied repetitive forearm prontation torques at a controlled pace and level. Levels of force and forearm Range of Motion (ROM) angles were related to the maximum capability of each participant while elbow angles and upper arm flexion/extension angles were expressed in absolute values so that the situation mimics the industrial scenario where the same workstation is used by different workers.

The term pronation torque has been used in this research to denote torque exertion in the anticlockwise direction for the right hand only. The terms prone and supine are used to denote the rotational position of the forearm only.

2.2 Design of experiment

The treatments comprised three levels of elbow angle (45^0, 90^0 and 135^0), three levels of forearm rotation angle (0, +/-60% Range of Motion), and three levels of upper arm angles (45^0 flexion/extension and neutral). These were based on the postures normally found in different industrial tasks (Table 1). The torque was constant at 20% MVC (O' Sullivan and Gallwey, 2005) and frequency of exertion constant at 15 exertions per minute (Carey and Gallwey 2005). The cycle was one second of exertion followed by three seconds of relaxation. These cycles lasted for five minutes followed by one minute of rest. McKenna and Gallwey (2002) reported a similar short cycle time in an electronic assembly task and Corlett and Bishop (1976) reported a similar work-rest cycle.

Modified Latin Square orders were used to determine the order of treatment combinations. As it took some time to adjust the fixture and in order to reduce inconvenience to the participants, the treatments were set in blocks of the same upper arm angles. Under each block the other treatment combinations were also ordered by means of a Latin Square design.

[Insert Table 1 here]

2.3Participants

Twenty-seven right-handed male University students, with no previous history of musculoskeletal disorders participated. Their mean age was 23.5 years (SD=3.1). The mean stature was 178.5 cm (SD=7.2) and body mass was 76.8kg (SD=8.0). The participants received an explanation of what needed to be done by a written instruction. They had to answer some questions regarding their health status, sign a consent form and only if they were not suffering from an injury and had no upper limb discomfort, were they allowed to proceed with the experiment. All participants who volunteered were paid at the rate of 7.50 Euro per hour. The Ethics Committee of the University of Limerick approved the experimental procedure.

2.4 Apparatus

2.4.1 Seat Fixture. The apparatus was in two parts, a seat fixture attachment to maintain the upper arm and elbow postures, and a variable position torque meter attached to a bench (Figure 1). The seat attachment comprising a steel fixture with hinge and height adjustment was fabricated in-house to maintain the upper arm flexed and extended at different angles, and to keep the elbow flexion/extension angle constant as per treatment combinations. The entire fixture was attached to the underside of a chair with variable height such that the participants could maintain an upright sitting posture with feet flat on the floor while performing the treatments. The fixture could be moved back and forth around a fixed point so as to support the upper arm (including the elbow and forearm) in different combinations to reduce the effects of static load.

[Insert Figure 1 here]

2.4.2 Torque meter. Forearm torque was measured using a meter built in-house (Figure 1). The meter comprised a shaft and handle (diameter 25mm) in a T-bar configuration identical to that used by O'Sullivan and Gallwey (2005). The handle made an angle of 70^0 to the shaft so as to provide for neutral wrist deviation. The shaft was reduced to 8mm thickness to provide gripping between the index and second finger. Strain gauges mounted on the shaft detected torques and these were further amplified by a strain gauge amplifier (Vishay Measurement Model Number 2150) and then passed to the data acquisition system. The torque measurement bar shaft rotation position was adjustable so as to enable testing of the prone, neutral and supine posture treatments. In turn the meter was attached via an arm to a variable height table so as to enable the correct positioning of the meter for the elbow and upper arm posture treatment combinations.

2.4.3 Goniometer. A Penny and Giles Biometrics electro-goniometer (model Z180) was used to record the forearm rotation angles. Voltage readings from the goniometer were amplified and zeroed using a Biometrics K100 amplifier.

2.4.4 EMG and applications. The main purpose of recording EMG was to measure activity of individual muscles to evaluate their relative contribution at each articulation. Elevated muscle activity and resultant fatigue is often a precursor to discomfort and this data help explain trends in the results. The Pronator Teres (PT) and Biceps Brachi (BB) were selected for study as they are a major forearm pronator and elbow flexor respectively.

EMG amplifiers (CB Sciences model ETH 2001) with input impedance of 10M-ohm, a CMRR of 100dB and adjustable gain set to x1000, were used for recording electrical activity of muscles at a sampling rate of 512Hz. RMS values for EMG recorded signals were calculated for 10 seconds duration at each span of 500ms with a 50% overlap. The RMS values were normalized in terms of % EMG on the basis of maximum and minimum electrical activity of the muscles while applying torque as per Strasser (2001). Electrode placement was determined on the recommendations of Delagi et al. (1980) and the skin was prepared in line with Wiker et al. (1989). In preparation for electrode attachment the relevant portion of the skin was shaved, then rubbed with fine sand paper and cleaned with absolute alcohol to ensure the skin resistance was below 10 k-ohms. After this pairs of surface electrodes were applied to the skin. The inter-electrode distance was 20mm for each muscle recording and the electrode-to-electrode distance for each muscle group was kept greater than 30mm to minimize cross-talk (Strasser 2001).

2.4.5 Data acquisition (computer interface). Signals from the goniometer were interfaced with the PC (333 MHz) using a National Instruments data acquisition and A/D converter board (model PCI-MIO-16XE-50) with a BNC adaptor board (model BNC2090). Voltage signals from the strain gauges and from the EMG amplifiers were also interfaced with the PC using the BNC adaptor board. Virtual Instruments (VIs) were written using G code in LabVIEW (V.6i) to control the experiment. Separate VIs were coded for each part of the experiment and loaded dynamically into memory. The electro-goniometer and torque signals were configured within LabVIEW and the readings were displayed in real time on the VDU for the VIs.

2.5. Procedure

2.5.1. Preliminary data collection. The participant rested his arm on the fixture and its height was adjusted so that the upper arm, elbow and forearm fitted comfortably in the fixture. Next the participant was strapped to the chair with a seat belt to prevent lateral movement of the body during the experiment. The torque meter was aligned with the centre line of the participant's arm. The electrogoniometers were attached in accordance with the manufacturer's guidance and zeroed. Maximum pronation torque strength was recorded at the standard position with the wrist and forearm at neutral and the arms abducted at 0^0 (Mogk and Kier 2003). Next endurance time at 50% MVC torque in the above position was recorded (O' Sullivan and Gallwey 2005, Carey and Gallwey 2005), as a possible covariate, to account for individual differences in pain tolerance. This was recorded after a break of ten minutes to minimize cumulative fatigue effect. Maximum range of motion of the forearm was measured with the elbow at 90^0. In all cases the participant was guided by the LabVIEW programme. When the participant exerted 50% MVC the counter turned green and any overshoot or undershoot caused a beep to warn him and also the pointer turned red. Five minutes rest was taken before completion of the next part of the experiment to prevent carry over of fatigue to the MVC testing.

Pronation torque MVC was measured at each of the 27 treatment posture combinations. Each of the treatment orders was presented to the participant using Lab VIEW VIs (Figure 2). Participants exerted their maximum MVC three times for each treatment at one minute intervals and the software automatically recorded the highest of the three.

[Insert Figure 2 here]

For the measurement of EMG activity from the Pronator Teres and Biceps Brachii muscles for the 27 treatments, the participant was presented with a VI (Figure 3) and asked to build up his maximum pronation torque and hold it for 10 seconds, as controlled by the software. Next the participant was asked to keep the arm on his lap for 10 seconds as the resting muscle EMG was being recorded. After this the participant was presented with a VI which displayed the combination of each articulation. At each articulation the participant was instructed through the software to exert 20% MVC torque for 10 seconds, the end of which was indicated by a beep, after which the participant released the force.

[Insert Figure 3 here]

2.5.2. Main experiment. For the main experiment on discomfort score, each of the 27 treatment orders were presented to the participant using another VI (Figure 4). This also controlled the frequency and level of exertion for each treatment during testing. After the five minutes repetitive exertion, the participant rated discomfort on a 100mm Visual Analogue Scale (VAS) using the cursor on the VI. The VAS had verbal anchors of “No Discomfort”, “Moderate Discomfort” and “Extreme Discomfort” as shown in Figure 4. The participant used the curser, or up and down arrows of the keyboard, with the left hand to mark a position on the VAS, and its position from the left extremity was converted to a value between 0 and 10. A rest of one minute followed testing of each treatment to reduce cumulative fatigue effects, during which the participant indicated the zone of maximum discomfort on a body part discomfort map. The entire experiment lasted for about five hours, thus mimicking more than half a shift in industry.

