Effects of combined wrist flexion/extension and forearm rotation and two levels of relative force on discomfort

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Abstract

This study investigated perceived discomfort in an isometric wrist flexion task. Independent variables were wrist flexion/extension (55%, 35% flexion, neutral, 35% and 55% extension ROM), forearm rotation (60%, 30% prone, neutral, 30% and 60% supine ROM) and two levels of flexion force (10% and 20% MVC). Discomfort was significantly affected by flexion force, forearm rotation and two-way interaction of force with forearm rotation (each $p<0.05$). High force for 60%ROM forearm pronation and supination resulted in increasingly higher discomfort for these combinations. Flexion forces were set relative to the MVC in each wrist posture and this appears to be important in explaining a lack of significant effect ($p=0.34$) for flexion/extension on discomfort. Regression equations predicting discomfort were developed and used to generate iso-discomfort contours which indicate regions where the risk of injury should be low, and others where it is likely to be high.

Relevance to Industry

Equations and iso-discomfort contours are presented which indicate combinations of upper limb postures for which discomfort is predicted to be low, and others where it is likely to be high. These are helpful in the study of limits for risk factors associated with upper limb musculoskeletal injury in industry.

Introduction

There is substantial evidence within the European Union (EU) member states that upper limb disorders are a significant problem within the workplace with respect to incidence and costs (European Foundation for Living and Working Conditions, 2007). Repetitiveness, force and posture lead to hand and wrist problems (Hagberg et. al, 1995). Silverstein (1998) associated epicondylitis with tasks requiring forceful laborious work, e.g., in foundries, building construction, manufacturing, and meat handling. A local investigation showed that similar postural deficiencies occurred in electronic assembly tasks in some Irish workplaces. The management of those companies reported cases of discomfort among workers involved in the repetitive tasks of small electronic assemblies, and packaging. Most of the latter tasks involved repetitive wrist deviations and wrist flexion/extension, combined with forearm rotation. They caused discomfort and occupational injuries (O'Sullivan, 2001).

In a few studies, wrist flexion angle and force have both been shown as significant main factors for determining maximum acceptable frequency and discomfort ratings (Lin et al, 1997, and Kim & Fernandez, 1993). These findings need to be extended to include more force and wrist posture combinations similar to those performed in industry. Lin et al. (1997) found the effect on discomfort of repetitive wrist flexion force to be significant ($p<0.05$). Khan et al. (2003) added grip force to repetitive wrist flexion force and found that wrist-flexion angle, frequency and grip force significantly affected discomfort ($p<0.01$, 0.01 and 0.001 respectively). But the majority of psychophysical studies of wrist posture effects have not studied the effects of forearm rotation. For example, Carey and Gallwey (2002) studied wrist deviation and flexion/extension combined, but the forearm was neutral. Separately, O'Sullivan and Gallwey (2005) developed a model for discomfort prediction for forearm pronation/supination (P/S) in a torquing task with a neutral wrist. A previous study by the current authors (Khan et al. 2009) found that wrist radial/ulnar deviation and forearm rotation had highly significant effects ($p<0.01$) on discomfort in a wrist flexion task. But in this case force was absolute, so there was a confounding effect due to differences in Maximum Voluntary Contraction (MVC) between participants, especially at non-neutral postures. Such an effect has been well demonstrated where grip exertions are strongest when close to neutral postures, due to more favourable biomechanical moment arms and length of muscle fibre overlap (Dempsey and Ayoub 1996, Kattel et al. 1996). Further studies are needed to address these points.

Therefore, there was a need for a study that combined wrist flexion/extension with forearm rotation for a repetitive task at different force levels. But to evaluate the effects more accurately it was necessary to set the force levels relative to MVC measured in each posture combination. The aim was to establish the relative differences in discomfort levels between the various combinations of these factors.

1. **Method**

1.1. Participants

The twenty-five participants were right-handed males and students at the University. The average age was 23 (SD 2.71), height 179 cm (SD 7.10), and body mass 74 kg (SD 10.15). They were paid €45 each. Approval from the ethics committee of the university was obtained for the experiment.

1.2. Postures

Angular movements were defined in terms of the Range Of Motion (ROM) of each individual. There were five levels of wrist posture, with the same values as Carey and Gallwey (2002), i.e. 0%, 35% and 55% of the ROM in flexion and extension. Five levels of forearm rotation were used, 0%, 30% and 60% of the ROM in supine and prone, from the range used by O'Sullivan and Gallwey (2005). Hence, for the main study a total of twenty five posture combinations were studied.

An additional objective of the study was to test if posture effects remained on discomfort when controlling for reduced MVC in deviated postures. Previous data indicated that grip strength was affected by wrist flexion/extension but not forearm rotation (Khan, 2004). Therefore, grip strength MVCs were recorded (with the forearm prone) for each of the five wrist flexion/extension postures but not for separate forearm rotation postures.

1.3. Repetitive task

The repetitive isometric flexion task of Carey and Gallwey (2002) was chosen with two levels of wrist flexion force (10%MVC & 20%MVC of the participant at each particular posture combination) at a frequency of 15 exertions per minute, as for Carey and Gallwey. Individual MVCs, as measured in each wrist posture (with the forearm neutral) were used for the respective treatments throughout the experiment. Hence, force for each treatment was relative to the MVC for that posture.

Participants exerted the wrist flexion force in each treatment for one second of a 4 second cycle (Figure 1). These levels were auto controlled within a LABVIEW software interface.

This was indicated to the participant by the markers on the running clock as shown in the screen shot of the LABVIEW interface (Figure 1).

1.4. Apparatus and Data Collection

A fixture was constructed (Figure 2) to allow participants to press their right palm on a board to depress a pinch meter (Biometrics Model E3000 Upper Limb Exerciser, pinch meter P100) at all posture combinations, on a height adjustable table. A forearm support used by Carey and Gallwey (2002) was modified to accommodate testing of the specific posture combinations. The participant sat on a fully adjustable chair with the elbow flexed at 90^0, forearm horizontal, and upper arm at approximately 45^0 in the coronal plane. A Velcro strap held the forearm on the table to prevent movement during the experiment.

[Place Figure 1 about here]
[Place Figure 2 about here]

Joint angles were measured and monitored by two Biometrics electro-goniometers attached as per the manufacturer's instructions. An XM110 goniometer measured the wrist flexion/extension and was placed on the extension side of the wrist and forearm. A Z180 goniometer measured forearm rotation attached to the flexor side of the forearm. Signals from these goniometers and the pinch meter were interfaced with a 333MHz PC, using a National Instruments' data acquisition board (PCI MIO 16XE-50). The experiment was controlled and data was captured using Virtual Instruments (VIs) coded in LabVIEW (V.6i) (Figure 1).

Angular movements of the wrist and forearm, and wrist flexion forces, were displayed in real time on the screen. Separately, a vertical bar indicated flexion force relative to the MVC recorded at the start of the experiment. The bar indicated the required force band (10 or 20%

MVC +/- 10%) for each treatment. Out of range exertions were denoted with an auditory tone and a change in colour of the bar from green to red.

1.5. Experiment Design

With 2 levels of flexion MVC and 25 combinations of postural articulations giving 50 treatments, it was decided to use twenty-five participants in a full factorial design. Experimental orders were obtained from a full Latin square of 50 x 50. Out of the selected Latin square, the first 25 rows were used as the order of experimentation for the participants.

1.6. Dependent Variable

Subjective discomfort was recorded on a 100 mm Visual Analogue Scale (VAS), with extreme markers of ‘No discomfort’ and ‘Extreme discomfort’. This was the same scale used by Carey and Gallwey (2002, 2005), Khan et al. (2009), O’Sullivan and Gallwey (2005) and de Looze et al. (2005). These scores were later converted to a scale from 0 to 10.

