Estimating upper limb discomfort level due to intermittent isometric pronation torque with various combinations of elbow angles, forearm rotation angles, force and frequency with upper arm at 90^0 abduction

*Prabir Mukhopadhyay

#Leonard W.O' Sullivan

#Timothy J. Gallwey

* Post Graduate Campus, National Institute of Design, GH-0 Extension Road, Gandhinagar 382007, India. e mail: prabirdr@gmail.com

#Ergonomics Research Centre, Department of Manufacturing and Operations Engineering, University of Limerick, Ireland

Corresponding author: Leonard W.O' Sullivan**,** e mail**:** leonard.osullivan@ul.ie

Abstract

Industrial jobs involving upper arm abduction have a strong association with musculoskeletal disorders and injury. But there is still paucity of data on the different risk factors that are responsible for the genesis of such disorders or injuries. The current laboratory study is an attempt that direction. Thirty-six right-handed male university students participated in a full factorial model of three forearm rotation angles (60% prone and supine and neutral range of motion), three elbow angles (45, 90 and 135 degrees), two exertion frequencies (10 and 20 per minute) and two levels of pronation torque (10% and 20% MVC). Discomfort rating after each five minute treatment was recorded on a visual analogue scale. Repeated measures ANCOVA with grip endurance time as a covariate indicated that forearm rotation angle (p=0.001), elbow flexion angle (p=0.016), MVC torque (p=0.001) and frequency (p=0.049) were significant. Grip endurance time was not significant (p=0.74). EMG activity of the Pronator Teres (PT) and the Extensor Carpi Radialis Brevis (ECRB) revealed that both muscles were affected by forearm rotation and level of MVC torque. A supplementary experiment in which MVC pronation torque at different articulations was measured showed that some of the increased discomfort appeared to be due to increased relative MVC at some of the extreme articulations. The findings indicated that, with the upper arm in abduction, an elbow angle of 45 degrees and forearm prone, are a posture vulnerable to injury and should be avoided. Grip endurance time as a covariate warrants further investigation.

Relevance to industry

There is still a paucity of data on risk factors for musculoskeletal disorders for upper arm articulations typical of industrial jobs, especially postures involving upper arm abduction. Industrial jobs involving upper arm abduction have a strong association with injury as operators must often maintain static upper arm abduction while performing tasks for long durations. This study presents discomfort and pronation torque MVC data at different upper arm articulations to identify and control high-risk tasks in industry well before they develop into Musculoskeletal Disorders, especially at the design stage when using biomechanical models.

Key words: Upper arm abduction, Pronation toque, Musculoskeletal Disorder, Discomfort score.

1. Introduction

Work-related Musculo-Skeletal Disorders (WMSDs) are among the most publicised occupational health problems in industry (Kattel et al. 1996). Wiker et al. (1989) found that workplace layout, product design or hand-tool design often force workers to adopt awkward postures for long periods and these have been identified as causative factors for WMSDs. Industrial tasks involving forceful exertions, repetition and poor postures, have been related to WMSDs but there is a lack of quantitative data on the relationship between these factors and injury (Kumar, 2001).

The Bureau of Labour Statistics (BLS, 1990) reported that, in 1989, of all the reported cases of occupational illness, 56% were associated with repeated traumas. Putz-Anderson (1988) suggested that, in the United States, the factors contributing to increased cases of musculoskeletal disorders were an increase in service and high tech jobs, an ageing work force, and a reduction in worker turnover. According to Bernard (1997), the Bureau of Labour Statistics (BLS, 1990) reported a further cause, in that there were approximately 705,800 (32%) cases of overexertion or repetitive motion injuries among all the injuries reported in industry, of which 13% affected the shoulder. They also reported that 92,576 injuries or illness occurred as a result of repetitive motions including the use of tools, repetitive placing, typing, grasping or moving of objects other than tools. These all suggest workplace design issues.

Many industrial tasks involve awkward postures of the upper arm and forearm. For example, Bjelle et al. (1981) reported that, next to low back pain, neck and shoulder pain were the most common in some industries. Further Sjogaard et al. (1986) reported that tasks in the woodworking industry involved neck flexion/rotation and repetitive arm movements with static contraction forces of 5% to 10% of Maximum Voluntary Contraction (MVC). Kilbom and Persson (1987) reported that manufacturing work in the electronics industry was associated with a high prevalence of shoulder and neck disorders, due to repetitive, manual short cycle tasks with the arms raised at 60^0 to 90^0 of abduction. Similarly Hagberg and Wegman (1987) found awkward postures that involved upper arm abduction and repetitive forearm movement among assembly line packers, shop assistants, slaughterhouse workers, scissors makers, and data entry operators. But such awkward postures also occur in combination with force or torque exertions, such that they account for approximately 45% of all industrial overexertion injuries in the United States, with a total cost estimated to be well over $150 billion per year (Mital and Kumar, 1998a &1998b). In the automobile industry especially, Chung et al. (2001) observed screw-driving tasks with an awkward posture, which required upper arm abduction and forearm rotation. Subjective rating of whole body discomfort increased from 2 to 4 points on a 10-point modified Borg scale. These studies highlight the prevalence of shoulder problems due to applying torques with an abducted upper arm but there is also an effect due to the elbow angle.

Herberts et al. (1980) studied elbow flexion combined with upper arm abduction and found an increase in localized muscle fatigue as abduction increased from 45^0 to 90^0. Wiker et al. (1989) studied the effect on localised muscle fatigue in the shoulder musculature for a Fitts' tapping task above shoulder level. Discomfort and fatigue were greatest when the hand load exceeded 0.40 kg with a relatively long cycle time (40-60s) and the hand adducted 35^0 (the author did not explain the exact posture) above the shoulder. Upper arm abduction was not included in the study. Kattel et al. (1996)

reported that the maximum grip strength occurred with the upper arm at 0^0 upper arm abduction, 135^0 elbow flexion, and neutral wrist. Coury et al. (1998b) studied the shoulder adduction strength in various body postures and observed discomfort, pain, and a reduction in grip strength at different postures of the elbow and shoulder flexion, but they did not look at upper arm abduction effects. The tasks described in all the above investigations involved grip strength, mainly at different articulations of the upper arm. In a typical industrial scenario, screw driving tasks (pronation/supination) are highly prevalent (Ciriello et al. 2002) and the above investigations did not consider such tasks.

In a laboratory study using intermittent torque exertions, O'Sullivan and Gallwey (2005), reported that discomfort for pronation torques were considerably higher than for supination torques and, for both supination and pronation torques, there was a significant forearm rotation effect that resulted in increasing discomfort for non-neutral forearm rotations. However their study did not consider the effect of upper arm abduction as is typical in industrial tasks. Mukhopadhyay et al. (2003) used intermittent torque along with grip force and reported an increase in discomfort with an increase in upper arm abduction angle from 0^0 to 90^0. However the elbow angle was fixed at 90^0 . In a study of repetitive screw driving tasks Ciriello et al. (2002) reported maximum acceptable torques ranging from 0.33Nm to 0.65 Nm. They examined clockwise and counter clockwise screw driving tasks with ulnar deviation but without upper arm abduction or torque exertions. In all these investigations it is evident that discomfort and fatigue of different body parts are important indicators of stress, and are likely to cause work related musculoskeletal disorders in the long run.

The major problem of using discomfort scores is that there are inter-subjective differences in pain tolerance. Hence it becomes difficult to draw firm conclusions from such scores. Such differences might confuse the results from experiments on such scores if an attempt is made to draw a general conclusion. Thus a relevant covariate needs to be incorporated in the experiment to adjust for this.

Laboratory studies show short-term effects such as trends of discomfort, but they also show relative differences in severity. Corlett and Bishop (1976) showed the usefulness of measuring body part discomfort and Annett (2002) demonstrated the validity of subjective methods. Zhang et al. (1996) showed that discomfort is primarily due to physiological and biomechanical factors e.g. in office work 75 out of 118 responses were related to these versus 16 related to fatigue. Hence subjective discomfort appears to be legitimate for use in research on factors causing musculoskeletal injury, and it is a valuable indicator of mismatches between the job and the human operator.

In summary, there appears to be a dearth of data on the effects of torque at high shoulder abduction angles, at different elbow angles, and at frequencies that might be found in industry. It was also necessary to extend earlier work by two of the authors, Carey and Galwey (2005) and O' Sullivan and Gallwey (2005) to make it more relevant to the postures found in industry.

2. Method

2.1. Approach

To reduce the effects of inter-subjective differences, the torque was defined relative to the strength of the subject and used the same values as O'Sullivan and

Gallwey (2005), namely 10% and 20% of MVC torque. These were similar to the muscular exertion data of Sjogaard et al. (1986) who reported static contractions of 5% to 10% of MVC.