[Insert Figure 4 here]

3. Results

All data were recorded in text file format on the computer hard drive during testing and imported into statistical analysis software (SPSS: Statistical Package for Social Sciences, SPSS V.11) for subsequent analysis.

3.1. Initial data collection phase

3.1.1. Maximum torque and endurance time. The mean pronation torque strength was 6.1Nm (SD=1.8). The mean holding time (endurance) for 50% of the maximum torque was 72.3 seconds (SD=40.1).

3.1.2. MVC torque strength at different articulations. Maximum value of pronation torque strength (6.6Nm) was with the upper arm flexed at 45^0, elbow angle at 90^0 and with forearm supine (Table 2). The minimum value of pronation torque (2.8Nm) was at 45^0 upper arm flexion, with elbow flexed at 45^0 and with forearm prone.

[Insert Table 2 here]

3.1.3. Analysis of Variance (ANOVA) on MVC torque. As MVC torque data were not normally distributed, the square root transformation [sqrt (X+0.5)] was used

(Levene's test, p=0.853). On the transformed data a mixed model Analysis of Variance (ANOVA) was done (Table 3). MVC torque was the dependent variable and upper arm flexion/extension angle, elbow angle and forearm rotation angles were fixed factors. Participant was taken as a random factor.

[Insert Table 3 here]

Forearm rotation (p=0.001) and participants (p=0.001) were highly significant. Of the two-way interactions, forearm angle*participant (p=0.001), elbow angle *participant (p=0.004) and participant*upper arm angle (p=0.005) were significant. No other factors were significant.

To differentiate between the levels of forearm rotation angle in the ANOVA, Student Newman Keuls tests were performed on factors significant in the ANOVA namely forearm rotation angle (Table 4). The discomfort data for all three forearm rotation angles were significantly different from one another.

[Insert Table 4 here]

3.2. Discomfort score

As in previous experiments (Carey and Gallwey 2005, O' Sullivan and Gallwey 2005) the intention was to standardize discomfort data using a min-max standardization procedure (Gescheider 1985) for each participant as follows:

$$\text{Standardized Discomfort Score (SDS)} = \frac{\text{Raw Data- Minimum Data}}{\text{Maximum Data- Minimum Data}} \times 10$$

This was to reduce between participant differences in perception of discomfort and for comparing the pattern of SDS change with the data existing in the literature. But the SDS data were not normally distributed and could not be normalized using different types of transformation. The Raw Discomfort Scores (RDS) were also not normally distributed, but the natural logarithm transformation was successful (Levene's test, p=0.876) and these Transformed Discomfort Scores (TDSs) were used to perform all statistical analysis including ANCOVA.

For comparison purposes the mean and standard deviation (SD) of Raw Discomfort Score (RDS), Standardized Discomfort Score (SDS) and Transformed Discomfort Score (TDS) at different articulations are presented in Table 5.

[Insert Table 5 here]

Maximum discomfort occurred at 45^0 upper arm extension, elbow at 135^0 with forearm prone. The values were RDS (3.1), SDS (6.3) and TDS (0.6). Similarly discomfort was minimum at neutral upper arm angle, 90^0 elbow angle with forearm at neutral, with values of 1.8 for RDS, 2.7 for SDS and 0.4 for TDS respectively.

3. 3. Analysis of Covariance (ANCOVA)

Mauchly's test of sphericity (Table 6) was performed on the TDS. Some of the factors violated the sphericity tests and hence the repeated measures ANCOVA (Table 7) was performed using the Greenhouse-Geisser Correction (GGC) with torque endurance time as covariate. Torque endurance time was not significant (p=0.153) and none of the main effects or the interactions were significant.

[Insert Table 6 here]

[Insert Table 7 here]

To investigate why main effects were not significant in the ANCOVA, the effect of articulations on RDS was examined with RDS as a percentage of the value at the standard position (Table 8).

[Insert Table 8 here]

The RDS values changed in a variety of ways with no clear pattern, showing that using relative MVC values at each posture combination only removed some of the cause of discomfort.

3.4. Interactions

The Transformed Discomfort Scores (TDS) were plotted against posture combinations (Figures 5 through 7). Where points appeared close together on the graph, a t-test was performed to test for parallelism. Subsequent linear equations were developed (Table 9) to get an insight into the rate of change of discomfort from the slope of the line.

[Insert Table 9 here]

TDS Vs forearm rotation at different elbow angles (Figure 5) indicated an increase in discomfort in prone compared to supine. Maximum rate of change of discomfort was at 45^0 elbow angle with forearm prone (slope: 0.000568). There was a similar rate of change of discomfort at elbow angles of 135^0 and 90^0 with forearm supine (t=0.233, p=0.818), elbow angles of 45^0 and 90^0 with forearm supine (t=0.259, p=0.798) and forearm prone (t=0.752, p=0.459).

[Insert Figure 5 here]

TDS Vs forearm rotation at different upper arm angles (Figure 6) indicated increased discomfort in extension compared to flexion. Maximum rate of change of discomfort was at 45^0 upper arm flexion with forearm prone (slope: 0.0011) and minimum rate of change of discomfort at 45^0 upper arm extension with forearm supine (slope: 0.00007). Similar rate of change of discomfort was noticed at 45^0 upper arm flexion and 45^0 upper arm extension with forearm prone (t=0.130, p=0.897), and at 45^0 upper arm flexion and neutral upper arm with forearm prone (t=1.652, p=0.111).

[Insert Figure 6 here]

TDS Vs upper arm angle at different elbow angles (Figure 7) indicated increased discomfort at upper arm extension compared to flexion. Maximum rate of change of discomfort was at 135^0 elbow angle with upper arm at 45^0 extension (slope: -0.00147) and minimum rate of change of discomfort at 45^0 elbow angle with upper arm at 45^0 flexion (slope: -0.000052). Similar rate of change of discomfort was observed at 135^0 and 90^0 elbow angles with upper arm at 45^0 extension elbow angles of 45^0 and 90^0 with upper arm at 45^0 flexion but these differences were not significant (elbow angles t=1.874, p=0.072, upper arm angles t=1.903, p=0.068).

[Insert Figure 7 here]

3.5. Body part discomfort mapping

Discomfort was most frequently reported in the forearm followed by the wrist and upper arm (Figure 8). The shoulder region had the lowest frequency of discomfort reports.

[Insert Figure 8 here]

3.6. Electromyography (EMG)

For both the Ponator Teres (PT) and Biceps Brachii (BB) muscles there were few articulations that exhibited significant change in muscle activity (Table 10).

[Insert Table 10 here]

In the case of PT muscle, forearm rotation from neutral to prone exhibited a 42.9% increase in activity that was significant (t=6.058, p=0.001). For all other articulations PT muscle activity was not significantly different. For BB muscle upper arm movement from neutral to flexion was manifested by a 7.6% decrease in muscle activity which was significant (t=3.810, p=0.005). Again for BB the change in elbow angle from 90^0 to 45^0 exhibited an 8.2% increase in activity (t=2.450, p=0.040). Similarly for the same muscle a change in elbow angle from 90^0 to 135^0 exhibited a 21.3% increase in muscle activity (t=7.498, p=0.001). No other differences were significant.

4. Discussion

4.1. Maximum torque and endurance time

The mean value of pronation torque recorded in this experiment (6.1 Nm) at the standard position of the arm was lower than reported (12.4Nm) by Kramer et al. (1994). It was however close to the value reported (7.2Nm) by Salter and Darcus (1952). The mean holding time recorded (72.3 seconds) in this experiment was somewhat higher than O’Sullivan and Gallwey (2005) with 47.7 seconds. The standard deviation was 40.1 in the current experiment signifying a big variation in the holding time of the participants.

4.2. MVC torque strength at different articulations

Decrease in torque MVC with forearm pronated, and increase with forearm supinated, was in agreement with Gordon et al. (2004). This group also reported greater pronation torque at the supine condition of the forearm, due to greater mechanical advantage of the Pronator Teres muscle. Richards et al. (1995) also demonstrated that as the forearm moves from supination to pronation, the direction of pull of the muscles in the anterior or flexor compartment changes, especially in those muscles that originate from the radius as it rotates around the ulna, which is stationary. As the hand moves from supine to prone the forearm muscles wrap around the radius. This leads to a possible change in length of these muscles leading to impairment of these muscles in achieving maximum force. The change in length of the long flexor muscles from supination to pronation also potentially changes the synergistic relationship among the long extensors of the fingers and the flexor and extensor muscles stabilizing the wrist. So primary pronators such as the Pronator Teres are affected, and so pronation torque declines compared to supination. The authors did not explain the exact change in length of these muscles, but it could be anticipated that the changes were significant so as to bring about a change in the force exerting capability of the hand muscles.