1.7. Preliminary data collection

The participants read a written explanation about the experiment before giving consent. Wrist flexion/extension and forearm pronation/supination ROMs and MVC were measured, with the elbow flexed at 90^0, the wrist at neutral, and the upper arm abducted 45^0.

The measurement of MVC in each of the five wrist postures involved repeat exertions at 2 minute intervals until two successive readings within 10% of each other were recorded. A rest of five minutes preceded each wrist posture MVC test. After a rest of 15 minutes, endurance time at 50% MVC flexion force was measured with the wrist neutral and forearm prone and 45^0 abduction of upper arm. This was for use as a covariate in an attempt to control for inter-individual differences in perceptions of discomfort as this was a significant factor in some previous experiments (Khan, 2004). It was also used to train participants in scoring on the Visual Analog Scale (VAS), so they indicated the time points during the grip endurance test at which their perceived forearm discomfort reached each of the major marks on the scale.

1.8. Procedure

In the main part of the experiment participants performed the task for five minutes, at the end of which they recorded discomfort on the VAS. They were advised that symptoms of discomfort could include aching, fatigue, soreness, warmth, cramping, pulling, numbness, tenderness, pressing or pain (Lin et al., 1997). A rest of at least one minute, or longer if necessary until the participant felt no discomfort, was given between each treatment, to mitigate against cumulative fatigue (Carey & Gallwey, 2002). After completing the first twenty-five treatments, there was a rest break of half an hour with refreshments. Then the second twenty-five treatments were undertaken. The whole experiment took about seven hours.

2. **Results**

All statistical analyses were carried out using SPSS 11.0.

2.1. Flexion strength and endurance time

Mean Endurance time was 64.8 seconds, SD 35.9. Table 1 shows the mean and standard deviations of MVC at each level of wrist flexion; percentages of the strength of the deviated wrist are also given relative to the neutral level. On average, strength reduced by about 15% at 35% ROM and by about 27% at 55% ROM. The posture effects on MVC were slightly greater for wrist extension over flexion. An ANOVA on these data indicated that both flexion/extension angle and participants had a significant effect on flexion MVC ($p<0.001$). But a Student-Newman-Keuls test grouped average values for each of the non-neutral postures in one group separate from the neutral wrist ($p<0.05$) i.e. there was no significant difference between 35% and 55% ROM.

[Place Table 1 about here]

2.2. Discomfort Score

The Raw Discomfort Score (RDS) data are presented in Table 2 with VAS on a scale from 0 to 10. To allow for differences in pain tolerance between participants and to improve the sensitivity of the discomfort ratings between treatments a Standardised Discomfort Score (SDS) was also calculated for each individual, using the procedure of Gescheider (1985) as follows:

Standardised Discomfort Score (SDS) = (raw data-min. data)/(max. data-min. data) x 10

[Place Table 2 about here]

The RDS and SDS data are presented in Table 2 for comparison with previous studies. But RDS and SDS scores were not normally distributed, so, for the ANOVA, the RDS data were transformed using $\text{Log}_{10}(X+1)$. These Transformed Discomfort Score (TDS) data were normally distributed (Levene's test, $p=0.965$) and were used for all statistical analyses. To assess for order effects, data for the first 17 treatments, the second 16 treatments, and the third 17 treatments were compared using ANOVA, but the differences were not significant ($p=0.52$). For the main effects in the experiment Mauchly's test showed violation of sphericity for wrist flexion/extension, the interactions of wrist flexion/extension with forearm rotation ($p=0.007$), and the three-way interaction ($p=0.001$). So the Greenhouse-Geisser correction was used in a repeated measures ANCOVA considering participant as repetitions, with endurance time as a covariate (Table 3).

[Place Table 3 about here]

Endurance time was not significant ($p=0.776$) but flexion MVC was highly significant ($p=0.001$), as was forearm rotation ($p=0.011$), but wrist flexion/extension was not ($p=0.34$). Two interactions were significant, MVC with forearm rotation ($p=0.014$) and MVC with forearm rotation and the covariate ($p=0.017$). A Student Newman Keuls test showed a significant difference ($p<0.05$), between 60 % ROM of forearm rotation versus both neutral and 30% ROM.

The TDS results are shown in Figures 3, 4 and 5. It can be seen (Figure 3) that, with the wrist at neutral, the effect of forearm rotation is not large, but away from neutral there is a big increase in discomfort, especially at 55% wrist ROM. There is some difference between the prone and supine sides but this differs with the % ROM. The increase in discomfort score from 35% ROM to 55% ROM in extension is about the same for the prone side, but on the supine side there is no real difference between them at 30% ROM of rotation. In flexion there is little difference at neutral and 35% prone, but at the other rotation postures the differences due to flexion are large.

[Place Figure 3 about here]

Figure 4 shows the profiles of the change in TDS value for the 10% and 20% MVC of the wrist flexion force with forearm rotation. It gives a clear picture of an increase in TDS that is of about 0.1 unit of TDS (i.e. approximately 0.7 unit of RDS) between 10% MVC and 20% MVC at all values of forearm rotation. Similarly, in Figure 5, there is a clear-cut difference in TDS of about 0.1 unit (i.e. approximately 0.7 unit of RDS) for all levels of wrist flexion/ extension.

[Place Figure 4 about here]

[Place Figure 5 about here]

Regression analysis was used to develop iso-discomfort contours based on % ROM, separately for 10 and 20% MVC (Table 4, & Figures 6 & 7), but it should be noted that these contain some predictions as there were no real scores measured beyond 55% wrist flexion/extension and 60% forearm rotation ROMs (shaded areas of Figures 6 and 7). In Figure 6, at 10% of flexion MVC, the lowest estimated discomfort score value of 2 units is centred at neutral wrist flexion/extension and forearm rotation postures. The data also estimated equally low discomfort for extreme forearm rotation postures when combined with a neutral wrist, but only for the low force condition (10% MVC).

[Place Table 4 about here]

[Put Figure 6 about here]

[Put Figure 7 about here]

For 20% MVC the lowest estimated discomfort (≤2) was for postures encompassing around 50% forearm rotation ROM, up to 45% wrist flexion and up to 62% wrist extension ROM (Figure 7). The model estimated low discomfort (approximately 2.5) for extreme forearm rotations postures combined with a neutral wrist. For 100% extension and a neutral forearm, the estimated value is also approximately 2.5 but above 3 for 100% flexion. A similar but more pronounced increase in discomfort is evident for the corners (combinations of extreme postures) as in Figure 6. For the combinations of 75% ROM of both postures estimated discomfort increases from 3.5 for 10% MVC to 5 for 20% MVC, a 43% increase.

The general outcome from the profiles for both force levels is that combined deviated wrist and forearm postures resulted in considerably higher estimated discomfort scores. The discomfort model estimated posture effects which are similar in the extremes of each corner of the profile. Values increased sharply for combinations of wrist flexion/extension of more than 50% ROM combined with forearm rotation greater than 60% supine and 70% prone ROM.

3. **Discussion**

3.1. ***Endurance Time***

The use of flexion endurance time as a covariate was based on previous experiments (Carey and Gallwey, 2002). Its non significance here was possibly because ROM and MVC were both relative to the participants’ abilities.

3.2. ***Discomfort Score***

Other ergonomics data on these posture combinations could not be found so it is difficult to compare directly with the results of others on an absolute basis. However comparisons with the data of some others (Carey & Gallwey 2002; Khan et al. 2009; and O'Sullivan and Gallwey 2005) who have studied these effects (but separately) are presented in Table 5. Because the data are standardised within each study (i.e. SDS) direct comparisons of the magnitudes of the values cannot be made, but the effect of posture can be compared between the studies. For the wrist, similar posture effects were reported by Carey and Gallwey (2002), with values for flexion marginally higher than extension. For the forearm, Khan et al. (2009) reported higher discomfort for supine postures over prone postures, for repetitive 10N wrist flexion exertions. These forces corresponded to about 14% MVC for the participants in the present study. O'Sullivan and Gallwey (2005) also reported higher discomfort for forearm torquing in supine over prone postures. But in this study the forearm posture effects were similar in magnitude for both the supine and prone postures.