2.2. Subjects

Thirty-six right-handed male University students, with no previous history of musculoskeletal disorders participated. Their mean age was 23.8 years (SD=3.4), mean stature was 176.9 cm (SD=7.3) and body mass was 74.3 kg (SD=11.9). The Ethics Committee of the University of Limerick approved the experimental procedure.

2.3. Apparatus

2.3.1. Seat fixture

A steel fixture (Figure 1) with hinge and height adjustment was fabricated in-house to maintain the upper arm abducted at 90^0 and parallel to the floor, to ensure that articulation effects were not confounded with static load problems. The entire fixture was attached to a chair the height of which could be adjusted as per the sitting height of the subject. The upper part of the fixture was padded with a layer of felt. The fixture could be moved back and forth around a fixed point so as to support the upper arm (including the forearm) in different combined upper arm postures with the upper arm abducted 90^0.

[Insert Figure 1]

2.3.2. Torque meter

Forearm torque was measured using a meter built in-house (Figure 2). 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 a neutral wrist. 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 shaft was attached to a height adjustable bench, which allowed rotation of the shaft in various forearm rotation angles as dictated by the treatments.

[Insert Figure 2]

2.3.3. Goniometers

A Penny and Giles Biometrics electro-goniometer (model Z180) was used to record the forearm rotation angles while a model XM100 was used to record elbow flexion. Voltage readings from the goniometers were amplified and zeroed using a Biometrics K100 amplifier.

2.3.4. EMG and applications

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 normalised 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). 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 minimise cross-talk (Strasser, 2001). Surface EMG from the Pronator Teres (PT) and Extensor Carpi Radialis Brevis (ECRB) muscles were recorded for each of the treatments to determine the relative levels of exertion for these muscle groups.

2.3.5. Data acquisition (computer interface)

Signals from the goniometers 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. A series of 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.

2.4. Design of experiment

The subject rated discomfort at the end of each of the thirty-six different treatment combinations. The treatments comprised two levels of MVC pronation torque (10% and

20% of MVC), three levels of elbow angle (angle between the upper arm and forearm: 45^0, 90^0 and 135^0), three levels of forearm rotation angle {0, +/-60% Range of Motion (ROM)}, with the upper arm abduction angle constant at 90^0. Two levels of intermittent forearm torque (10% and 20% MVC pronation torque) were applied at two different frequencies (10 and 20 exertions per minute). Treatment combination blocks were ordered by Latin Squares and, as it took some time to adjust the fixture and in order to reduce inconvenience to the subjects, the treatments were set in blocks of the same elbow angles. Within each block the sub-combinations were also randomised by means of Latin Squares. A few orders were modified to avoid having two "difficult" treatments in succession.

Although the levels of force and forearm ROM were related to the maximum capability of each subject, elbow angles and upper arm abduction angles were expressed in absolute values so that it mimicked the industrial scenario where the same work station 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. Similarly supination torque denotes torque exertion in the clockwise direction for the right hand. The terms prone and supine are used to denote the rotational position of the forearm only.

2.5. Procedure

2.5.1. Preliminary data collection

The fixture height was adjusted so that the upper arm was abducted 90^0 in the coronal plane and the subject 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 subject's forearm. Maximum grip strength was recorded at the standard position of the arm, with the wrist and forearm at neutral, elbow flexed at 90^0 and the upper arm abducted at 0^0 (Mogk and Kier, 2003). Then endurance time at 50% MVC grip in the above position was measured after a break of ten minutes to minimise a cumulative fatigue effect. Maximum range of motion of the forearm was measured with the elbow at 90^0 followed by the maximum pronation torque strength with the upper arm at approximately 0^0 abduction, forearm neutral and elbow flexed at 90^0 (Fess and Moran, 1981). In all cases the subject was guided by LabVIEW. When the subject exerted 50% MVC (+/- 5%) the counter turned green and any overshoot or undershoot caused a beep to warn him and also the pointer turned red.

For the measurement of muscle activity from the PT and ECRB for the 18 treatments, the subject was presented with a VI (Figure 3) and asked to build up to maximum pronation torque and hold it for 10 seconds, as controlled by the software. Then the subject rested his arm on his lap for 10 seconds to record the resting muscle EMG followed by a VI to display each articulation combination. Each torque was exerted for 10 seconds with the end indicated by a beep.

[Insert Figure 3 here]

2.5.2. Main experiment

Each of the 36 treatment orders was presented by a VI to control each treatment (Figure 4) which lasted 5 minutes, followed by one minute of rest during which the subject rated discomfort on a 100mm Visual Analogue Scale (VAS) using the cursor**.** The entire experiment lasted for about five hours with a 30 minute break in between, thus simulating more than half a shift in industry.

[Insert Figure 4 here]

2.5.3. Supplementary experiment

It appeared that some of the increase in discomfort at non-neutral positions could be due to reduced MVC torque at these positions. A supplementary experiment was carried out on a separate group of subjects, to measure the pronation MVC torque at each of the articulations, excluding the effect of frequency. Twelve right-handed male University students, with no previous history of injury to the arm, participated in this study. Their mean age was 23.6 years (SD=3.8). The mean stature and body mass were 182.4 cm (SD=5.4) and 75.8 kg (SD=7.0), respectively. Again a LabVIEW VI screen presentation was used. After each exertion there was one minute of rest (Mogk and Kier, 2003) before testing in the next posture. Each subject exerted MVC torque three times and the software automatically recorded the highest value.

3. Results

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

3.1. MVC values

Mean grip strength was 377.8 N (SD =121.1). The average holding time (endurance) for 50% of the maximum grip strength was 48.6 seconds (SD=25.9). The maximum pronation torque strength was 6.7Nm (SD=2.3). All measurements were taken at the standard position of the arm.

3.2. Discomfort score

To reduce between-subject differences in discomfort perception, and to compare the results with other data in the literature, the raw discomfort values were standardised for each subject using a min-max standardisation procedure (Gescheider, 1985):

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

3.2.1. Transformation of data

SDS was not normally distributed and could not be normalised using different types of transformation, but Raw Discomfort Score (RDS) could be normalised by using the natural logarithm (Levene’s test, p=0.331). This Transformed Discomfort Score (TDS) was used to perform all statistical analyses and for all figures.

3.2.2. Discomfort score

Tables 1, 2 and 3 show the mean and standard deviation (SD) for the RDS, SDS and TDS at different articulations. Discomfort scores were maximum at 45^0 elbow angle, with forearm prone, 20% MVC and the frequency of 20 per minute. Similarly discomfort scores were minimum at 135^0 elbow angle, forearm neutral, 10% MVC and 10 exertions per minute.

Forearm rotation from neutral to prone led to an increase in discomfort by 25%. Similarly, with the change in forearm rotation from neutral to supine, discomfort increased by 12.2%. When elbow angle changed from 90^0 to 45^0 discomfort increased by 25.4%. But there was a fall in discomfort score with change in elbow angle from 90^0 to

135^0 by just 5.2%. At the higher torque level discomfort increased by 17.4% while the higher exertion rate increased discomfort by 15.6%.

[Insert Table 1]

[Insert Table 2]

[Insert Table 3]

3.2.3. Analysis of Covariance (ANCOVA)

Mauchly's test of sphericity showed that elbow angle, forearm rotation angle, forearm rotation* frequency, forearm rotation*torque*frequency and elbow angle* forearm rotation*torque* frequency violated this requirement. Hence the repeated measures ANCOVA (Table 4) was performed using the Greenhouse-Geisser Correction (GGC). Grip Endurance time was not significant (p=0.74). Of the main effects, elbow angle (p=0.011), forearm rotation (p=0.001), torque (p=0.001) and frequency (p=0.031) were all significant. The only significant interaction was forearm rotation*frequency (p=0.013).

[Insert Table 4 here]

3.2.4. Student Newman Keuls Test

To differentiate between the levels of factors in the ANCOVA, Student Newman Keuls tests were performed on the elbow angle and forearm rotation (Table 5). Other significant factors could not be tested as they had only two levels. As can be seen there was almost no difference in discomfort between elbow angles of 90^0 and 135^0, but at 45^0 it was significantly different from both of the others. For forearm rotation all three angles were significantly different from each other.

[Insert Table 5]

3.3. Interactions

TDS for different frequencies of exertions at different elbow angles (Figure 5) indicated a substantial increase in values with the increase of frequency from 10 to 20 per minute by about 25% at each elbow angle. But the big jump was for the 45^0 elbow angle relative to the other two by an amount of about one-third.

[Insert Figure 5 here]

For forearm rotation angles at different frequencies of exertion (Figure 6) there was a greater increase from discomfort at neutral with a prone forearm compared to supine. The increase in discomfort for a frequency of 20 per minute compared to 10 was less than that due to prone when compared to the score at neutral.

[Insert Figure 6 here]

TDS increased with increase in relative MVC from 10% to 20% for all elbow angles (Figure 7), by 17.9% (45^0 elbow), 16.7% (90^0 elbow) and 20% (135^0 elbow). The increase at 45^0 relative to 90^0 is very noticeable but the negligible difference between the two higher larger elbow angles is striking.