However the non-significance of the upper arm flexion/extension angles and elbow angle, were in agreement with that reported by Salter and Darcus (1952). This group performed a similar experiment and measured the pronation torque with forearm at neutral, 30^0 and 60^0 in prone and supine with elbow angles at 90^0, 150^0 and 180^0. However they did not specify the exact upper arm flexion/extension angles. This group reported that, in their experiment with MVC torque (pronation) with upper arm flexed, considering all elbow positions, “there was neither a consistent increase nor decrease in statistical significance in any of the participants during the experimental period.” It might be that the range of upper arm flexion/extension in the current experiment was not sufficient to elicit significant change in the shoulder arm system and hence no change in MVC torque.

Acosta et al. (2002) measured isometric torque in the horizontal plane at 35^0, 55^0 and 75^0 upper arm flexion angles. The elbow angles were 90^0 and 120^0 with the forearm at neutral. They also reported that there was no significant change in isometric torque with the change in arm configuration. The reasons that they cited such results were that the range of upper arm flexion angles included in the experiment was not sufficient to effect changes in the joint torque. A close look at the anatomy of the shoulder arm system reveals that the maximal upper arm flexion range for the human is 110^0 and for extension is 70^0 (Palastanga et al. 1998). In the current experiment the range of upper arm flexion and extension angles was only 90^0 (45^0 each way from neutral). Thus it could be inferred that this small range of flexion or extension angles was possibly not sufficient for eliciting any suitable change in MVC torque at different articulations (Table 1). Only forearm rotation affected MVC pronation torque, probably as the primary forearm prontator muscles (Pronator Teres and Pronator Quadratus) moment arms are largely unaffected by upper arm and shoulder joint angle changes.

4.3. ANCOVA on discomfort score

The reason for no significant factors for discomfort score in the ANCOVA was not clear. As interaction plots of discomfort at different articulations did indicate changes, it was felt necessary to explore the discomfort scores (TDS) of each individual participant. Box and whisker plots for each participant were constructed (Figure 9) with TDS. The plots show that there is a large variation in the data with the smallest observation at about 0.05 (Participant 2) and the largest observation at about 1.05 (Participant 23) as indicated by the smallest and largest length of the whiskers of the boxes. Few of the plots indicated central tendency but rather considerable skewness of the data. For Participants 1, 8, 9, 14 and 25 the medians were extremely skewed. There were extreme outliers (indicated by asterisk) for Participants such as 1, 3 and 25. Mild outliers were noticed for Participants 1, 6, 7, 9, 16, 17, 19, 20, 22, 23, 25 indicated by a small circle. Based on these data it is concluded that there were posture effects but that these were more pronounced for some participants than others.

[Insert Figure 9 here]

4.4. Forearm rotation

Discomfort was higher with deviated forearm rotation postures. SDS value was greater in prone (5.0) than when supine (4.2). These trends were similar to that reported by O' Sullivan and Gallwey (2005) who reported a mean SDS of 6.9 with forearm prone and 4.1 with forearm supine.

The radial and ulnar bones are parallel to each other in supination (Gill Coury et al. 1998b). When the forearm is prone there is crossing over of the radial and the ulnar bones. An exertion of a pronation torque with the forearm already prone possibly leads to tendon or ligament strain, thus giving rise to more discomfort. There are many blood vessels supplying the forearm musculatures, and complete or partial blockage of some of these in the prone condition might have caused discomfort. Some connective tissue strain also cannot be ruled out as indicated by Wiker et al. (1989), which might have caused more discomfort at prone when compared to the supine or neutral positions. O'Sullivan and Gallwey (2005) reported similar discomfort score data indicating an increase in the prone condition.

Pressure on the median nerve of the hand has been reported to be one of the many factors causing WMSDs in industry (Kattel et al. 1996). In this regard Kleinrensink et al. (1995) studied the median nerve tension in three areas (axial, pronator teres muscle and the radial bone) at different elbow and forearm rotation angles. With the forearm prone, tension was greater at the axial region (near the axial or arm pit region of the arm). The increased tension on the median nerve at the axial region is referred all through the arm and probably causes an increase in discomfort in the arm with the forearm pronated. A cumulative effect of all these factors might lead to an increase in discomfort in the arm with forearm rotation from neutral.

4.5. Elbow angle

Elbow angles of 135^0 were found to result in the least discomfort. Even graphs of discomfort score at elbow angles of 135^0 and 90^0 with forearm supine were found to be parallel indicating a similar rate of change of discomfort. This is mainly due to very little change in moment arm of muscles such as PT, PQ, and Biceps, as reported by Murray et al. (1995). The authors however did not mention the exact change in moment arms, but it could be anticipated that the change was not significant for elbow angles of 135^0 and 90^0. The only change here was increased discomfort with the elbow flexed at 45^0. This could be explained in the light of muscle architecture. Ettema et al. (1998) reported, that the moment arm of the PT muscle (the prime muscle in pronation) is at a maximum at 95^0 elbow flexion (25mm) and gradually decreases after this as the elbow is flexed more. At 70^0 elbow flexion the moment arm of the muscle decreases to 21.4 mm, and after this no values have been reported by Ettema et al. or in the literature. It could be inferred from this data that at 45^0 elbow flexion, the moment arm of the PT muscle would decrease further and, with the forearm prone, the moment arm of the PT muscle becomes least (at 30^0 pronation it is 6.1 mm as reported by the same group). Thus at this articulation with the least moment arm of the prime muscle the entire shoulder arm system is at a disadvantage. Thus to exert the requisite torque it has to do more work and hence becomes more stressed, leading to more discomfort.

4.6. Upper arm flexion/ extension

Extension of the upper arm leads to more discomfort compared to flexion or neutral. As the upper arm is extended it moves backwards (Palastanga et al. 1998). As the upper arm moves backwards past the neutral position the greater tubercle of the humerus bone comes into contact with the coracoacromial arch. So movement at or near this position might lead to increased discomfort. In flexion or neutral upper arm position, movement of the humeral bone is not limited as such, thus leading to less discomfort in the arm.

4.7. Discomfort score as percentage of standard position

To get an insight into why none of the factors on discomfort score in ANCOVA were significant, RDS was tabulated as percentage of standard position value (Table 8). A close look at the row by column means of Table 8 shows a pattern when the upper arm is in flexion or extension. In flexion the scores at elbow angles of 45^0 and 90^0 are about the same (106.5 and 103.0) and similarly for extension at elbow angles of 45^0 and 90^0 the scores are similar (124.7 and 118.9). This might be due to the fact that there is no change in muscle length at these articulations. But there is a big jump when the elbow angle changes to 135^0 for flexion (115.1) and for extension (138.0), possibly due to the fact that muscle length changes as the forearm moves away from the body with the upper arm in flexion/extension pushing the shoulder-arm system to a mechanically disadvantageous position. But for neutral upper arm angle there was very little difference in discomfort score at 45^0, 90^0 and 135^0 elbow angles (110.8, 103.7 and 107.6). This is also evident from the 3D plot of RDS values at Upper arm angles Vs Forearm rotation angles (% ROM) (Figure 10) as well.

[Insert Table 8 here]

[Insert Figure 10 here]

Previous work by the authors (Mukhopadhyay et al. 2007a) found higher discomfort for supine and prone forearm postures over neutral postures and that this was partly related to the exertion of higher percentages of MVC in deviated postures. In this study force was relative to MVC measured in each posture combination, but the percentage change in RDS from standard position still suggests a posture effect. Limb posture affects force output of muscles crossing a joint due to changes in the moment arms over which the muscle acts. Joint angle also affects the length of the muscle, i.e. the level of sacromere overlap, which in turn directly affects force output and fatigability depending on the proportions of type I and type II fibre types. Given that force was set relative to the

MVC of each posture the increased discomfort in deviated postures may be partly attributed to an increased fatigability due to the muscle sacromere length overlap. Knowledge on the effects of sacromere overlap and force output is considerable but effects on fatigue have not received the same level of research. No scientific journals were sourced that verify or discount the hypothesis that when exertions are relative to the force output in a deviated posture, increased discomfort may be affected by muscle fatigability due to sacromere overlap effects. This remains and open question for studies of posture effects in ergonomics.