[Place Table 5 about here]

Greater discomfort for exertions in wrist flexion over extension in this study, while not statistically significant, is similar to the results of other studies of wrist posture. Fernandez et al. (1995) reported that at 40^0 wrist flexion/extension their maximum acceptable frequency was reduced to 54% of the neutral rate for flexion, but just 91% for extension. They also showed a similarly greater difficulty in flexion than in extension with a consequent reduced ability to perform a repetitive task. Ciriello et al. (2001), in a study of maximum acceptable wrist torques for power and pinch grips, also reported higher levels (lower risk) for extension over flexion. The present findings are in agreement with previously published studies that included wrist flexion/extension by previous authors (Carey and Gallwey 2002, 2005).

The finding of lower discomfort for the wrist neutral versus deviated is in agreement with several studies of upper limb posture effects. But it remains unclear if this is because of reduced strength at higher percentages of ROM. In Khan et al. (2009) wrist radial/ulnar deviation significantly effected discomfort ($p<0.01$), but the force was absolute (10N). In the present study the magnitudes of flexion/extension effects on discomfort, while remarkable, were not statistically significant, most likely because the forces were relative to the MVC as measured in each wrist posture. However, wrist flexion/extension significantly effected MVC. The outcome is that increased discomfort associated with wrist deviation is contributed to a large extent by an increase in % MVC exerted due to strength reduction.

The experience of slightly greater discomfort for pronation at the 10% MVC condition, compared to supination, was also reported by O'Sullivan & Gallwey (2005) but for forearm torques (as shown in Table 5). But forearm torque involves using a number of muscles that are different from, and additional to, those used in wrist flexion. Mogk and Keir (2003) found marginal grip strength reductions for pronation (to 85%) and supination (to 90%) compared to a neutral wrist. This is in agreement with the study by Khan (2004) which did not find forearm rotation to have a significant effect on wrist flexion MVC.

The highly significant effect of flexion MVC is in line with other studies of force effects. For Carey and Gallwey (2002) it was a significant ($p<0.01$) factor on discomfort score. Of particular interest is the significant interaction of %MVC with forearm rotation. The statistical analysis, and the discomfort profile for 10% MVC (Figure 6), suggest that forearm rotation within the range of +/- 60% ROM forearm does not appear to be an important risk factor when combined with a neutral wrist, at low forces. However, as force increases it becomes important, and this is possibly due to the effects of forearm rotation on the moment arms of the flexors (prime movers) and extensors (wrist stabilizers). Many of the these muscles cross the elbow joint and are affected by forearm rotation (O'Sullivan and Gallwey, 2002). There is evidence from industry of a link between high force upper limb work and injury to the elbow/forearm region, for activities such as foundry work (Dimberg 1987), pipefitting (Ritz 1995), servicing of paint mixing tanks (Chatigny et al. 1995), and high grip force (>2.7kg) upper limb activities in an aluminium smelter facility (Hughes et al. 1997). Hägg and Milerad (1997) studied fatigue in the wrist flexors and extensors for an intermittent gripping force of 25% MVC at three work/rest regimes, and they found more pronounced fatigue on the extensor side of the forearm than the flexor side. Also, an EMG study by O'Sullivan and Gallwey (2002) found that Extensor Carpi Radialis Brevis activity was significantly affected by forearm rotation. The combined effect of increased flexion force to 20% MVC, with forearm rotation, would therefore be expected to increase fatigue, especially in the extensors, and this is a concern for risk of injury.

de Looze et al. (2005), in a study of acceptable work pace for simulated assembly of electric shavers, used ratings of 3 (on a 0-10 scale) as the criterion for intervention to adjust cycle times. Carey and Gallwey (2005) obtained similar results using the data of Kilbom et al. (1993) to arrive at an acceptable discomfort score as being between 2 and 3, say 2.5. Applying this criterion value to the discomfort models (Figures 6 & 7) suggests that for 10% of wrist flexion MVC, wrist flexion and forearm posture combinations encompassing 50/75% and 75/50% rotations respectively are acceptable. But this reduces to 50% ROM of both postures for 20% MVC. Of course these would only apply to this exact experimental task of wrist flexion at 15 exertions per minute, but the iso-discomfort contours do suggest regions that may be reasonably acceptable for some light assembly tasks. They also indicate regions that are comparatively much more likely to result in discomfort and hence injury. But obviously a lot more work is needed before any really generalised guidelines can be established.

Extrapolated discomfort values were very high (up to 7) for the combined extremes of ROM and this raised two issues. Firstly, these postures should be avoided in industry as there may be a very high risk of injury. In addition, the data suggest that testing combinations of extreme postures in laboratory conditions may involve an unacceptably high level of risk. This is problematic for developing more accurate models encompassing the full ROM.

3.3. Biomechanics and Physiology

Armstrong & Chaffin's (1978) pulley model may also explain the changes for wrist flexion/extension. The prime movers in gripping, the wrist flexors, transfer tensile loads via tendons to the fingers. For a neutral wrist, the supporting tissues (the synovia and flexor retinaculum ligament) and the median nerve will not be greatly stressed. But with a deviated wrist the tendons are forced to curve around either bones of the wrist or the flexor or extensor retinaculum, thereby forming contact arcs analogous of a pulley. Smaller contact arcs due to smaller radi of curvature will result in higher stress concentrations for same tendon loads. Keir and Wells (1999) found that the addition of tendon force with wrist flexion reduced the radius of curvature, which further increased the contact stress on the median nerve and other wrist structures. Chaffin et al. (2006) point out that the median nerve can be directly compressed when forces are applied to the fingers. As the median nerve is located between the wrist flexors and the flexor retinaculum in the carpal tunnel the median nerve may be compressed more in flexion than extension. But data on Carpal Tunnel Pressure (CTP) by Keir et al. (2007) does not agree with this specific point, so the hypothesis remains inconclusive and warranting of further research.

Findings on posture effects on CTP are helpful in interpreting posture effects on upper limb discomfort. It has been shown that CTP is affected by wrist flexion/extension, and radial/ulnar deviation, (Keir et al., 2007) and also tension applied to the flexor tendons during wrist flexion (Smith et al., 1977). Keir et al. (2007) found that for 25% of their population (n=37) CTP reached 30 mm of Hg at 27^0 extension and 38^0 flexion. They proposed these as limits to protect 75% of people from injury. In the present study the 20% MVC and 50% ROM combination of wrist flexion/extension with forearm rotation had estimated discomfort values of approximately 2.5, the Carey and Gallwey (2005) recommended discomfort limit. So these were converted back to angles based on the average ROM of the participants, for comparison with the recommendations of Keir et al. (2007). The values for extension were similar (27^0 versus 32.7^0) but Keir et al.'s limits are almost 41% greater (34.5^0 versus 48.7^0) than the angle derived from the data for 20% MVC in this study. However, the Keir et al. recommended limit for flexion corresponds to 75% flexion ROM of our participants, which was within the acceptable 2.5 discomfort level when combined with neutral forearm postures. In essence, the objective data (CTP) and subjective data (discomfort) from both studies are in close agreement on the effects of extension, but there are some differences in the extent of the effects of flexion.

3.4. Limitations

A simple flexion task such as this one is not likely to be found on its own in an industrial workplace. But it is quite possible for such an action to be a sub-task of an actual job, and for other muscles to be employed during the other parts of the cycle, what Konz and Johnson (2008) have called "working rest". Similarly, although the task cycle was only for five minutes at a time, the total experiment lasted for seven or more hours with only half an hour break in the middle, which is not untypical of many normal job durations. Hence it is arguable that the conditions that applied to this task were quite relevant to real working conditions. Also, the experiment did not include frequency of movement (repetition), and other posture and force levels, or their interactions, which have a significant effect on WMSD risk (Bernard, 1997). Nevertheless the aim was merely to indicate relative differences in discomfort between different combinations of posture, so these results cannot be used to estimate absolute discomfort levels. Provided that these limitations are borne in mind the results should be useful when considering postural issues in workplace design.