[Insert Figure 7 here]

With forearm rotation the effect of different relative MVC is clear (Figure 8). Again prone gave a bigger increase from neutral than did supine. The change in elbow angle (Figure 9) from 90^0 to 45^0, resulted in a notable increase in TDS from the neutral position with the forearm prone, and slightly less when supine. At the neutral forearm position and at elbow angles of 90^0 and 135^0 there was no significant difference in TDS (t=0.894, p=0.337). Similarly with forearm supine and at elbow angles of 90^0 and 135^0

there was no significant difference in TDS (t=0.910, p=0.368). The increase in relative MVC at different frequencies shows a clear-cut increase in TDS values (Figure10).

[Insert Figure 8 here]

[Insert Figure 9 here]

[Insert Figure 10here]

3.4. Electromyography (EMG)

3.4.1. Pronator Teres (PT) Muscle

There was a significant forearm rotation effect for the PT muscle when the forearm was pronated (t=3.196, p=0.024) but no such effects were observed when the forearm was supinated from neutral (t=0.394, p=0.709). There was no significant elbow angle effect (t=0.505, p=0.635) and no significant relative MVC torque effect (t=0.536, p=0.606).

3.4.2. Extensor Carpi Radialis Brevis (ECRB)

There was a significant forearm rotation effect – an increase from neutral to prone (t=3.273, p=0.022), and a decrease when going to supine (t=3.182, 0.024). Elbow angle was not significantly different from 90^0 to 45^0 (t=1.517, p=0.190) or from 135^0 to 90^0 (t=0.668, p=0.534). As expected there was a significant torque effect from 10% MVC to 20% MVC (t=3.800, p=0.005).

3.5. Supplementary experiment

Table 6 represents MVC Torque and RDS values as percentages of the values at the standard position of the arm. It is evident that the increase in relative MVC with respect to the standard position of the arm was maximum (143.9%) at 90^0 elbow angles with the forearm supine. At the same articulation the relative increase in RDS value with respect to the standard position was 76.3%. These values indicate that while the subjects exerted a nominal 10% MVC or 20% MVC in the main experiment, they were in reality exerting more than that in the non-standard positions of the arm.

[Insert Table 6]

4. Discussion

4.1. Experimental task

An earlier experiment (Mukhopadhyay et al. 2003) had shown that the increase of discomfort with change of abduction from 0^0 to 90^0 was not large so this was fixed at 90^0, which is in line with the values reported by Herberts et al. (1980). Levels of other design factors were based on O'Sullivan and Gallwey (2005) but the results cannot be compared directly between the two experiments. However the task cycles were the same. Compared to some experiments in the literature (e.g. Snook et al. 1995) these are short but McKenna and Gallwey (2002) reported a similar short cycle time in an electronics assembly task, and Corlett and Bishop (1976) reported a similar work-rest cycle. Similarly the values of elbow angle (45^0, 90^0 and 135^0) with the forearm maintained parallel with the transversal plane were similar to those found in various industrial tasks (Table7).

[Insert Table 7]

4.2. MVC values

The mean grip strength recorded in this experiment (377.8 N) closely resembles that reported by Mital and Kumar (1998a) i.e. 381.5 N with the standard position of the arm. The values are also close to that reported by Carey and Gallwey (2005) i.e. 327 N. The average holding time for 50% of the maximum grip strength (48.6 s) resembles that reported by Carey and Gallwey (2005) i.e. 63 s. But the maximum value (6.7 Nm) of pronation torque recorded in the standard position of the arm was lower than that reported by Kramer et al. (1994) which was 12.4 Nm for pronation torque. In similar experiments Salter and Darcus (1952) reported a value of 7.2 Nm, which is very close to the value recorded in the current experiment.

4.3. Forearm rotation

The SDS value was greater when pronated (4.2) than when supinated (3.0) which, though in agreement with the direction of difference in O'Sullivan and Gallwey (2005), the values were a bit lower. The group reported a mean SDS value of 6.9 when pronated and 4.1 when supinated. The reason for such low values in the current experiment might be due to the fact that the treatment conditions were not only completely different but also the upper arm was at abduction. The normal physiological mechanism for forearm rotation with the upper arm in abduction suggests that the rotator cuff tendons are entrapped between the acromion process of the scapula and the greater tubercle of the humerus (Palastanga et al. 1998). The impingement increases when the upper arm is in internal rotation and decreases when in external rotation, with the internal rotation (of the humerus) taking place with pronation, and external rotation taking place with supination of the forearm (Stokdijk et al. 2003). In pronation the radial bone crosses and wraps around the ulnar bone (which still remains stationary) whereas they are parallel to each other in supination (Coury et al. 1998b). Hence with the forearm in prone, exertion of a pronation torque possibly leads to more tendon or ligament strain, thus giving rise to more discomfort. Complete or partial blockage of some blood vessels, and/or some connective tissue strain (Wiker et al.1989) in the prone condition might lead to increased discomfort as well.

O'Sullivan and Gallwey (2005) reported similar discomfort score data indicating an increase in the prone condition. It is supported further by the increase in pronator teres muscle activity in pronation (c.12% greater than neutral) and supination (8.9%). Basmajian and DeLuca (1985) indicated that both PT and Pronator Quadratus (PQ) were prime pronating muscles. As the forearm rotates into the prone position there is a significant shortening (Buchanan et al. 1989, Gordon et al. 2004) of the length of the PT and PQ muscles (extent not mentioned), and hence its EMG activity is found to increase. This might be due to the fact that, with the decrease in muscle length, more muscle activity is required, hence EMG activity increases to reach the required torque. It was also noted in this case that there was an increased EMG activity of the PT muscle. In some of the articulations ECRB activity was unchanged. This was in agreement with Ljung et al. (1999), who reported that ECRB muscle length remains unchanged in some articulations, as it lies parallel to the axis of forearm rotation.

4.4. Median nerve tension

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 90^0 upper arm abduction and 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 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

At elbow angles of 90^0 and 135^0 with the forearm supine, the discomfort score was not significantly different. There might be multiple reasons for this. Physiological Cross Sectional Area (PCSA) and length of a muscle is directly related to the torque generating capacity (Edwards, 1972). With the upper arm abducted and the elbow angle at 90^0 and 135^0 degrees in the supine position, the muscle length and PCSA of the forearm muscles such as PT, PQ, etc do not change significantly (Salter and Darcus, 1952) from the neutral forearm position. As Liu et al. (1997) reported, muscles with a larger moment arm could generate more torque than muscles with a smaller moment arm given the same force. Murray et al. (1995) reported that the moment arm of PT and Biceps (BIC), changed negligibly in the range of 100^0 to 120^0 elbow angle. It was 2 mm at 100^0 and 2.4 mm at 120^0 elbow angle for the PT muscle, and 2.8mm at 100^0 and

2.3mm at 120^0 elbow angles for the BIC. This might be the reason for the discomfort score being not significantly different between 90^0 and 135^0 elbow angle. These were close to the range of elbow angles cited by Murray et al. (1995) as well, where there were almost no changes in length of muscle fibres and the moment arm.

During the course of the experiment, many of the subjects complained about severe discomfort in the whole arm at 45^0 elbow angle compared to 90^0 or 135^0. Dempster (1964) reported that the movement of the humerus bone reaches its maximum with the elbow pointed backwards, upwards and outwards at 45^0. Possibly this extreme was reached in this experiment at this particular articulation. He also reported that after this angle the shoulder sinus limits the motion of the joint structure, which might partly explain increased discomfort at 45^0 elbow angle compared to 90^0 and 135^0 elbow angle. Salter and Darcus (1952) reported that when the elbow was flexed to 30^0 there was a fall in pronation torque. According to them this might be due to the fact that elbow flexion at such a low angle might shorten (to what extent was not mentioned) the length of the muscles PT and PQ. As a result of shortening, the contractile forces of the muscles were smaller. So elbow flexion shortens the length of the muscles and pronation shortens it further. Thus the subjects had to apply more force at 45^0 elbow angle at a disadvantageous position of the arm, thus causing more discomfort. Such a relationship between discomfort and strength has also been reported by Coury et al. (1998a). As PT muscle originates from the medial epicondyle of the humerus and terminates about one third down the radial bone, its length is not significantly altered by a minute change in elbow angle. But in extreme flexion or extension of the elbow, there is a change. At 90^0 and 45^0 elbow angle PT activity was significantly greater at prone compared to the same at supine or neutral, possibly due to the fact that extreme flexion was reached, leading to significant change in the lengths of the PT and PQ muscles.