4.8. Endurance time as a covariate

In an effort to control inter-individual differences in perception of discomfort the authors used endurance time at 50% MVC as a covariate as it was significant in previous studies (O' Sullivan and Gallwey 2005, Carey and Gallwey 2005), but in this study it was not. To explore this further, mean endurance times of all the participants were plotted against their mean TDS (Figure 11). The scatter plot shows that a slightly negative relationship was evident but that it was not an accurate fit (y=-73.352X + 107.8, $R^2 = 0.08$) thereby reinforcing the lack of significance for endurance time in the ANCOVA.

[Insert Figure 11 here]

4.9. Body part discomfort map

High discomfort in the forearm was indicative of the fact that muscles of the forearm, including the flexors and extensors in gripping and the pronators in forearm rotation, are highly active in such tasks. Increased discomfort at the wrist was due to the fact that the finger flexors are prime movers in any gripping task (Mogk and Kier 2003) while the wrist extensors act simultaneously as stabilizers of the wrist. Mechanical force (tension) by the flexors and extensors are transferred to the fingers via tendons which pass through the center of the wrist, a tightly compacted "duct" and site of many musculoskeletal injuries such as carpal tunnel syndrome. High stress levels in the tendons at this site combined with friction with the surrounding tissues of the carpal tunnel are considered to be the key source of discomfort at this site. Very little discomfort in the upper arm region is indicative that the muscles of these parts, mainly Biceps Brachii and Triceps, have a negligible role to play in pronation torque.

4.10. Electromyography

Significant increase in PT muscle activity with forearm prone supported the fact that PT is the prime muscle in pronation. It has been reported by Ettema et al. (1998) that PT muscle activity increases in pronation, and especially that this increase is significantly more when the elbow is flexed. This might be the case in the current experiment also.

BB muscle was only affected by elbow angle change and by no other factors. Jamison and Caldwell (1993) investigated the EMG activity of three muscles with MVC torque: Brachioradialis (BRD), Triceps Brachii (TB), and Biceps Brachii (BB). The elbow angle was at 90^0 with abduction at 20^0 and forearm midway between full supine and full prone. A significant increase in BB muscle activity in the supine condition of the forearm, at 135^0 elbow angle compared to 90^0, and significant increase also at elbow angle of 135^0 compared to 45^0 elbow angle, is in agreement with the works of Buchanan et al. (1989). This group, studying EMG on different muscles of the arm while exerting MVC torque (load varying between 10% to 30% MVC), reported an increase in BB EMG activity due to decrease in its length.

5. Conclusions

Forearm rotation angle (% ROM) affected MVC pronation torque with maximum torque recorded with the forearm supine. However, forearm angle, elbow flexion and upper arm flexion/extension did not have a significant effect on discomfort in the ANCOVA. But, each of the postures was significant when combined with Participants in the two way interactions. Further investigation of the data revealed that some of the participants experienced posture effects more so than others and in these cases some of the deviated postures resulted in considerably higher discomfort ratings, specifically for the forearm prone, the elbow flexed and the upper arm extended.

Given that the dependent variable was subjective responses (discomfort ratings) which are sometimes vulnerable to perception errors the authors used torque endurance time as a covariate in an attempt to control for inter-individual differences in perceptions of pain. In this experiment the covariate was not significant and the conclusion is that it is not a good discriminator of between participant effects for the types of exertions studied.

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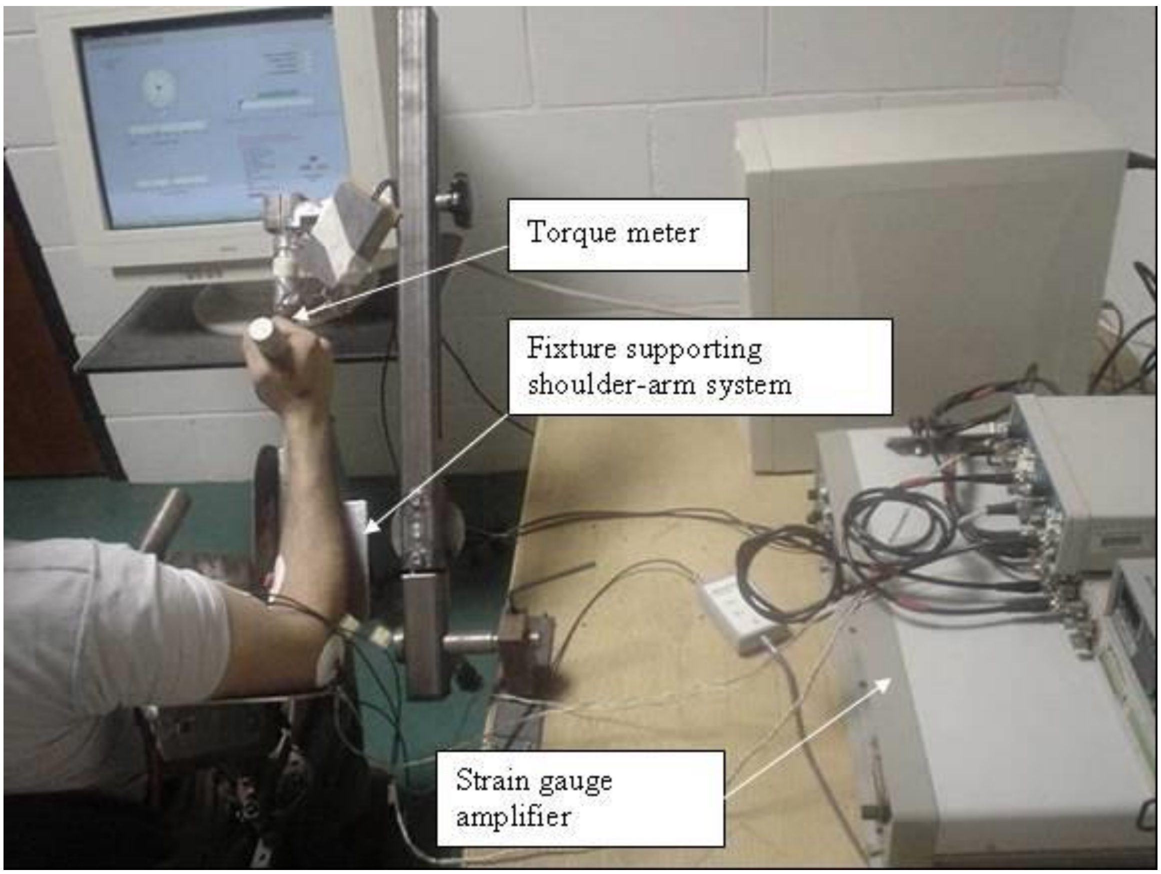