In this study data were extrapolated to cover up to 100% ROM, but these results come with a caveat that the accuracy of the predictions are unknown. Regression equation independent variables should be limited to the ranges used to develop the models. Extrapolation of values outside these ranges should be avoided, and if used, interpreted with caution. This is necessary in this case to gain insight to the potential risks of fully deviated postures in advance of testing those conditions in further laboratory tests.

In a previous laboratory experiment (Khan, 2004) forearm posture did not have a significant effect on grip strength. But that study did not test combinations of forearm rotation with flexion extension combined. For completeness future studies of posture effects, similar in nature to this study, should record the MVC in each posture combination as this may be helpful in interpreting the data from the repetitive exertions, especially two-way interactions of combined posture deviations.

4. **Conclusions**

Average wrist flexion MVC decreased by 27% at 55% ROM of wrist flexion and 29% at 55% ROM of wrist extension when compared to neutral. For the repetitive task discomfort was not significantly affected by wrist deviation ($p=0.34$). Wrist flexion MVC was affected by wrist flexion/extension posture, so exertion forces in the repetitive task were set to the MVCs as measured in each wrist posture. The result is that setting the forces in the repetitive task relative to the strength in each posture negated a wrist posture effect on discomfort. This implies that reduced strength for the non-neutral wrist plays an important role in explaining posture effects as a risk factor for MSDs.

Force, forearm rotation and force*forearm rotation (each $p<0.05$) significantly effected discomfort. This indicates a strong independent but also synergistic effect for high forces and deviated pronation/supination postures and discomfort. In light of this, caution is particularly needed to avoid such conditions, as when combined, there is a considerable increase in discomfort. This may lead to injury in tasks similar to that performed in this study if repeated for long durations of time, even at low frequency of repetition.

Iso-discomfort contours were developed within which the discomfort for different experimental treatments is expected to be the same. These data suggest that forearm rotation up to 60% ROM may be acceptable for neutral wrist flexion/extension at low force exertions (<10%MVC). For the task studied, a discomfort level of 2.5 (on a scale of 0-10) would encompass posture combinations of 75/50% and 50/75% ROM for the wrist and forearm for low forces (<10%MVC). But this contracts to 50% ROM for the wrist and forearm for higher forces between 10 and 20% MVC. The data also indicate that discomfort remained low for forearm rotation within the range of +/- 60% ROM forearm when combined with a neutral wrist, at low forces (≤10% MVC).

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References

Armstrong, T. J. and Chaffin, D.B., 1978. An investigation of the relationship between displacements of the finger and wrist joints and the extrinsic finger flexor tendons, *Journal of Biomechanics*, 11, 119-128.

Bernard, B.P., 1997. *Musculoskeletal Disorders and Workplace Factors,* Cincinnatti: National Institute for Occupational Safety and Health.

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

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

Chaffin, D.B., Andersson, G.B.J. and Martin, B.J., 2006. *Occupational Biomechanics*, 4th Ed., New Jersey: Wiley.

Chatigny, C., Seifert, A.M. and Messing, K., 1995. Repetitive strain in nonrepetitive work: A case study, *International Journal of Occupational Safety and Ergonomics,* 1, 42-51.

Ciriello, V.M., Snook, S.H., Webster, B.S. and Dempsey, P., 2001. Psychophysical study of six hand movements, *Ergonomics*, 44, 922-936.

Dempsey, P.G. and Ayoub, M.M., 1996. *The influence of gender, grasp type, pinch width and wrist position on sustained pinch strength,* International Journal of Industrial Ergonomics, 17, 259-273.

Dimberg, L., 1987. The prevalence and causation of tennis elbow (lateral humeral epicondylitis) in a population of workers in an engineering industry, *Ergonomics*, 30, 573-580.

European Foundation for Living and Working Conditions, 2007, *Managing Musculoskeletal Disorders*, Dublin.

Fernandez, J.E., Fredericks, T.K. and Marley, R.J., 1995. The psychophysical approach in upper extremities work, *In:* S.A., Robertson, ed. *Contemporary Ergonomics 1995.* London: Taylor and Francis, 456 - 461.

Gescheider, G.A., 1985. *Psychophysics – Method, Theory, and Application*. 2nd ed., Hillsdale: Earlbaum.

Hagberg, M., Silverstein, B., Wells, R., Smith, M., Hendrick, Carayon, P. and Perusse, M., 1995. *Work Related Musculoskeletal Disorders: A Reference Book of Prevention*, London: Taylor & Francis.

Hägg, G.M. and Milerad, E., 1997. Forearm extensor and flexor muscle exertion during simulated gripping work – an electromyographic study, *Clinical Biomechanics,* 12, 39-43.

Hughes, R.E. Silverstein, B.A. and Evanoff, B.A., 1997. Risk factors for work-related musculoskeletal disorders in an aluminium smelter, *American Journal of Industrial Medicine,* 32, 66-75.

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

Keir, P.J. and Wells, R.P., 1999. Changes in geometry of the finger flexor tendons in the carpal tunnel with wrist posture and tendon load: an MRI study on normal wrists, *Clinical Biomechanics,* 14, 635-645.

Keir, P.J., Bach, J.M., Hudes, M. and Rempel, D.M., 2007. *Guidelines for Wrist Posture Based on Carpal Tunnel Pressure Thresholds,* Human Factors, 49, 88-99.

Khan, A. A., 2004. *Effects on discomfort of wrist articulation combined with forearm rotation,* Thesis (Ph.D.), University of Limerick, Limerick, Republic of Ireland.

Khan, A.A., Gallwey, T.J. and O'Sullivan, L.W., 2003. Effects of grip force when combined with wrist flexion and frequency of exertions, *In:* H. Strasser, K. Kluth, H. Rausch and H.

Bubb. eds. *Quality of Work and Products in Enterprises of the Future*, Stuttgart: Ergonomica Verlag, 391-394.

Khan, A.A., O'Sullivan, L.W. and Gallwey, T.J. 2009, Effects of combined wrist deviation and forearm rotation on discomfort score, *Ergonomics*, 52, 345 - 361

Kilbom, A., Makarainen, M., Sperling, L., Kadefors, R. and Liedberg, L., 1993. Tool design, user characteristics and performance: a case on plate-shears, *Applied Ergonomics*, 24, 221-230.

Kim, C.H. and Fernandez, J.E., 1993. Psychophysical frequency for a drilling task, *International Journal of Industrial Ergonomics*, 12, 209-218.

Konz, S. and Johnson, S. L., 2008. *Work Design: Occupational Ergonomics*. 6th ed. Arizona: Holcomb Hathaway.

Lin, M. L., Radwin R.G. and Snook, S., H., 1997. A single metric for quantifying biomechanical stress in repetitive motions and exertions, *Ergonomics*, 40, 5, 543-558.

de Looze, M.P, van Rhijn, J.W, Schoenmaker, N., van der Grinten, M.P. and van Deursen, J., 2005. Productivity and discomfort in assembly work: The effects of an ergonomics workplace adjustment at Philips DAP. *In:* P.Vink, ed. *Comfort and design: Principles of Good Practice.* Boca Raton, CRC Press, 129-136.

Mogk, J.P.M. and Keir, P.J., 2003. The effects of posture on forearm muscle loading during gripping, *Ergonomics*, 46, 9, 956-975.

O'Sullivan, 2001. *Estimating forearm discomfort due to Pronation-Supination Torques for Elbow and Forearm Angles*, Thesis (Ph.D.), University of Limerick, Limerick, Republic of Ireland.