It has been reported (Lieber and Frieden, 2001**)** that at shorter muscle length, the cross bridges are in overlap in the region between the thick and thin filaments leading to maximum tension in the muscles. In contrast with longer muscle length the number of cross bridges in the overlap region decreases and the tension falls. Thus the increase and decrease of tension in the muscle, with resultant lengthening and shortening, might lead to different degrees of discomfort, with discomfort being possibly more with muscle shortening (as tension increases).

4.6. MVC torque

Increased discomfort with an increase in torque might be due to the fact that more and more muscles are involved. At 90^0 and 135^0 elbow angle and at a torque of 20% MVC, the discomfort values were not significantly different, possibly due to the PT and PQ muscles not undergoing any significant change in length as seen before. Thus elbow angle made no change with increased torque on discomfort score as the amount of torque exerted remained almost the same at these two articulations with almost no change in muscle length.

A two-way interaction was apparent between forearm rotation and torque MVC for the discomfort scores in almost all the positions. This might be partly explained by Buchanan et al. (1989) who reported that as the forearm moved into the prone position there was a significant shortening of the length of the PT and PQ muscles. Thus, to reach the desired torque of 20% MVC, much less effort was required in supine and neutral as the posture was at a mechanical advantage compared to prone, (Gordon et al. 2004) leading to more discomfort at the prone condition. This was in agreement with Carey and Gallwey (2002).

4.7. Frequency of exertion

With increase in frequency of torque exertion there was an increase in discomfort score. As more and more work is done by the hand musculatures there is less recovery time for washing out the metabolites being produced. Thus accumulation of these metabolites probably led to more discomfort.

4.8. Endurance time

That grip endurance was not a significant covariate might be due to the fact that the two activities were completely different from one another. As gripping and torquing activities each involve recruitment of totally different muscle groups and motor end plates (Herberts et al. 1980), it's quite obvious that the endurance time task might be too different from the experimental task. The data suggest that for a torquing activity, grip endurance time is probably unable to nullify the between subject difference in pain tolerance, and this probably means that the endurance time task must be task specific but it warrants further investigation.

4.9. Supplementary experiment

The increase in discomfort score at different non-neutral positions, especially at extreme articulations such as 45^0 elbow angle with the forearm prone, was probably due to exertion of more than 10% and 20% MVC at the respective articulations. These RDS values did not show any specific patterns and hence further investigation using the actual MVC at each articulation is probably needed to get a clearer picture.

4.10. Implications of the results

It has been observed from this experiment that it is always better to work with the forearm at neutral or supine, and that working with the forearm at prone requires extreme caution. At elbow angles of 135^0 and 90^0 there was hardly any difference in the discomfort scores at the supine forearm position. These types of activities are common in the automobile industry, for example unscrewing a nut, and might be considered relatively safe with the upper arm in abduction. But, with the upper arm abducted, an elbow angle of 45^0 was found to be extremely stressful. Thus any work demanding upper arm abduction should be done with extreme caution when the elbow is flexed at much less than 90^0. Also, any unscrewing activities (involving pronation of the right hand) should preferably be avoided at all costs. With an increase in pronation torque at increased frequency of exertion, an increased rate of change of discomfort was noticed which also warrants extreme caution on the part of a worker doing such jobs at high MVC torque and at high frequency.

In cases where work demands pronation torque, the workers should be rotated on the job so that no particular worker is stressed for a long cumulative period. Another option would be to have a left handed person do the unscrewing activity in which case the powerful forearm supinator muscles would be in use, as it would be a supination torque for that particular subject.

5. Conclusions

- With the upper arm at 90^0 abduction and elbow angles of 135^0 and 90^0, there was no significant change in discomfort score showing no effect of elbow angle within this range of articulations
- In general, the prone condition of the forearm resulted in more discomfort compared to the supine or neutral conditions, indicting that work at this articulation should be undertaken with extreme caution
- Discomfort in general was maximum at 45^0elbow angle compared to 90^0 and 135^0 indicating extreme caution for having operators work at such articulations
- When % MVC torque was defined relative to MVC at the standard position of the arm, the MVC exerted at non-neutral postures was more than the intended 10% or 20% MVC, complicating interpretation of the results.
- Grip endurance time was not a significant covariate in this experiment and warrants further investigation

Acknowledgements

Funding for this work was provided by the MIRTH project (GIRTH-CT-2001-005740) of the European Commission Competitive and Sustainable Growth Programme. The comments of the anonymous reviewers were most helpful.

References

Akesson I, Johnsson B, Rylander L, Moritz U, Skerfving S., 1999, Musculoskeletal disorders among female dental personnel clinical examination and a 5-year follow-up study of symptoms, International Archives of Occupational Environment and Health, 72, 395-403.

Annett, J. 2002, Subjective-rating scales in ergonomics: a reply, Ergonomics, 45, 1042-1046.

Basmajian, J.V., Deluca, C.J., 1985, Muscle alive: Their functions revealed by electromyography, 5th ed., (Baltimore: Williams and Wilkins).

Bernard, B.P., (ed) 1997, Musculoskeletal Disorder and Workplace Factor, 2nd Edition, National Institute of Occupational Health and Safety (NIOSH), Cincinnati, Ohio.

Bjelle, A., Hagberg, M., Michaelson, G., 1981, Occupational and individual factors in acute shoulder-neck disorders among industrial workers, British Journal of Industrial Medicine**,** 39,356-363.

BLS, 1990, Workplace injuries and illness in 1989, U.S. Department of Labour, Bureau of Labour Statistics, Washington DC, 98-112.

Buchanan, T.S., Rovai, G.P., Rymer, W.R., 1989, Strategies for muscle activation during isometric torque generation at the human elbow, Journal of Neurophysiology, 62, 1201-1212.

Carey, E.J., Gallwey, T.J., 2002, Effects of wrist posture, pace and exertion on discomfort, International Journal of Industrial Ergonomics, 29, 85-94.

Carey, E.J., Gallwey, T.J., 2005, Wrist discomfort levels for combined movements at constant force and repetition rate, Ergonomics, 48, 171-186.

Christensen, H., 1986, Muscle activity and fatigue in the shoulder muscles of assembly-plant employees, Scandinavian Journal of Work Environment Health, 12, 582-587.

Chung, M.K., Lee, I., Yeo, Y.S., 2001, Physiological workload evaluation of screw driving tasks in automobile assembly jobs, International Journal of Industrial Ergonomics, 28, 181-188.

Ciriello, V.M., Webster, B.S., Dempsey, P.G., 2002, Maximal acceptable torques of highly repetitive screw driving, ulnar deviation, and hand grip tasks for 7- hour workdays, American Industrial Hygiene Association Journal, 63, 594-604.

Corlett, E.N., Bishop, R.P., 1976, A technique for assessing postural discomfort, Ergonomics, 19, 175-182.

Coury, G.C.J.H., Kumar, S., Narayan, Y., 1998a, An electromyographic study of upper limb adduction force with varying shoulder and elbow postures, Journal of Electromyography and Kinesiology, 8, 157-168.

Coury, G.C.J.H., Kumar, S., Rodgher, S., Narayan, Y., 1998b, Measurements of shoulder adduction strength in different postures, International Journal of Industrial Ergonomics, 22, 195-206.

Delagi, E.F., Perotto, A., Iazetti, J., Morrison, D., 1980, Anatomical guide for the elctromyographer, 2nd ed. Charles C.Thomas, New York, 78-83.

Dempster, W.T., 1964, Mechanisms of shoulder movement, paper presented at the Scientific session of the American Academy of Physical Medicine and Rehabilitation, Boston, August 24, 49-69.

Edwards, R.H.T., 1972, Studies of muscular performance in normal and dystrophic subjects, British Medical Bulletin, 36, 159-164.

Fess, E., Moran, C., 1981, Clinical assessment recommendations, Philadelphia, American Journal of Physical Medicine, 62, 135-144.

Gescheider,G.A., 1985, Psychophysics-Method Theory and Application, 2nd Edition, Lawrence Earlbaum Hillsdale, N.J.

Gordon, K.D., Pardo, R.D., Johnson, J.A., King, G.J.W., Muller, T.A., 2004, Electromyographic activity and strength during maximum isometric pronation and supination efforts in healthy adults, Journal of Orthopaedic Research, 22, 208-213.

Hagberg, M., Wegman, D.H., 1987, Prevalence rates and odd ratios of shoulder-neck diseases in different occupational groups, British Journal of Industrial Medicine, 44, 602-610.

Herberts, P., Kadefors, R., Broman, H., 1980, Arm positioning in manual tasks an electromyographic study of localized muscle fatigue, Ergonomics, 23, 655-665.

Kattel, B.P., Fredericks, T.K., Fernandez, J.E., Lee, D.C., 1996, The effects of upper extremity posture on maximum grip strength, International Journal of Industrial Ergonomics, 18, 423-429.

Kilbom, A., and Persson, J., 1987, Work technique and its consequences for Musculoskeletal disorders, Ergonomics, 30, 273-279.