Figure 1 Fixture for keeping the shoulder arm system in position

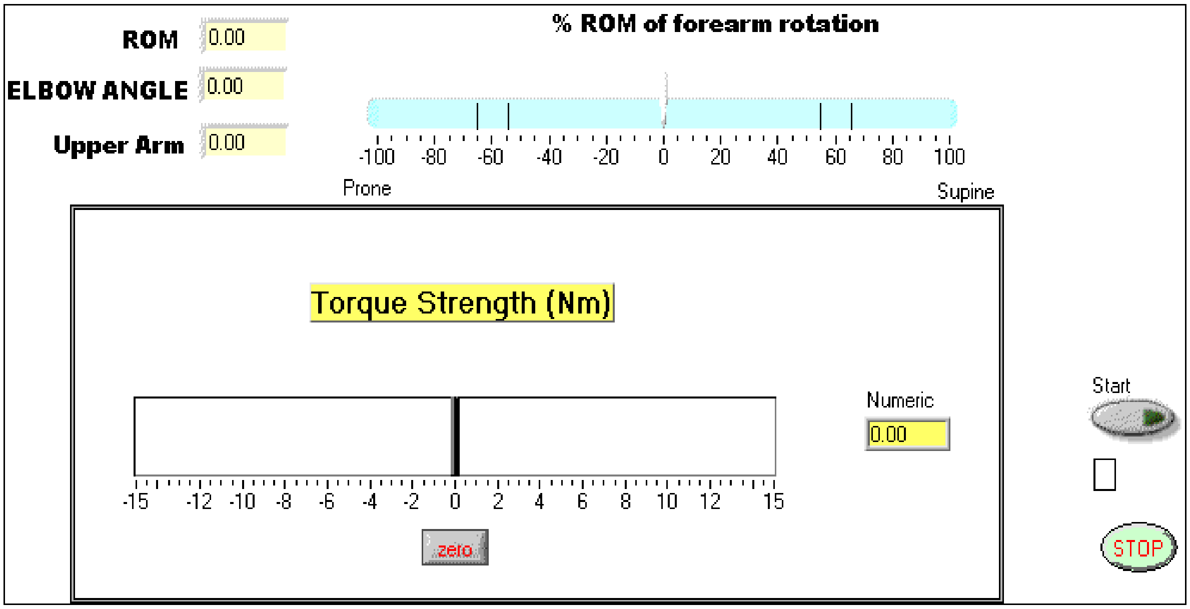

Figure 2 Screen shot of LabVIEW Virtual Instrument (VI) for recording torque

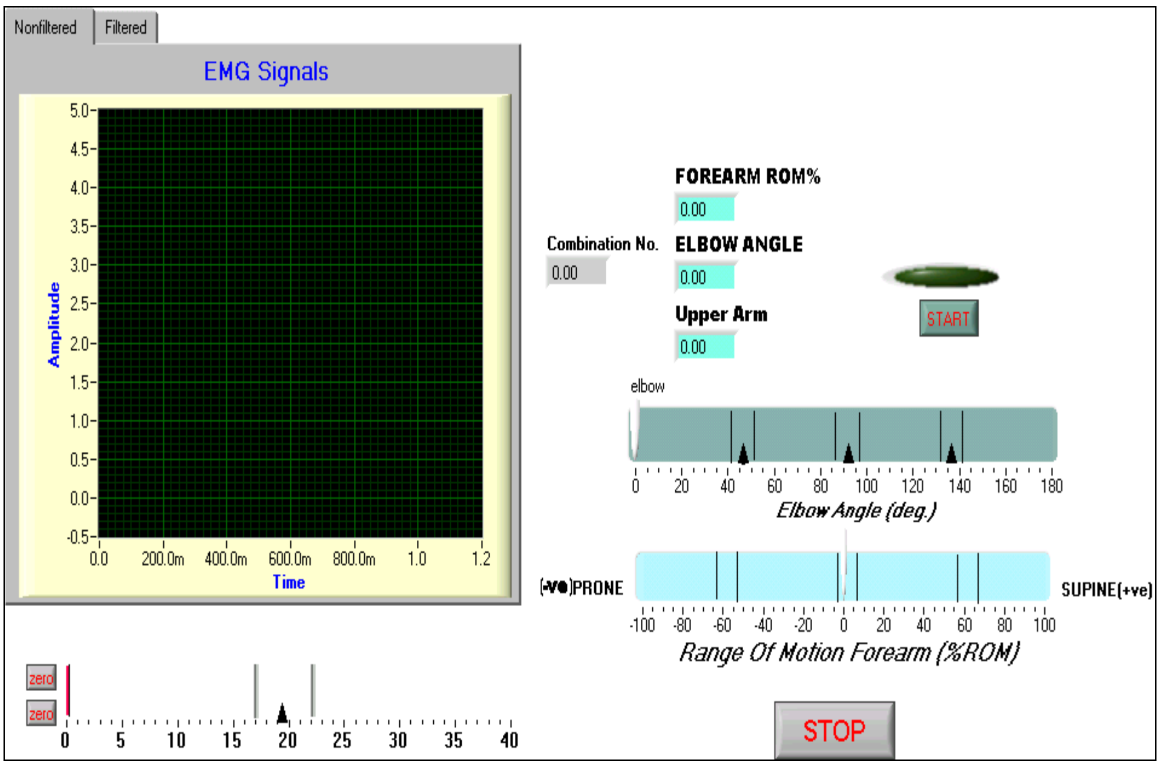

Figure 3 Screen shot of LabVIEW VI for EMG recording

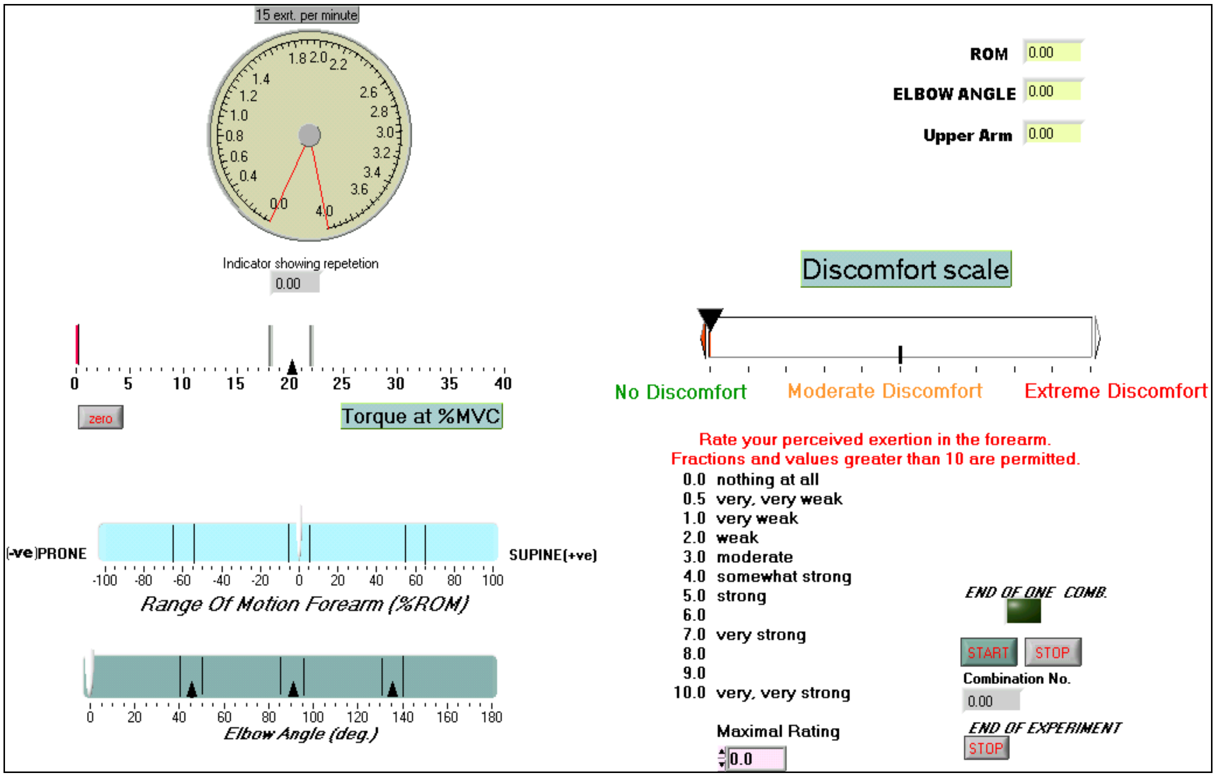

Figure 4 Screen shot of LabVIEW VI for discomfort recording

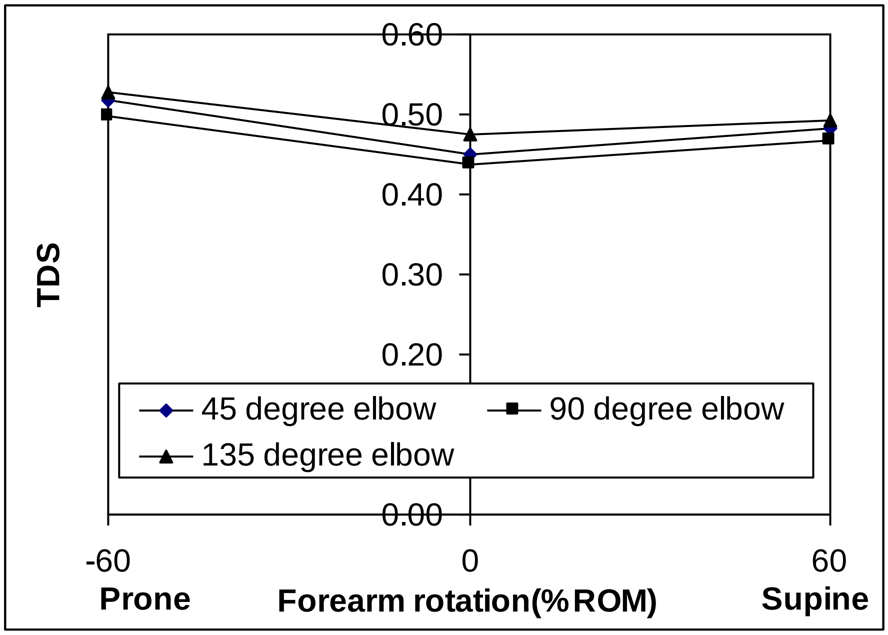

Figure 5 Transformed discomfort score (TDS) Vs Forearm rotation angle (%ROM) at different elbow angles