O'Sullivan, L.W. and Gallwey, T.J., 2002. Upper-limb surface electro-myography at maximum supination and pronation torques: The effect of elbow and forearm angle, *Journal of Electromyograhy and Kinesiology*, 12, 275-285.

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

Ritz, B.R., 1995. Humeral epicondylitis among gas and waterworks employees, *Scandinavian Journal of Work Environment and Health*, 21, 478-486.

Silverstein, B.A., 1998. *Claims incidence of work related disorders of the upper extremities*: *Washington State 1987-1995*, Public Health, 88, 1827-1833.

Smith, E.M., Sonstegard, D.A. and Anderson, W.H., 1977. Carpal tunnel syndrome: contribution of flexor tendons, *Archives of Physical Medicine and Rehabilitation*, 58, 379-385.

Figure Captions

Figure 1: LABVIEW screen shot of main experiment

Figure 2: Experimental rig

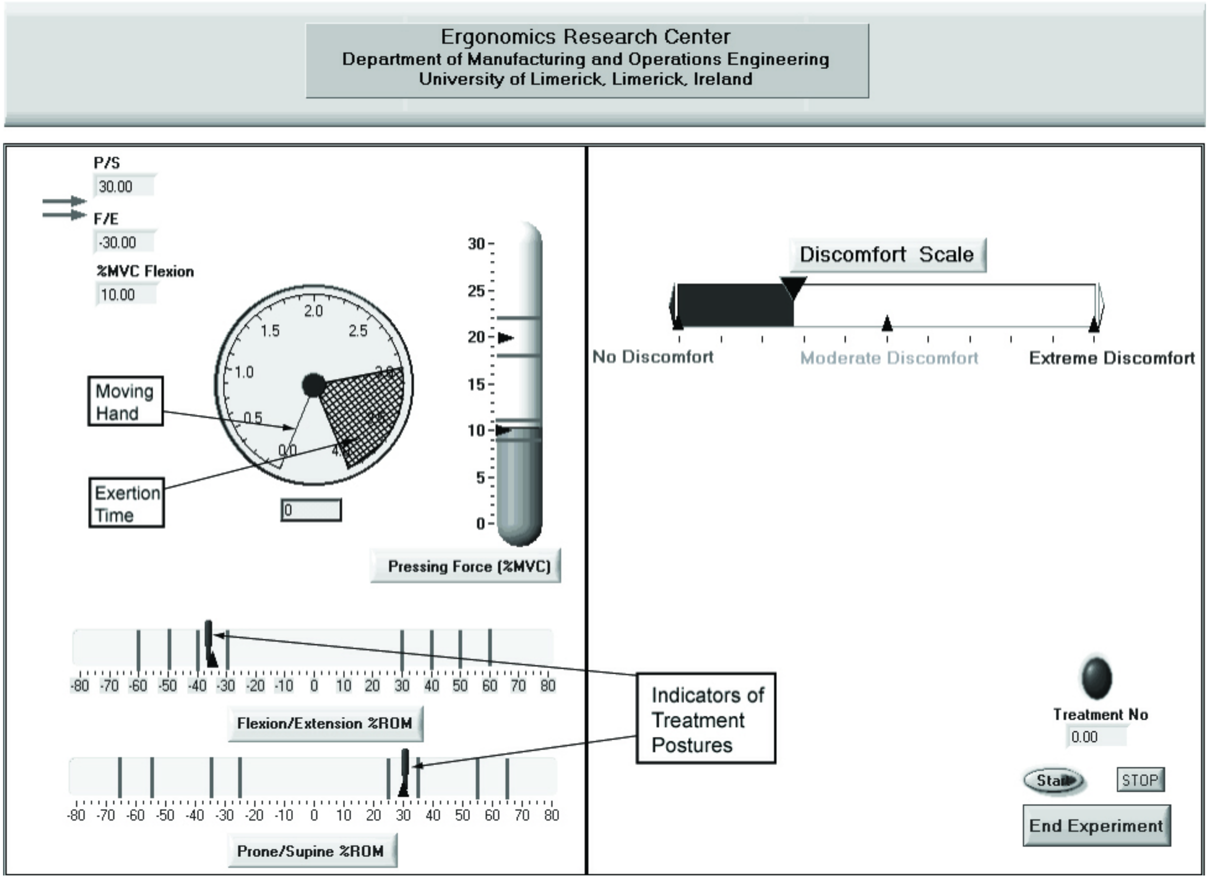
Figure 3: Transformed Discomfort Score vs. Forearm Rotation at different levels of wrist flexion/extension

Figure 4: Transformed Discomfort Score vs. Forearm Rotation at different levels of flexion MVC

Figure 5: Transformed Discomfort Score vs. Wrist flexion/extension at different levels of flexion MVC

Figure 6: Iso-Discomfort Contours (antiLog(TDS)-1) at five minutes, for 10% MVC flexion force and wrist flexion/extension combined with forearm rotation. Note: The shaded areas comprise estimates beyond the ranges of motion tested.

Figure 7: Iso-Discomfort Contours (antiLog(TDS)-1) at five minutes, for 20% MVC flexion force and wrist flexion/extension combined with forearm rotation. Note: The shaded areas comprise estimates beyond the ranges of motion tested.



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P/S 30.00
F/E -30.00
%MVC Flexion 10.00
Treatment No 0.00

Figure 1

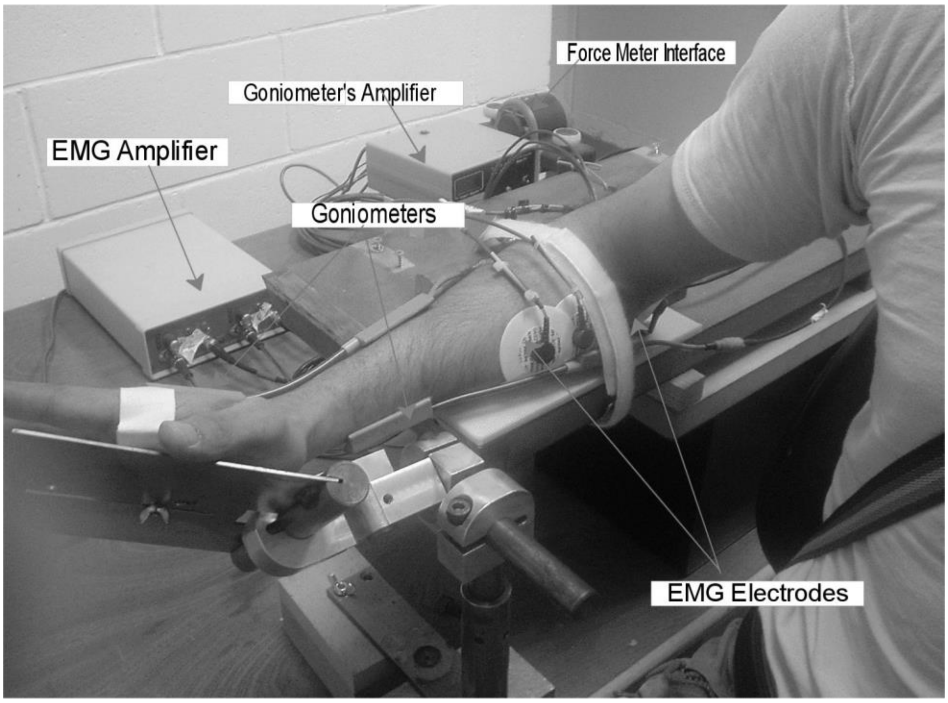

Force Meter Interface
Goniometer's Amplifier
EMG Amplifier
Goniometers
EMG Electrodes