Kleinrensink, G.J., Stoeckart, R., Vleeming, A., Snijders, C.J., Mulder, P.G.H., 1995, Mechanical tension in the median nerve, the effects of joint positions, Clinical Biomechanics, 10, 240-244.

Kramer, J.F., Nusca, D., Bisbec, L., Macdermid, J., Kemp, D., Boley, S., 1994, Forearm pronation and supination: reliability of absolute torques and non-dominant /dominant hand ratios, Journal of Hand Therapy, 1, 15-20.

Kumar, S., 2001, Theories of musculoskeletal injury causation, Ergonomics, 44, 17-47.

Lieber, R.L., Frieden, J., 2001, Clinical significance of muscle architecture, Clinical Orthopaedics and Related Research, 383, 140-151.

Liu, J., Hughes, R.E., Smutz, W.P., Niebur, G., An, K.N., 1997, Roles of deltoid and rotator cuff muscles in shoulder elevation, Clinical Biomechanics, 12, 32-38.

Ljung, B.O., Frieden, J., Lieber, R.L., 1999, Sarcomere length varies with wrist ulnar deviation but not forearm pronation in the extensor carpi radialis brevis muscle, Journal of Biomechanics, 32, 199-202.

McKenna, R.E., Gallwey, T.J., 2002, Some variables affecting WMSDs in electronic assembly work, Irish Ergonomics Review, ISSN 1649-2102, 1-6.

Melin, E., 1987, Neck-shoulder loading characteristics and work technique, Ergonomics, 30, 281-285.

Mital, A., Kumar, S., 1998a, Human muscle strength definitions, measurements, and usage: Part I- Guidelines for the practitioner, International Journal of Industrial Ergonomics, 22, 101-121.

Mital, A., Kumar, S., 1998b, Human muscle strength definitions, measurements, and usage: Part II- The scientific basis (knowledge base for the guide), International Journal of Industrial Ergonomics, 22, 123-144.

Mogk, J.P.M., Kier, P.J., 2003, The effects of posture on forearm muscle load during gripping, Ergonomics, 46, 956-975.

Mukhopadhyay, P., Gallwey, T.J., O'Sullivan, L.W., 2003, Effect of grip force and shoulder abduction angles in repetitive clockwise forearm pronation/supination movements, in Proceedings of the International Annual Occupational Ergonomics and Safety Conference, 7th – 9th May, Munich, 81-88.

Murray, W.M., Delp, S.L., Buchanan, T.S., 1995, Variation of muscle moment arms with elbow and forearm position, Journal of Biomechanics, 5, 513-525.

O'Sullivan L.W., Gallwey, T.J., 2005, Forearm torque strengths and discomfort profiles in pronation and supination, Ergonomics, 48, 703-721.

Palastanga, N., Field, D., Soames, R., 1998, Anatomy and human movement, structure and function, 2nd edition, Butterworth Heinemann, Oxford.

Putz-Andersson, V., 1988, Cumulative trauma disorders – a manual for musculoskeletal diseases of the upper limbs, Taylor and Francis, London.

Salter, N., Darcus, H.D., 1952, The effect of the degree of elbow flexion on the maximum torques developed in pronation and supination of the right hand, Journal of Anatomy, 89, 197-202.

Sjogaard, G., Christensen, H., Pedersen, M.B., 1986, Neck and shoulder disorders due to prolonged uncomfortable working postures. Proceeding of Eleventh Congress of The International Ergonomics Association, Paris, 1, 123-125.

Snook, S.H., Vaillancourt, D.R., Ciriello, V.M. and Webster, B.S., 1995, Psychophysical studies of repetitive wrist flexion and extension, Ergonomics, 38, 1488-1507**.**

Stokdijk, M., Eilers, P.H.C., Nagels, J., Rozing, P.M., 2003, External rotation in the glenohumeral joint during elevation of the arm, Clinical Biomechanics, 18, 296-302.

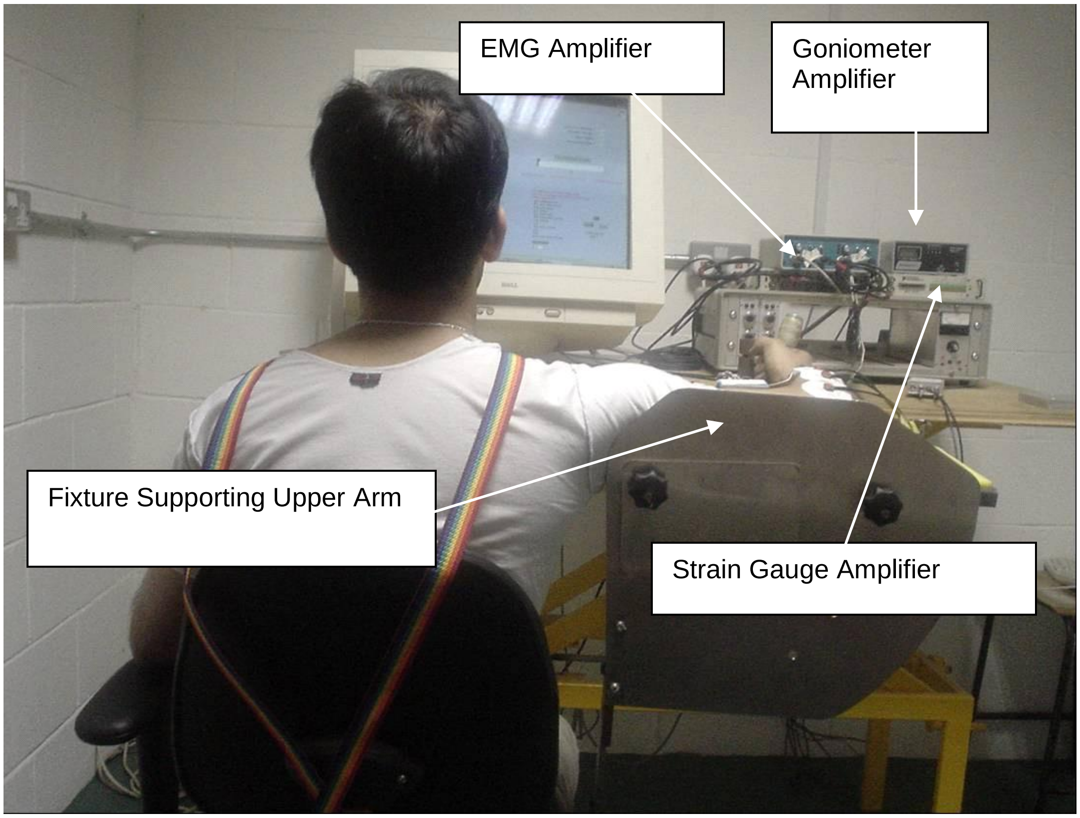
Strasser, H., 2001, Electromyography: Methods and techniques, edited by Karwowski, W., International Encyclopaedia of Ergonomics and Human Factors, Taylor and Francis, London, 3, 1801-1804.

Trevelyan, F.C., Haslam, R.A., 2001, Musculoskeletal disorders in a hand made brick manufacturing plant, International Journal of Industrial Ergonomics, 27, 43-55.

Wiker, F.S., Chaffin, D.B., Langolf, G.D., 1989, Shoulder posture and localized muscle fatigue and discomfort, Ergonomics, 32, 211-237.

Zhang, L., Helander, M.G., Drury, C.G., 1996, Identifying factors of comfort and discomfort in sitting, Human Factors, 38, 377-389.

List of Figures


EMG Amplifier
Goniometer Amplifier
Fixture Supporting Upper Arm
Strain Gauge Amplifier