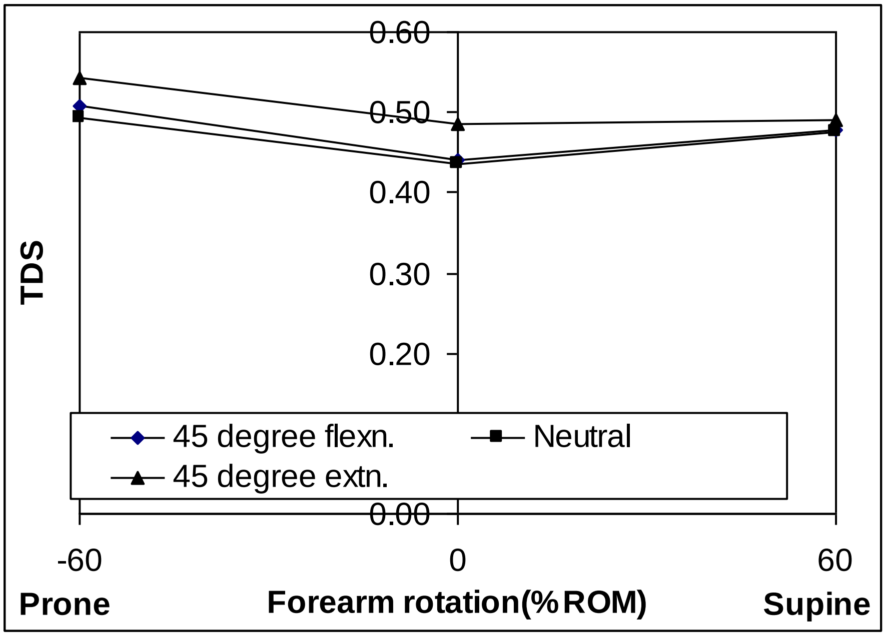

Figure 6 TDS Vs Forearm rotation (%) ROM at different upper arm angles

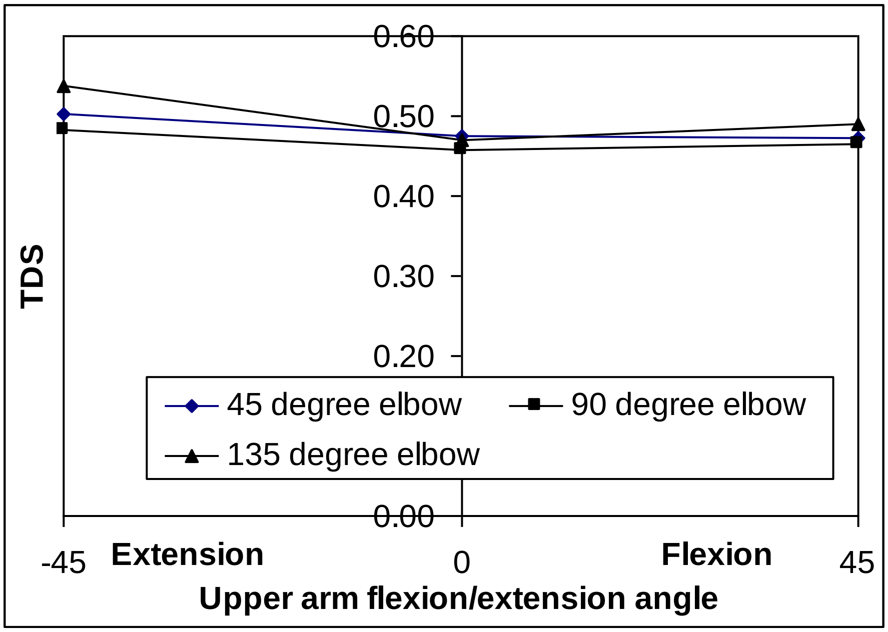

Figure 7 TDS Vs Upper arm angle at different elbow angles

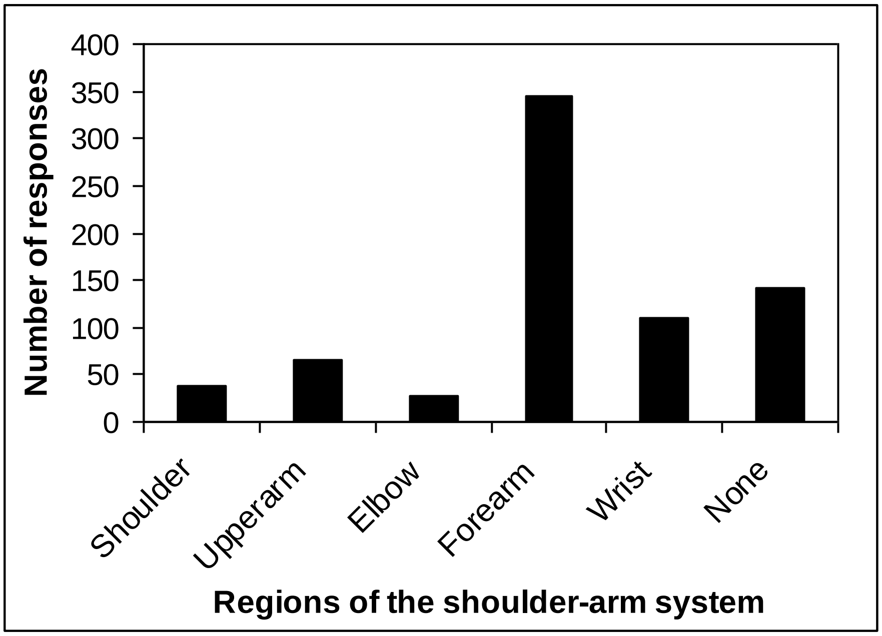

Figure 8 **Discomfort profile in different parts of the arm after each treatment combinations. As there were multiple responses the total add up to more than 100.**