Figure 2

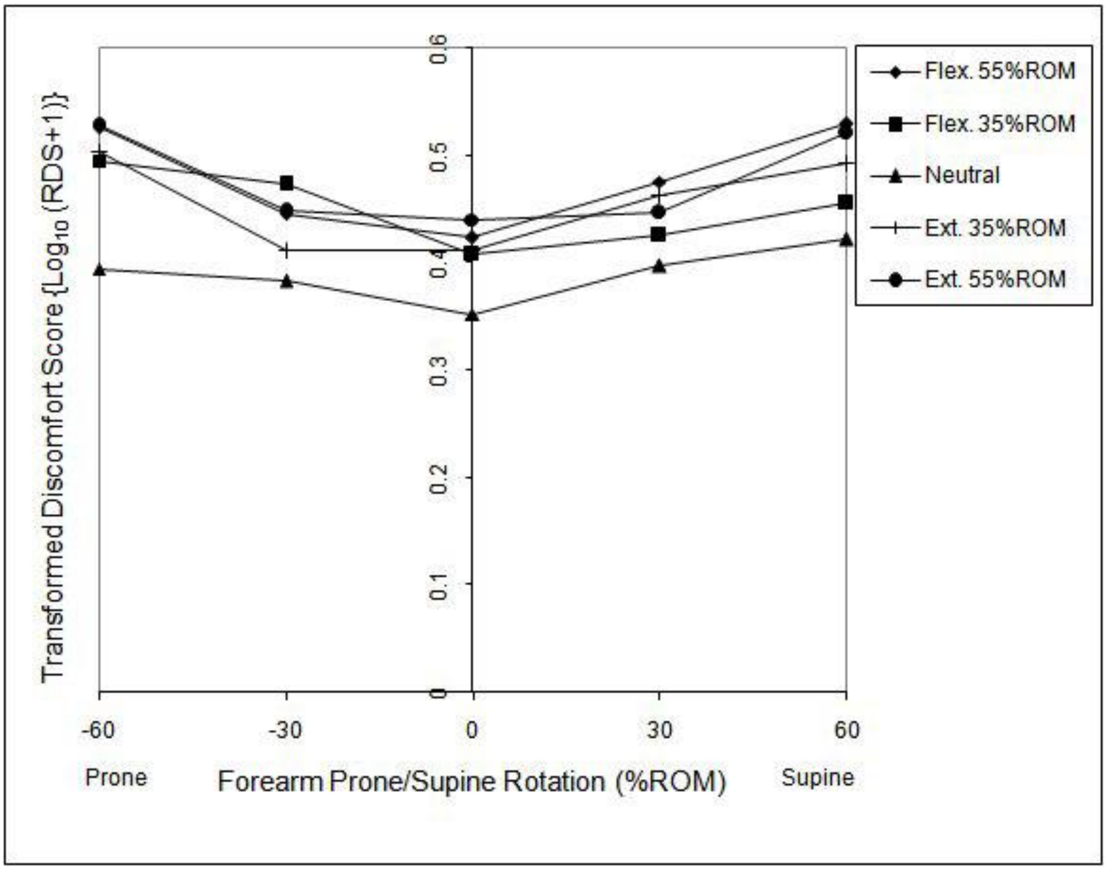

Transformed Discomfort Score {Log10 (RDS+1)}
0
0.1
0.2
0.3
0.4
0.5
0.6
-60
-30
0
30
60
Prone
Forearm Prone/Supine Rotation (%ROM)
Supine
Flex. 55%ROM
Flex. 35%ROM
Neutral
Ext. 35%ROM
Ext. 55%ROM

Figure 3

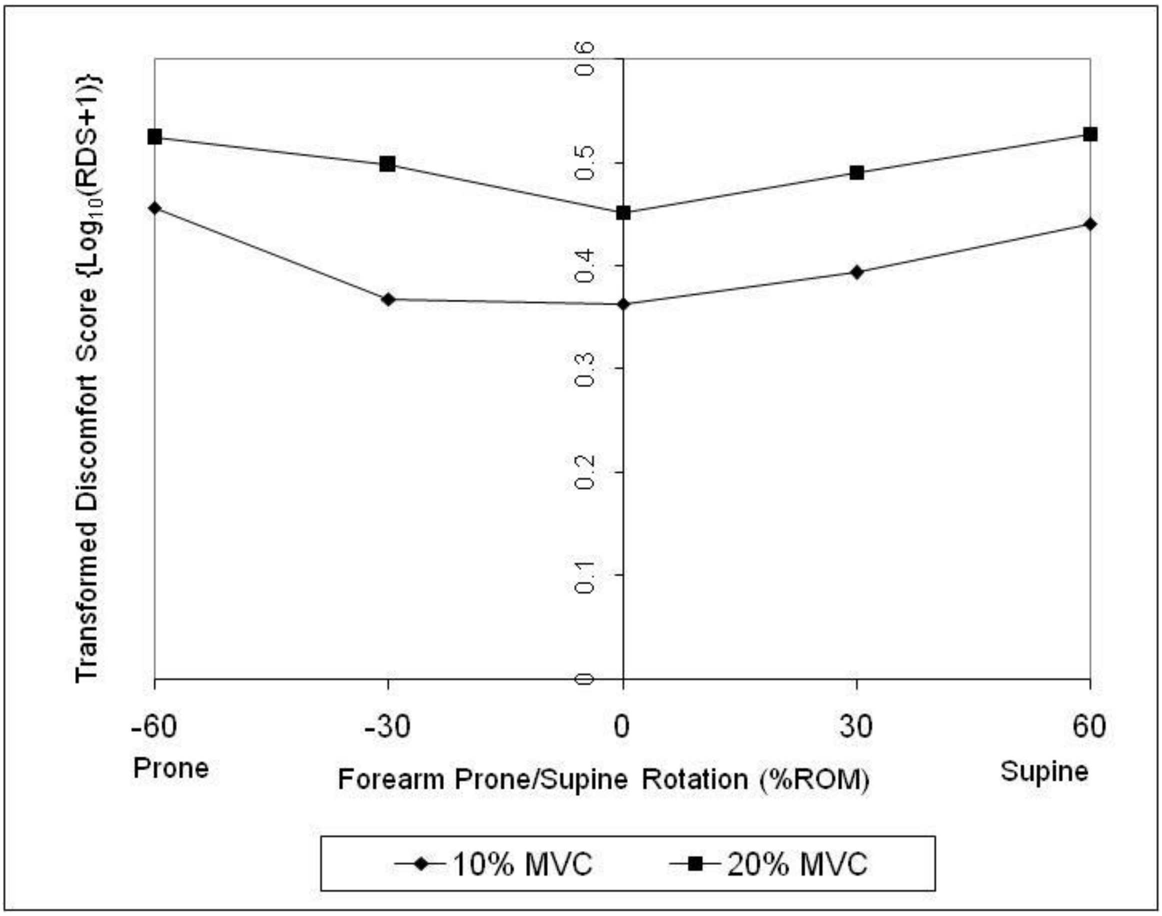

Transformed Discomfort Score {Log_{10}(RDS+1)}
0
0.1
0.2
0.3
0.4
0.5
0.6
-60
-30
0
30
60
Prone
Forearm Prone/Supine Rotation (%ROM)
Supine
10% MVC
20% MVC