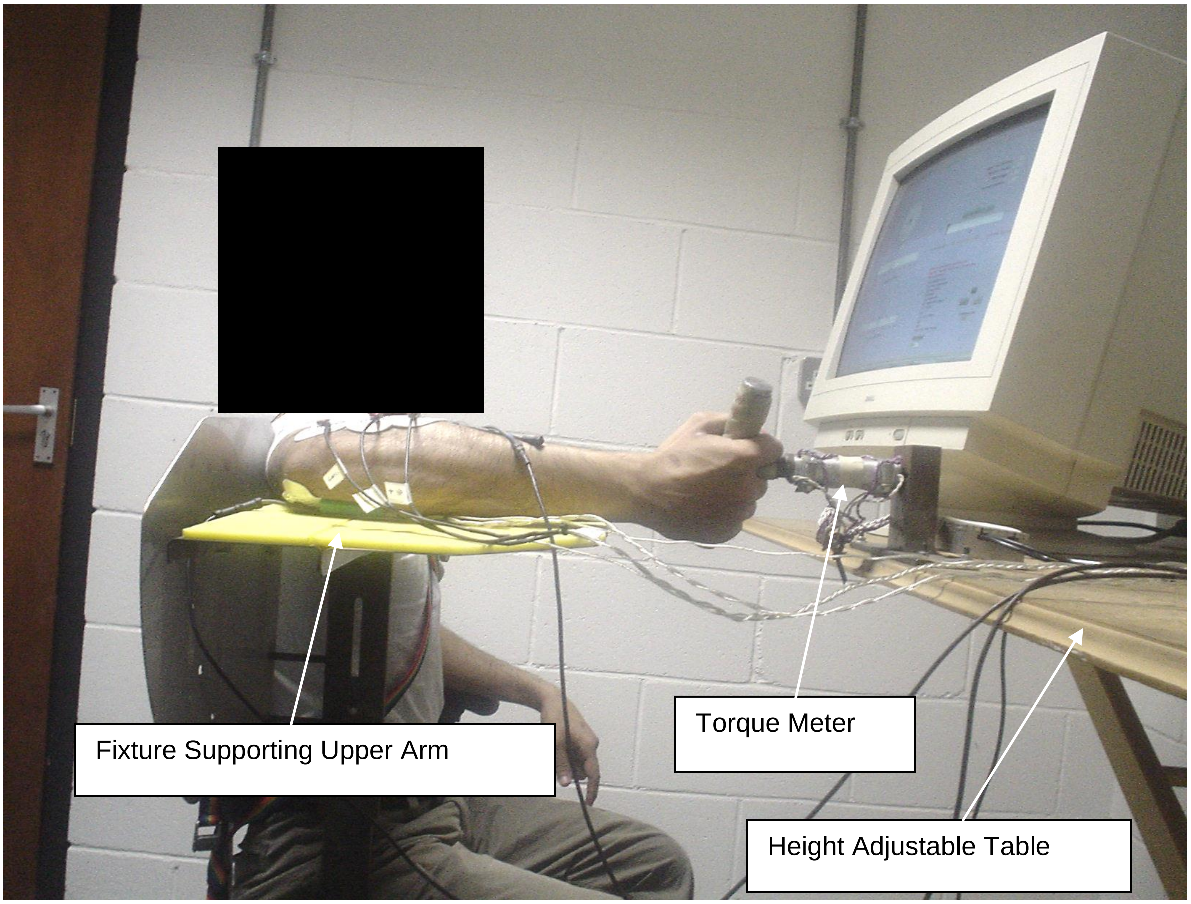
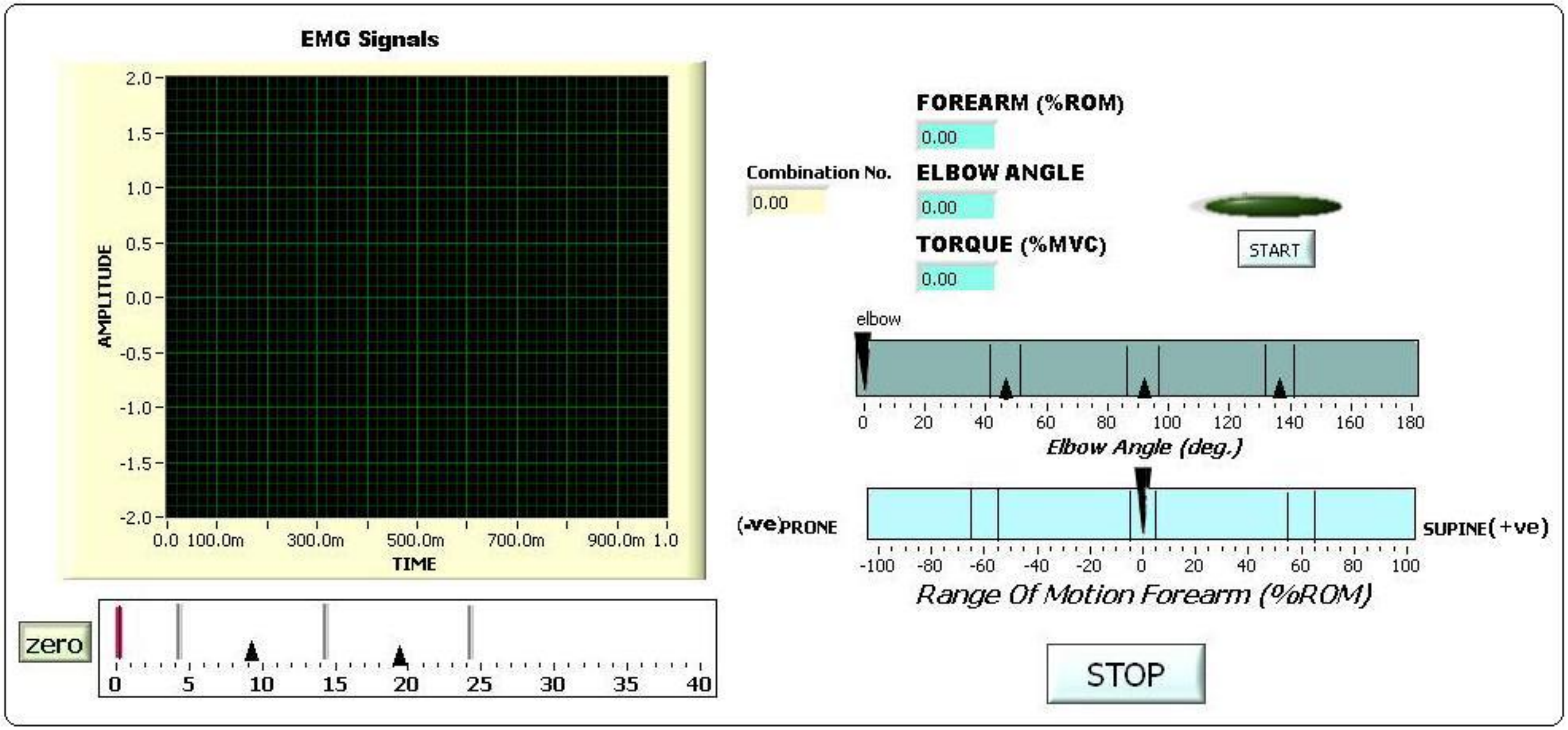

[redacted]