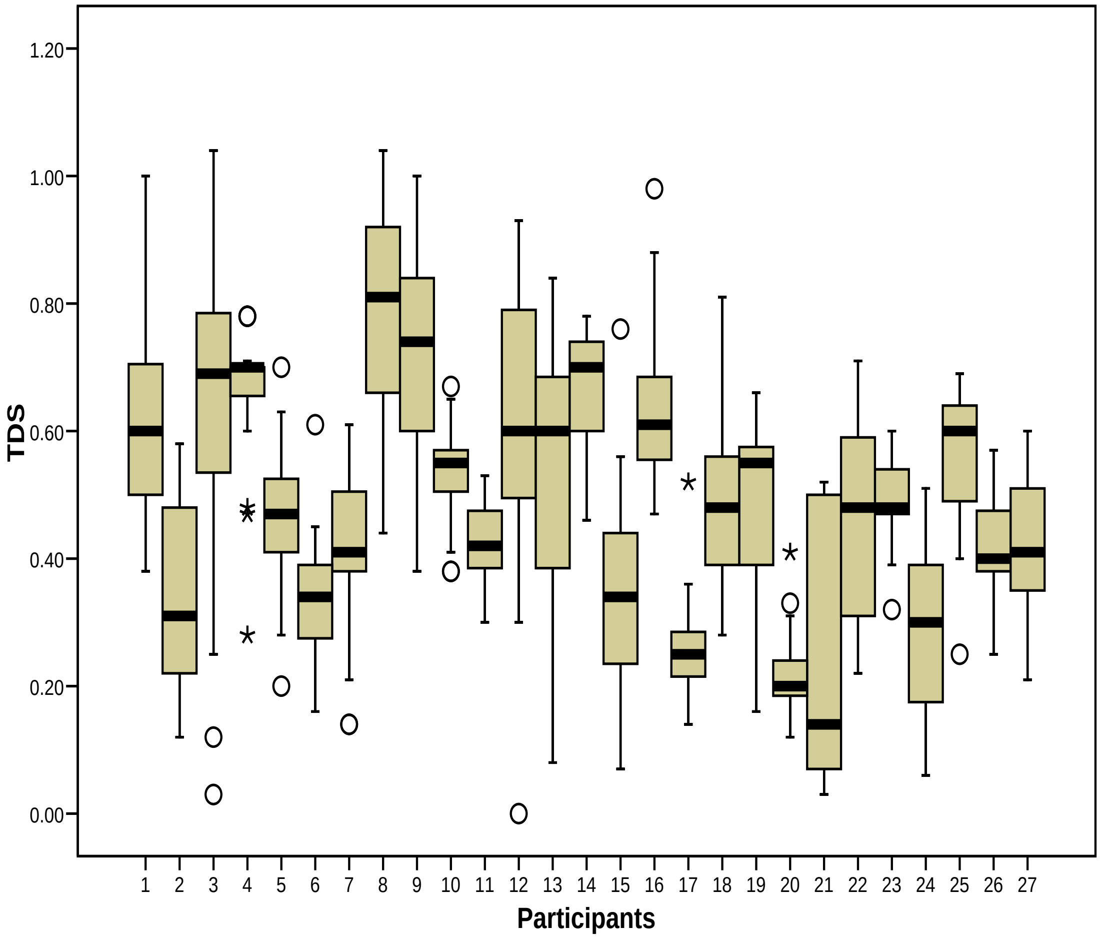

Figure 9 Box plot for Transformed Discomfort Score (TDS) Vs Participants.

* Denotes extreme outliers, and o denotes mild outliers. Extreme outliers are data values more than 3.0 times Interquartile Range (IQR) below the 1st Quartile or above the 3rd Quartile. Mild outliers are data values lying between 1.5 times and 3.0 times the IQR below the 1st Quartile or above the 3rd Quartile.

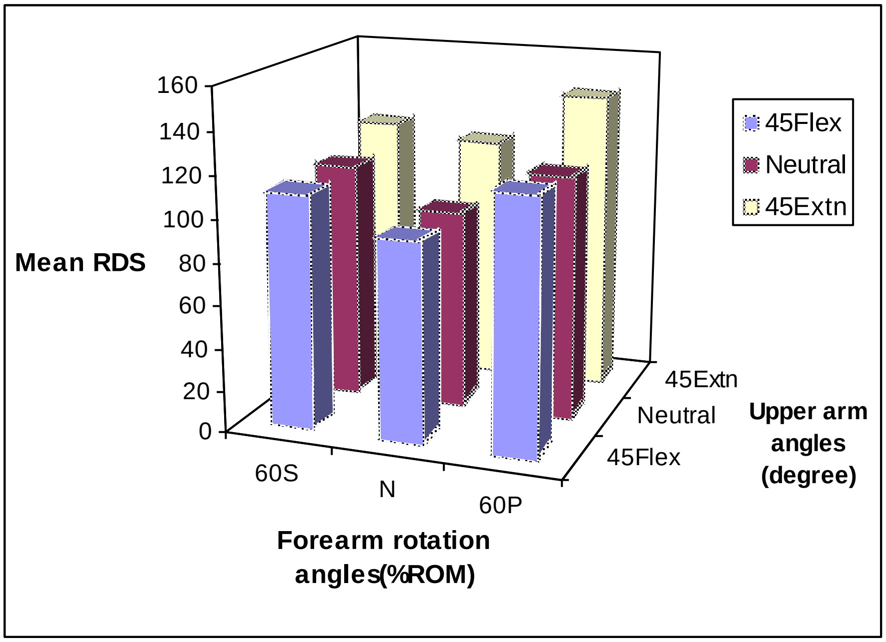

Figure 10 Mean RDS values at Upper arm angles Vs Forearm rotation angles (% ROM)).

45 Flex= 45^0 upper arm flexion, Neutral = upper arm at neutral, 45Extn= 45^0 upper arm extension, 60S= 60% supine forearm, N= neutral forearm, 60P= 60% prone forearm.

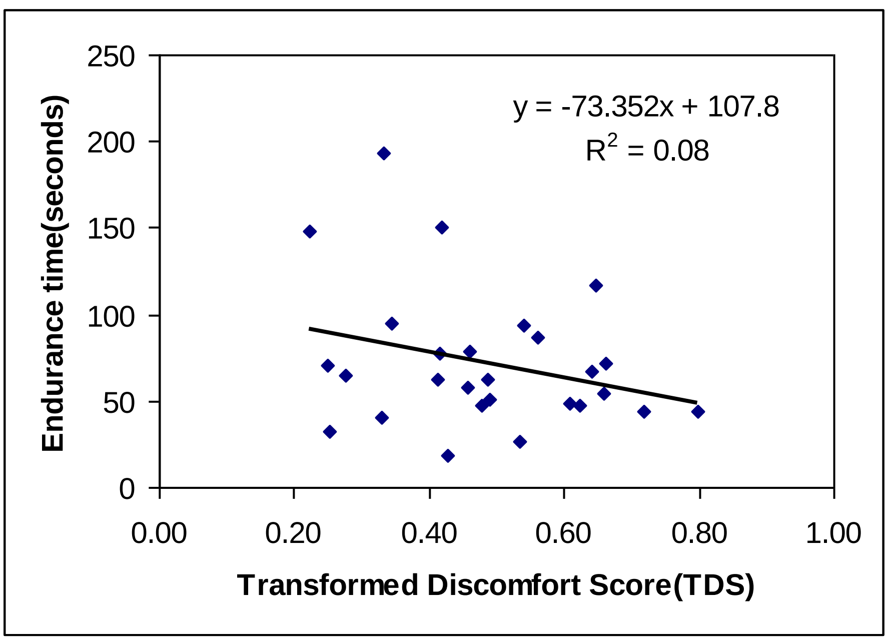

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Table 10 Change in electrical activity of PT and BB muscles at different articulations

Table1 Upper limb postures observed in different industries

Industry	**Posture types**	**Joint angles**	**Reference**
Meat cutting	Upper arm flexion	90^0	Kilbom & Persson (1987)
	Elbow flexion	90^0	
Assembly	Upper arm Flexion	0^0-60^0	Melin (1987)
Dentist	Upper arm flexion	>90^0	Akesson et al. (1999)
Packaging pencil factory	Upper arm flexion / elbow flexion	30^0/90^0	Gill Coury et al. (1998a)
Dentist	Flexion of upper arm	30^0	Finsen et al. (1998)
Electronic assembly	Elbow flexion	90^0	Christensen (1986)
Automobile assembly	Elbow angle	110^0	Gill Coury et al. (1998a)
Hand made brick manufacturing plant	Upper arm/Elbow	45^0/90^0	Trevelyan & Haslam (2001)

Assembly task in industry	Elbow angle	90^0	Gill Coury et al. (1998a)
	Shoulder angle in saggital plane	20^0-90^0	

Table 2 MVC torque (Nm) at different articulations of the shoulder-arm system

Forearm rotation (%ROM)	***Upper arm angles*** **45^0 (extension)**			**0^0 (neutral)**			**45^0 (flexion)**		
	Elbow angle			***Elbow angle***			***Elbow angle***		
	45^0	**90^0**	**135^0**	**45^0**	**90^0**	**135^0**	**45^0**	**90^0**	**135^0**
60% Supine	6.2	6.6	6.5	6.4	6.5	6.6	6.4	6.6	6.5
Neutral	5.1	5.6	5.3	5.4	5.3	5.9	5.0	5.6	5.3
60% Prone	3.4	3.0	3.7	3.0	3.0	3.5	2.8	2.8	3.1

Table 3 ANOVA for MVC torque

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Elbow angle (E)	11.057	2	5.529	2.579	0.086
Forearm rotation (R)	1422.555	2	711.278	174.363	0.001
Upper arm angle (U)	3.916	2	1.958	1.050	0.357
Participant (P)	995.705	26	38.296	6.097	0.001
E * R	8.879	4	2.220	2.200	0.074
E * U	4.369	4	1.092	1.196	0.317
R* U	7.096	4	1.774	2.121	0.083
E * P	111.467	52	2.144	2.212	0.004
R* P	212.123	52	4.079	4.573	0.001
U* P	96.923	52	1.864	2.340	0.005
E * R* U	5.716	8	0.714	0.749	0.648
E * R* P	104.953	104	1.009	1.058	0.362
E * U* P	95.022	104	0.914	0.958	0.592
R* U* P	86.984	104	0.836	0.877	0.772
E * R* U* P (Residual)	198.346	208	0.954	.	.
Total	3365.11	728			