Figure 4

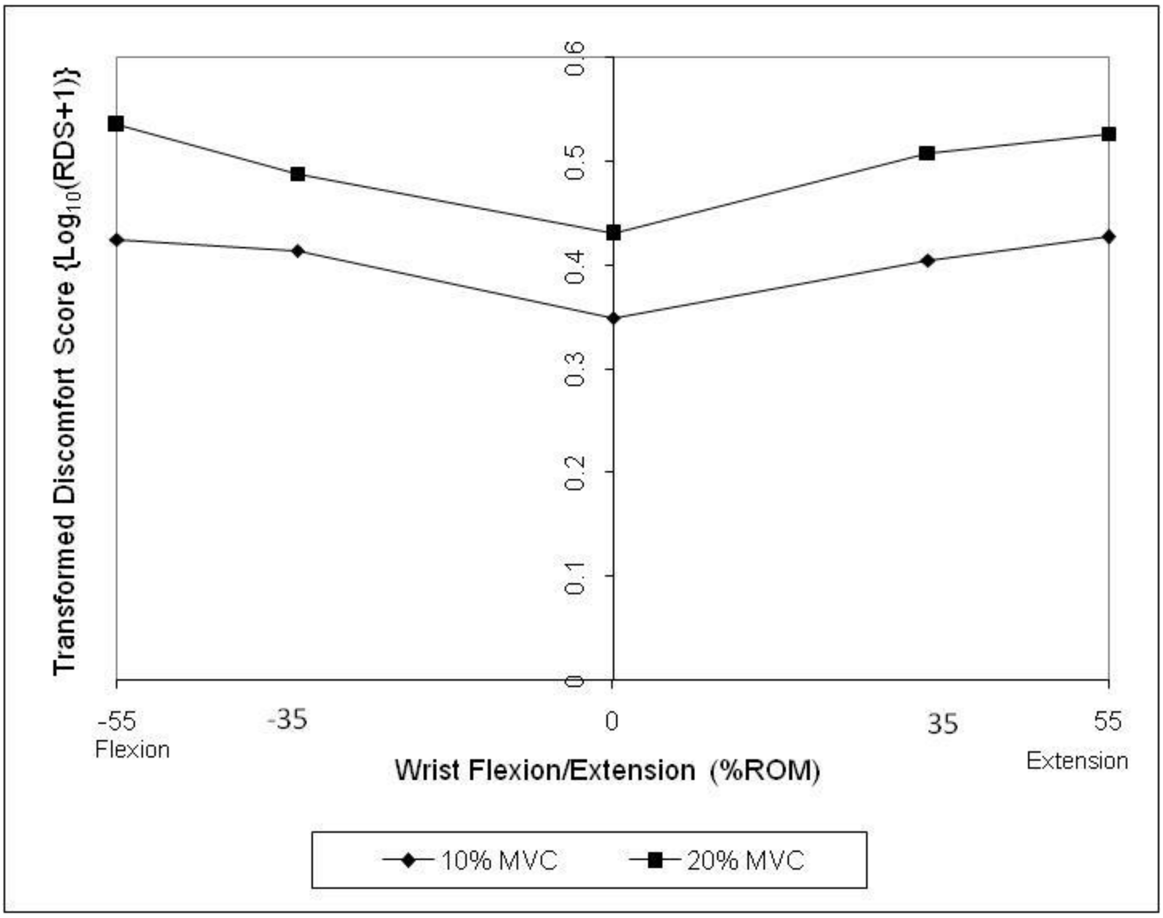

Transformed Discomfort Score {Log10(RDS+1)}
0
0.1
0.2
0.3
0.4
0.5
0.6
-55
Flexion
-35
0
35
55
Extension
Wrist Flexion/Extension (%ROM)
10% MVC
20% MVC

Figure 5

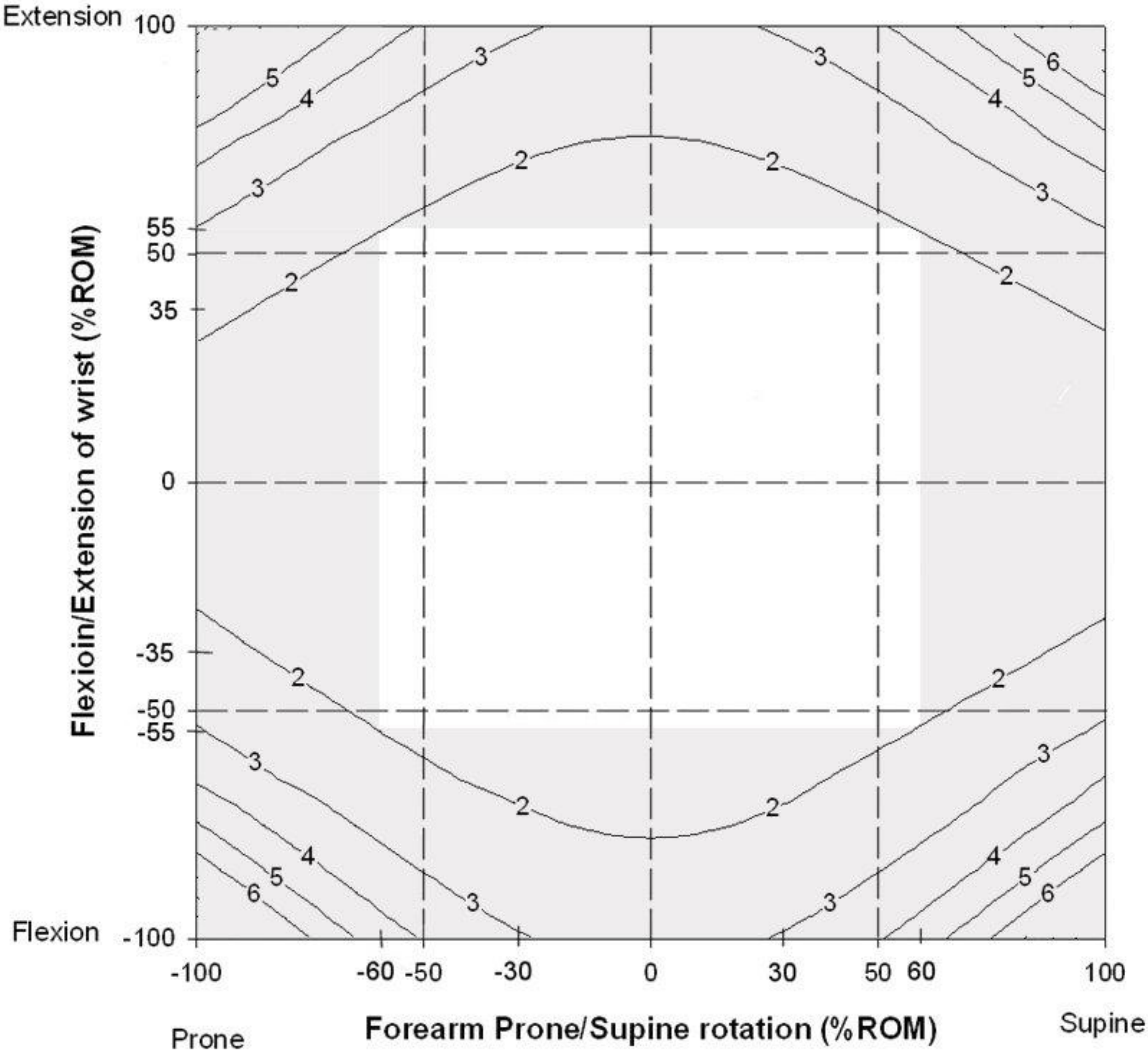
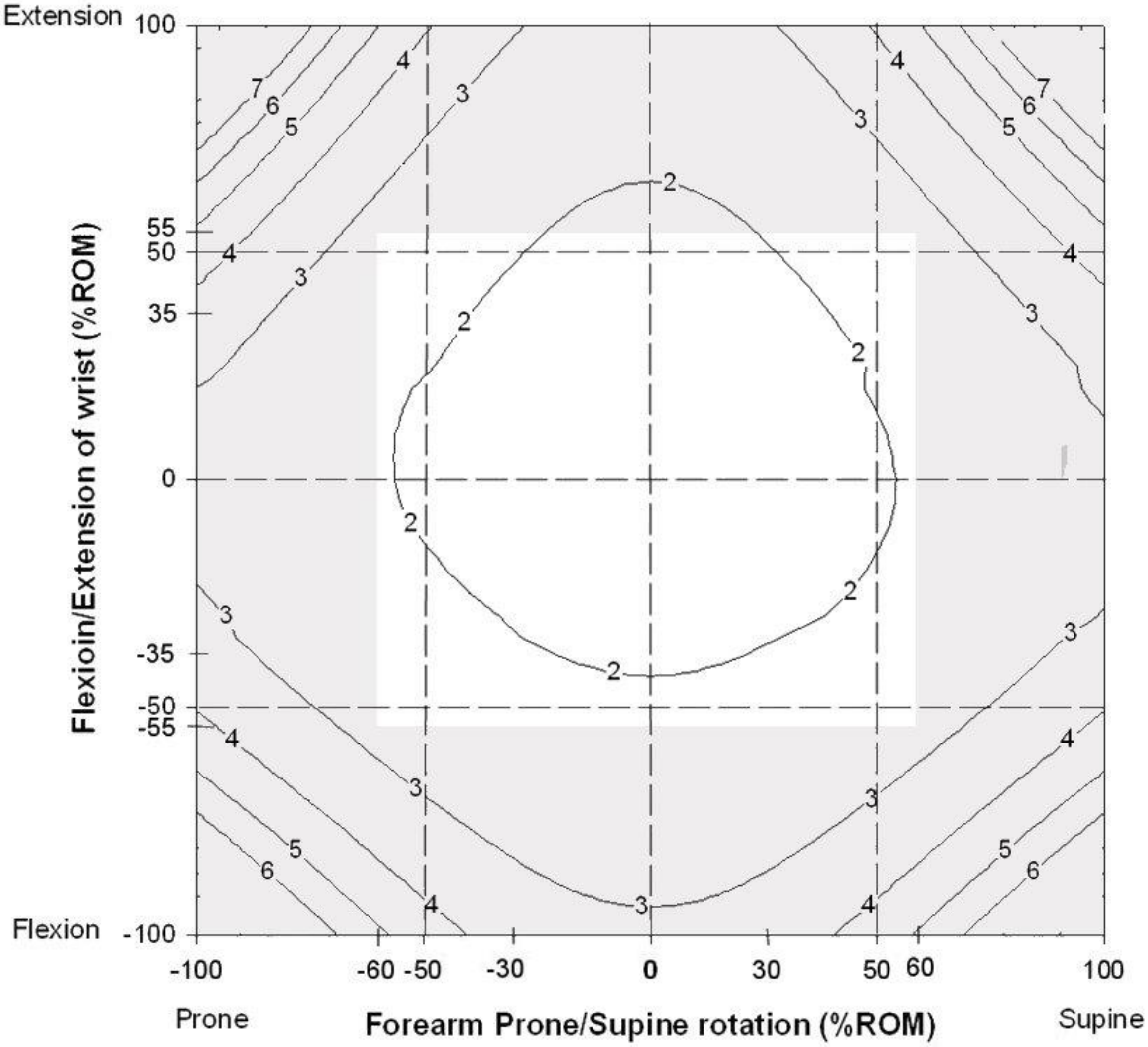