Figure 2 Experimental set up showing the torque meter and the fixture



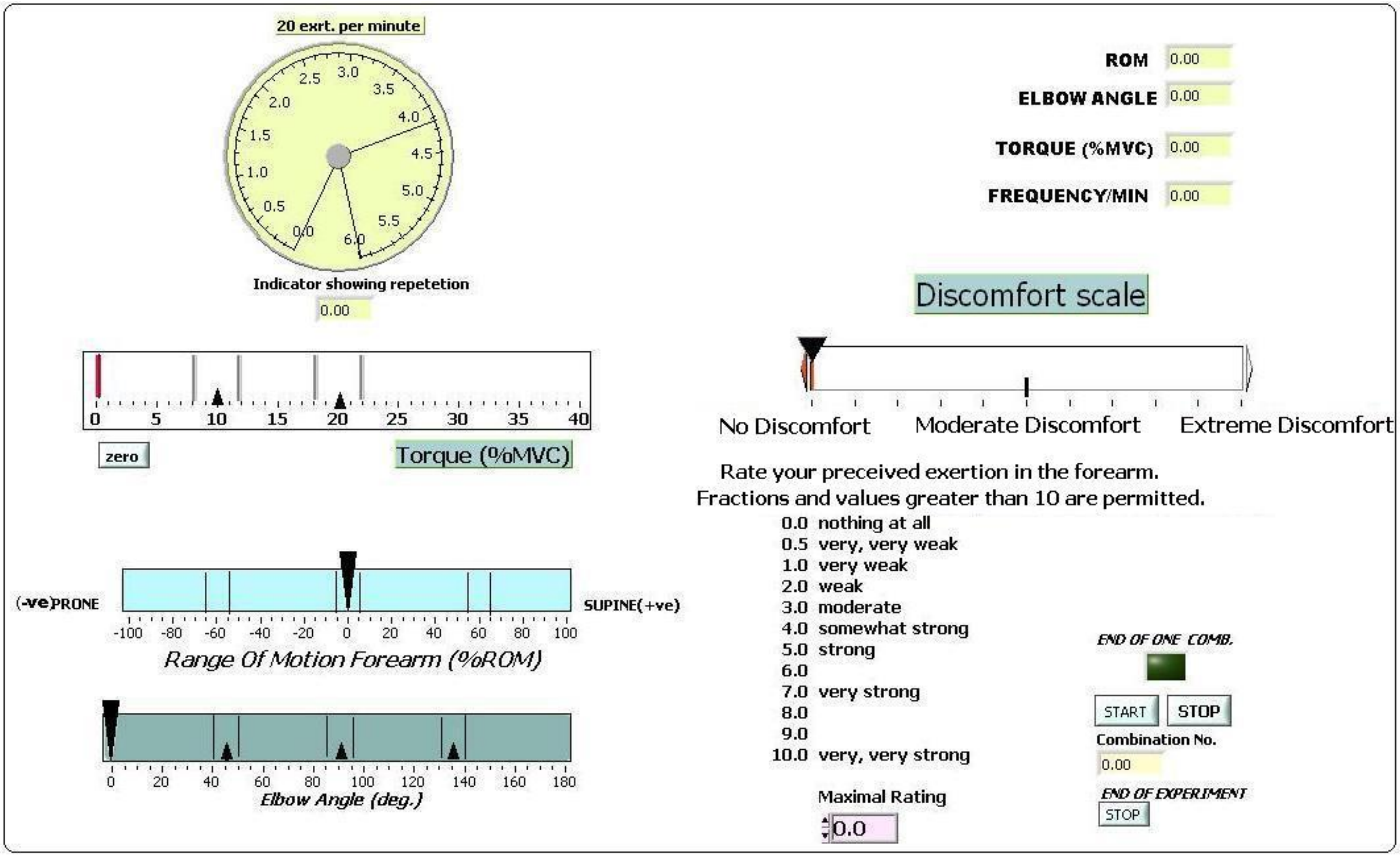
Combination No. 0.00

FOREARM (%ROM) 0.00

ELBOW ANGLE 0.00

TORQUE (%MVC) 0.00

Figure 3 Screen shot of LabVIEW VI for EMG recording



Indicator showing repetetion 0.00

ROM 0.00

ELBOW ANGLE 0.00

TORQUE (%MVC) 0.00

FREQUENCY/MIN 0.00

Rate your preceived exertion in the forearm.
Fractions and values greater than 10 are permitted.

0.0	nothing at all
0.5	very, very weak
1.0	very weak
2.0	weak
3.0	moderate
4.0	somewhat strong
5.0	strong
6.0	
7.0	very strong
8.0	
9.0	
10.0	very, very strong

Maximal Rating 0.0

Combination No. 0.00

Figure 4 Screen shot of LabVIEW VI for discomfort recording

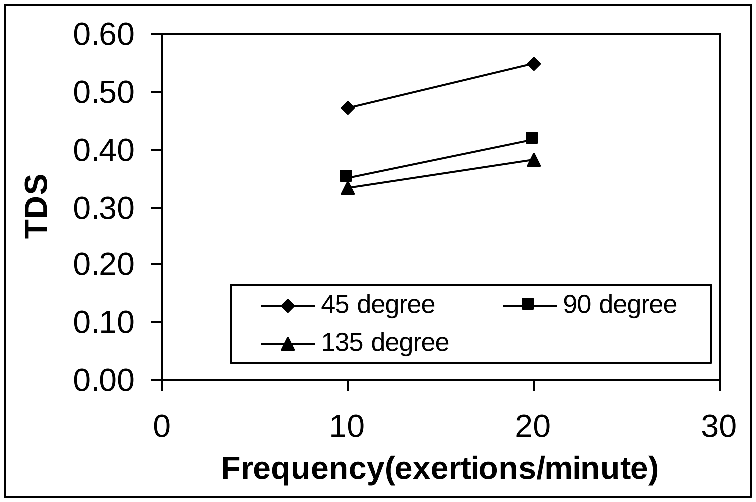


Figure 5 TDS Vs Frequency at different elbow angles

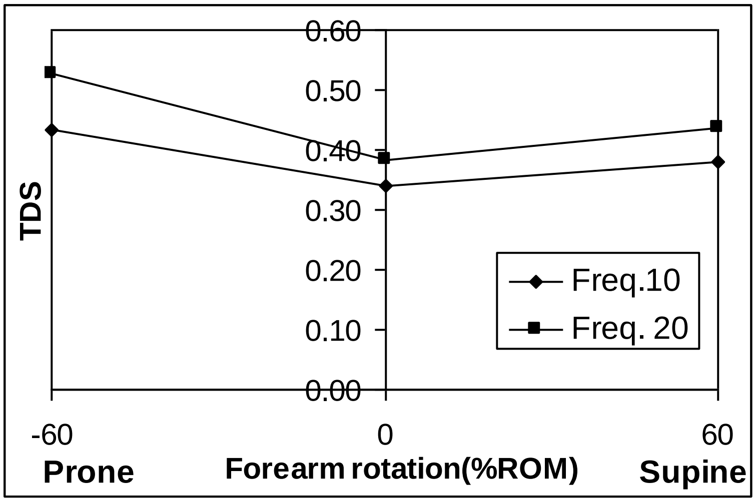


Figure 6 TDS Vs Forearm rotation angles (%ROM) at different frequencies

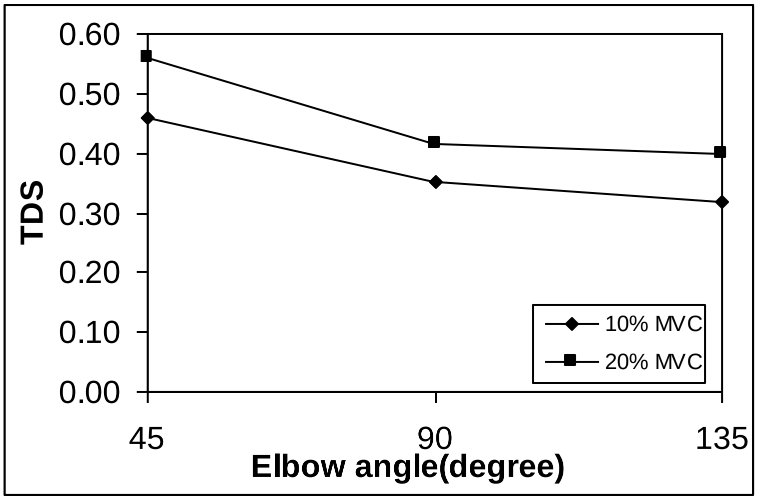


Figure 7 TDS Vs Elbow angles at different MVC Torque

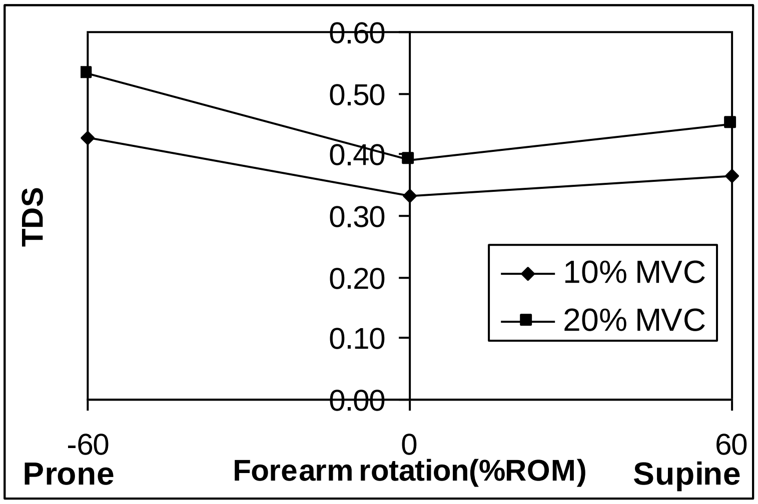


Figure 8 TDS Vs Forearm rotation (%ROM) at different MVC torque

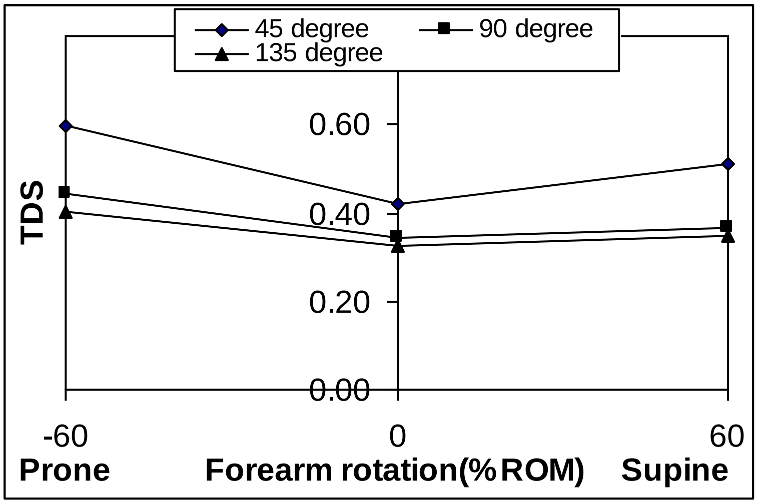


Figure 9 TDS Vs Forearm rotation (%ROM) at different elbow angles

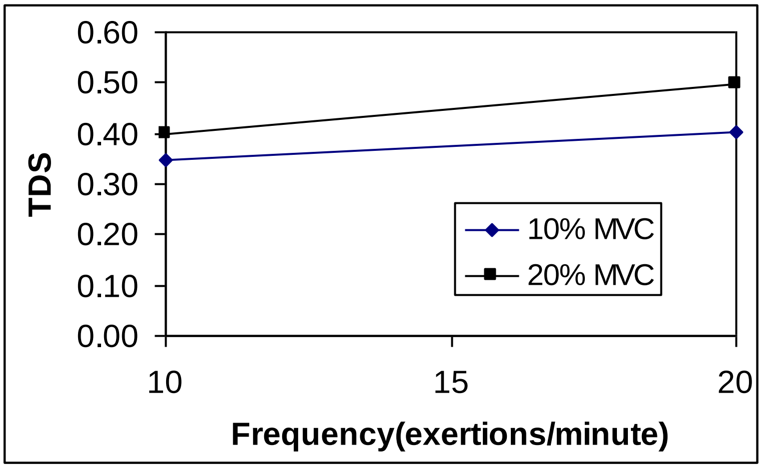


Figure 10 TDS Vs Frequency at different relative MVC torque

List of Tables

Table 1 Mean values of Raw Discomfort Score (Standard Deviation)