Table 4 Student Newman-Keuls for forearm rotation angle (% ROM) for torque MVC

Forearm rotation angle (%)	**Mean of MVC** Group 1	Group2	Group3
60 Prone	1.734		
Neutral		2.293	
60 Supine			2.514

Table 5 Mean values of RDS, SDS and TDS (standard deviation) at different articulations

Upper arm angle	Elbow angle	Forearm rotation angle								
		60%Supine			Neutral			60%Prone		
		RDS	SDS	TDS	RDS	SDS	TDS	RDS	SDS	TDS
45^0 Flexion	45^0	2.3 (1.5)	4.5(3.0)	0.5(0.2)	2.0 (1.3)	3.4 (2.7)	0.4(0.2)	2.4(1.3)	4.9(3.3)	0.5(0.2)
	90^0	2.2 (1.3)	4.0 (2.7)	0.5(0.2)	1.8(1.0)	3.1 (2.5)	0.4(0.2)	2.5 (1.6)	4.8(2.7)	0.5(0.2)
	135^0	2.5 (1.8)	4.3 (2.5)	0.5(0.2)	2.1 (1.2)	3.8 (2.9)	0.5(0.2)	2.7(2.1)	4.8 (3.0)	0.5(0.2)
Neutral	45^0	2.6 (1.9)	4.5 (3.0)	0.5(0.2)	1.8(1.0)	2.7(2.2)	0.4(0.2)	2.6 (2.2)	4.8(2.9)	0.5(0.2)
	90^0	2.2(1.7)	3.5 (2.7)	0.4(0.2)	2.1 (1.6)	3.2(2.5)	0.4(0.2)	2.3 (1.4)	4.2(2.8)	0.5(0.2)
	135^0	2.3(1.6)	3.8 (2.9)	0.5(0.2)	2.1 (1.4)	3.3(2.3)	0.4(0.2)	2.4 (1.4)	4.4 (3.3)	0.5(0.2)
45^0 Extension	45^0	2.4(1.9)	4.2 (2.9)	0.5(0.2)	2.4(1.5)	4.2 (2.4)	0.5(0.2)	3.1 (2.5)	5.8 (3.5)	0.5(0.2)
	90^0	2.6(2.1)	4.2(2.5)	0.5(0.2)	2.2 (1.7)	3.6(2.6)	0.5(0.2)	2.8 (2.4)	4.9 (3.5)	0.5(0.2)
	135^0	2.8 (2.2)	4.8(2.6)	0.5(0.2	2.8(2.1)	4.9 (2.9)	0.5(0.2)	3.1(1.9)	6.3 (2.8)	0.6(0.2)

Table 6 Mauchly's test of sphericity for transformed discomfort score (p= or < 0.05 means spherecity is violated)

Within participant effect

	Mauchly's W	Epsilon	df	Sig.	Greenhouse-Geisser	Huynh-Feldt	Lower bound
Elbow (E)	0.932	1.700	2	0.42	0.936	1.000	0.500
Upper arm (U)	0.951	1.214	2	0.54	0.953	1.000	0.500
Forearm (F)	0.519	15.743	2	0.00	0.675	0.729	0.500
E * U	0.461	18.130	9	0.03	0.723	0.861	0.250
E * F	0.622	11.131	9	0.26	0.844	1.000	0.250
U * F	0.596	12.120	9	0.20	0.793	0.957	0.250
E * U * F	0.112	48.345	5	0.07	0.675	0.917	0.125

Table 7 **Repeated measure ANCOVA for Transformed Discomfort Score with Greenhouse Geisser Correction (GGC) factor for factors violating sphericity.**

Source	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Elbow (E)	0.134	2.000	0.067	0.798	0.456
Upper arm (U)	0.029	2.000	0.014	1.153	0.324
Forearm (F) GGC	0.183	1.350	0.136	2.378	0.124
Endurance time (ET)	1.336	1.000	1.336	2.170	0.153
E * ET	0.028	2.000	0.014	0.166	0.848
U* ET	0.000	2.000	0.000	0.011	0.989
F * ETGGC	0.024	1.350	0.017	0.306	0.652
E * UGGC	0.026	2.894	0.009	0.534	0.654
E * F	0.022	4.000	0.006	0.458	0.766
U * F GGC	0.012	4.000	0.003	0.292	0.882
E * U* ETGGC	0.028	2.894	0.010	0.574	0.628
E * F* ET	0.010	4.000	0.003	0.212	0.931
U * F * ET GGC	0.022	4.000	0.006	0.541	0.706
E* U* F	0.094	8.000	0.012	0.959	0.470
E * U* F* ET	0.065	8.000	0.008	0.664	0.723
Residual	28.041	675.000	0.042		
Total	42.696	728.000			

Table 8 RDS as percentage of standard position (0^0 adduction/abduction, elbow angle at 90^0, forearm and wrist at neutral)

Upper arm angle	Elbow angles	Forearm rotation angles				
		60% Supine	**Neutral**	**60% Prone**		**Mean**
45^0 Flexion	45^0	109.7	96.5	113.3	=	**106.5**
	90^0	104.9	85.2	119.0	=	**103.0**
	135^0	118.0	100.8	126.5	=	**115.1**
	Mean	**110.9**	**94.2**	**119.6**		
Neutral	45^0	124.8	83.0	124.6	=	**110.8**
	90^0	102.8	100.0	108.2	=	**103.7**
	135^0	108.6	100.0	114.1	=	**107.6**
	Mean	**112.1**	**94.3**	**115.6**		
45^0 Extension	45^0	112.6	113.6	147.8	=	**124.7**
	90^0	121.6	104.5	130.6	=	**118.9**
	135^0	133.3	132.3	148.3	=	**138.0**
	Mean	**122.5**	**116.8**	**142.2**		
	Grand mean:	**114.8**	**101.8**	**125.8**		

Table 9 Linear equations at different articulations on TDS

Treatment	Equation	Treatment	Equation	Figure
Supine forearm rotation(S)		Prone forearm rotation (P)		
45^0 elbow angle	TDS=0.000568S+0.45	45^0 elbow angle	TDS=-0.00112P+0.45	**5**
90^0 elbow angle	TDS=0.000504S+0.44	90^0 elbow angle	TDS=-0.00099P+0.44	
135^0 elbow angle	TDS=0.000296S+0.47	135^0 elbow angle	TDS=-0.00089P+0.47	
Supine forearm rotation(S)		Prone forearm rotation (P)		
45^0 upper arm flexion	TDS=0.000632S+0.44	45^0 upper arm flexion	TDS=-0.0011P+0.44	**6**
Neutral upper arm	TDS=0.000667S+0.43	Neutral upper arm	TDS=-0.00099P+0.43	
45^0 upper arm extension.	TDS=0.00007S+0.49	45^0 upper arm extension.	TDS=-0.00093P+0.49	
Upper arm flexion at 45^0 (FL)		Upper arm extension at 45^0 (EX)		
45^0 elbow angle	TDS=-0.000052FL+0.47	45^0 elbow angle	TDS=-0.000609053EX+0.47	**7**
90^0 elbow angle	TDS=0.000203FL+0.46	90^0 elbow angle	TDS=-0.00056EX+0.46	
135^0 elbow angle	TDS=0.000406FL+0.47	135^0 elbow angle	TDS= -0.00147EX+0.47	

Table 10 Change in electrical activity of PT and BB muscles at different articulations

Muscle	Part of shoulder-arm system	(%) increase in muscle activity	Result of t-test
PT	Forearm: neutral to prone	42.9	t=6.058, p=0.001
PT	Forearm: neutral to supine	2.7	N.S
PT	Upper arm: neutral to flexion	8.6	N.S
PT	Upper arm: neutral to extension	0.5	N.S
PT	Elbow: 90^0 to 45^0	*4.3	N.S
PT	Elbow: 90^0 to 135^0	*3.5	N.S
BB	Forearm: neutral to prone	5.2	N.S
BB	Forearm: neutral to supine	3.2	N.S
BB	Upper arm: neutral to flexion	*7.6	t=3.810, p=0.005
BB	Upper arm: neutral to extension	2.4	N.S
BB	Elbow: 90^0 to 45^0	8.2	t=2.450, p= 0.040
BB	Elbow: 90^0 to 135^0	21.3	t=7.498, p= 0.001

*These muscles exhibited decrease in muscle activity.
PT = Pronator Teres, BB = Biceps Brachii, N.S= not significant