			Forearm rotation (%)		
Elbow angle	**Torque (%MVC)**	**Frequency**	**60 Supine**	**Neutral**	**60 Prone**
45^0	10	10	2.3(1.8)	1.7(1.6)	2.5(1.8)
		20	2.3 (1.6)	2.0 (1.9)	3.3(2.2)
	20	10	2.8(2)	2.1(1.7)	3.5(2)
		20	3.7(2.3)	2.5 (1.1)	5(2.4)
90^0	10	10	1.1 (0.8)	1.2(1)	1.6(1.1)
		20	1.5(1.1)	1.5(1.2)	2.1 (1.7)
	20	10	1.6(1.2)	1.5(1.2)	2.0 (1.6)
		20	2.1(1.4)	1.7(1.3)	2.8 (1.6)
135^0	10	10	1.2 (1.0)	1.0 (0.9)	1.3(1.0)
		20	1.4(1.1)	1.3(1.1)	1.7 (1.3)
	20	10	1.5(1.1)	1.6(1.3)	1.9 (1.5)
		20	1.9 (1.4)	1.6(1.3)	2.6(1.9)

Table 2 Mean value of Standardised Discomfort Score (Standard Deviation)

			Forearm rotation (%)		
Elbow angle	**Torque (%MVC)**	**Frequency**	**60 Supine**	**Neutral**	**60 Prone**
45^0	10	10	3.5 (2.5)	2.2(2.0)	3.9 (2.6)
		20	3.6 (2.3)	2.9 (2.2)	5.5(2.6)
	20	10	4.4 (2.7)	3.1(2.3)	6.0 (2.7)
		20	6.2 (2.8)	3.1(2.5)	9.2 (1.6)
90^0	10	10	1.5 (1.4)	1.6 (1.6)	2.4(1.8)
		20	2.4(2.0)	2.0(1.6)	3.4(2.9)
	20	10	2.7 (2.1)	2.2(1.7)	3.4(2.8)
		20	3.4(2.5)	2.7 (2.4)	4.9 (2.4)
135^0	10	10	1.6 (1.6)	1.0 (1.2)	1.7 (1.5)
		20	1.8(1.5)	1.7 (1.6)	2.5 (1.7)
	20	10	2.2(1.6)	2.1(1.7)	3.0 (2.3)
		20	3.0(2.0)	2.3(1.9)	4.1(2.6)

Table 3 Mean value of Transformed Discomfort Score (Standard Deviation)

			Forearm rotation (%)		
Elbow angle	**Torque (%MVC)**	**Frequency**	**60 Supine**	**Neutral**	**60 Prone**
45^0	10	10	0.5(0.2)	0.4(0.2)	0.5(0.2)
		20	0.5 (0.2)	0.4(0.2)	0.6(0.2)
	20	10	0.5(0.3)	0.4(0.2)	0.6(0.2)
		20	0.6(0.2)	0.5(0.2)	0.7(0.2)
90^0	10	10	0.3(0.2)	0.3(0.2)	0.4(0.2)
		20	0.4(0.2)	0.3(0.2)	0.4(0.2)
	20	10	0.4(0.2)	0.3(0.2)	0.4(0.3)
		20	0.4(0.2)	0.4(0.2)	0.5(0.2)
135^0	10	10	0.3(0.2)	0.3(0.2)	0.3(0.2)
		20	0.3(0.2)	0.3(0.2)	0.4(0.2)
	20	10	0.4(0.2)	0.4(0.2)	0.4(0.2)
		20	0.4(0.2)	0.4(0.2)	0.5(0.2)

Table 4 Repeated-measures ANCOVA for Transformed Discomfort Score with Greenhouse Geisser Correction (GGC) for factors violating sphericity.

Source	**Sum of square**	**df**	**Mean square**	**F**	**Sig.**
Grip Endurance time (ET)	0.600	1	0.600	0.110	0.742
Elbow angle (E) GGC	7.664	1.75	4.370	5.140	0.011
Forearm rotation (R) GGC	4.550	1.677	2.714	15.391	0.001
Torque (T)	3.918	1	3.918	21.339	0.001
Frequency (FR)	0.726	1	0.726	4.988	0.031
E * ET	0.078	2	0.039	0.053	0.949
R * ET GGC	0.278	1.677	0.166	0.940	0.382
T * E	0.051	2	0.026	0.323	0.725
FR* ET	0.264	1	0.264	1.811	0.186
E * R	0.245	4	0.061	0.786	0.536
FR * T	0.063	1	0.063	1.638	0.208
R * T	0.259	2	0.130	2.529	0.086
E * FR	0.231	2	0.115	1.948	0.149
R * FR GGC	0.424	1.739	0.244	4.914	0.013
T * ET	0.106	1	0.106	0.557	0.452
E * R * ET	0.175	4	0.044	0.562	0.691
E * T * ET	0.034	2	0.017	0.213	0.808
R * T * ET	0.024	2	0.012	0.236	0.79
E * R * T	0.093	4	0.023	0.463	0.763
E * FR * ET	0.093	2	0.046	0.785	0.46
R * FR* ET GGC	0.080	1.739	0.046	0.933	0.387
E * R * FR	0.123	4	0.031	0.805	0.524
T * FR* ET	0.001	1	0.001	0.022	0.883
E * T* FR	0.073	2	0.036	0.685	0.507
R * T * FR GGC	0.124	1.745	0.071	0.977	0.372
E * R * FR * ET	0.136	4	0.034	0.890	0.471
E * R * T * ET	0.138	4	0.035	0.690	0.6
E * T * FR * ET	0.063	2	0.031	0.589	0.557
R * T * FR * ET GGC	0.016	1.745	0.009	0.127	0.854
E * R * T * FR GGC	0.180	3.08	0.058	0.760	0.522
E * R * T * FR * ET GGC	0.358	3.08	0.116	1.511	0.214
Residual	367.813	1440	0.255		
Total	438.413	1511			

Table 5 Student-Newman-Keuls for elbow angle and (%) forearm rotation angle for Transformed Discomfort Score (TDS)

Elbow angle

	Mean of TDS	
	Group 1	Group 2
135^0	0.826	
90^0	0.882	
45^0		1.172

Forearm rotation	**Mean of TDS**		
	Group 1	Group 2	Group 3
Neutral	0.833		
60% Supine		0.950	
60% Prone			1.105

Table 6 MVC Torque and RDS as percentage of standard position (0^0 abduction, elbow angle 90^0, forearm neutral, wrist neutral)

Forearm rotation angle (%)	**Elbow angle**					
	45^0		**90^0**		**135^0**	
	MVC	**RDS**	**MVC**	**RDS**	**MVC**	**RDS**
60% Supine	133.5	133.1	143.9	76.3	137.3	79.7
Neutral	76.1	143.4	100.0	100.0	106.7	93.9
60% Prone	43.5	244.0	65.8	147.5	60.8	129.0

Table 7 Upper limb postures observed in different industries

Industry	**Posture types**	**Joint angles range**	**Reference**
Electronic assembly	Upper arm at abduction	0^0 to > 60^0	Kilbom and Persson (1987)
Meat cutting	Elbow flexion	0^0 to 90^0	Kilbom and Persson (1987)
Assembly	Abduction	0^0 to 90^0	Melin (1987)
Dentist	Abduction	>90^0	Akesson et al. (1999)
Packaging pencil factory	Upper arm flexion / elbow flexion	0^0 to 90^0/ 0^0 to 120^0	Coury et al. (1998a)
Electronic assembly	Elbow flexion	0^0 to 90^0	Christensen (1986)
Automobile assembly	Elbow flexion	110^0	Coury et al. (1988a)
Hand made brick manufacturing plant	Upper arm/ Elbow flexion	45^0 medial rotation, 90^0 flexion/, 45^0 abduction/90^0 flexion, 45^0 forward flexion	Trevelyan and Haslam (2001)
Assembly Task in industry	Elbow flexion/ Shoulder angle in saggital plane	0^0 to 90^0 / 20^0 to 90^0	Coury et al. (1998a)