Extension
Flexion
Flexioin/Extension of wrist (%ROM)
100
55
50
35
0
-35
-50
-55
-100
-100
-60
-50
-30
0
30
50
60
100
Prone
Forearm Prone/Supine rotation (%ROM)
Supine
2
3
4
5
6

Figure 6



Extension
Flexion
Flexioin/Extension of wrist (%ROM)
100
55
50
35
0
-35
-50
-55
-100
-100
-60
-50
-30
0
30
50
60
100
Prone
Forearm Prone/Supine rotation (%ROM)
Supine
2
3
4
5
6
7

Figure 7

Table Captions

Table 1: Means and standard deviations of wrist flexion/extension MVCs

Table 2. Summary data of Raw Discomfort Score (RDS) & Standardised Discomfort Score (SDS)

Table 3: Repeated Measure ANCOVA with Greenhouse Geisser (GG) correction for factors violating sphericity

Table 4 Regression equations of TDS for combinations of wrist Flexion/Extension and forearm Pronation/Supination

Table 5: Comparison of Standardised Discomfort Scores due to changes in wrist posture

Table 1. Means and standard deviations of wrist flexion/extension MVCs

	MVC (N)					% of MVC with wrist in neutral posture				
	Wrist Flexion/Extension (%ROM)					Wrist Flexion/Extension (%ROM)				
	F 55	F 35	Neu	E 35	E 55	F 55	F 35	Neu	E 35	E 55
Mean	52.6	60.8	72.1	59.4	50.7	73.0	84.4	100.	81.1	70.8
SD	16.51	16.47	18.98	24.67	15.59	13.21	10.55	-	19.59	13.88

Table 2. **Summary data of Raw Discomfort Score (RDS) & Standardised Discomfort Score (SDS)**

Flexion MVC of wrist	Wrist F/E	Forearm Rotation																			
		60% P				30% P				Neutral				30% S				60% S			
		RDS		SDS		RDS		SDS		RDS		SDS		RDS		SDS		RDS		SDS	
		Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
10% MVC	55% F	2.33	1.30	4.71	3.05	1.65	1.33	2.67	2.17	1.66	1.32	2.45	2.34	1.87	1.33	3.25	2.35	2.21	1.19	3.75	1.97
	35% F	2.06	1.20	3.58	2.07	1.84	1.01	3.21	1.93	1.58	1.11	2.51	2.28	1.75	1.12	2.75	2.22	1.88	1.08	3.25	2.09
	Neutral	1.51	0.91	2.33	1.85	1.27	0.74	1.66	1.01	1.13	0.82	1.27	1.34	1.51	1.10	2.10	1.76	1.61	0.96	2.31	1.58
	35% E	2.28	1.49	3.93	2.74	1.40	0.90	2.00	1.58	1.53	1.08	2.05	1.89	1.82	1.25	2.72	2.06	1.93	1.09	3.34	1.92
	55% E	2.35	1.13	4.42	2.68	1.64	1.29	2.65	2.48	1.82	1.31	3.22	2.60	1.62	1.15	2.66	2.24	2.33	1.44	4.01	2.19
20% MVC	55% F	2.96	1.48	6.34	2.88	2.69	1.92	4.79	2.51	2.23	1.35	4.17	2.29	2.83	1.67	5.52	2.65	3.14	1.50	6.53	2.70
	35% F	2.78	1.43	5.67	2.69	2.64	1.46	5.02	2.46	2.10	1.48	3.72	2.45	2.13	1.42	3.87	2.68	2.41	1.52	4.43	2.68
	Neutral	1.93	1.35	3.66	2.93	1.93	1.07	3.24	1.95	1.73	0.91	3.06	1.76	1.99	1.38	3.68	2.34	2.06	1.16	3.81	2.15
	35% E	2.72	1.45	5.24	2.09	2.36	1.61	4.24	2.48	2.20	1.44	3.83	2.68	2.67	1.76	4.88	2.89	2.83	1.49	5.58	2.66
	55% E	2.91	1.57	6.07	2.54	2.80	1.79	5.19	2.89	2.19	1.13	4.01	1.97	2.58	1.55	5.03	2.69	3.09	1.96	5.90	3.26

Table 3: Repeated Measure ANCOVA with Greenhouse Geisser (GG) correction for factors violating sphericity using TDS as dependent variable

Source	**Type III Sum Of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Endurance Time (ET) as Covariate	0.08	1	0.08	0.08	0.776
MVC	0.89	1.00	0.89	29.54	**0.001**
MVC * ET	0.01	1.00	0.01	0.49	0.489
Forearm Rotation (P/S)	0.39	4.00	0.10	3.47	**0.011**
P/S * ET	0.16	4.00	0.04	1.39	0.244
Wrist Flex./Ext. (F/E) with GG	0.11	2.47	0.04	1.13	0.340
F/E * ET with GG	0.12	2.47	0.05	1.29	0.290
MVC * P/S	0.19	4.00	0.05	3.32	**0.014**
MVC * P/S* ET	0.18	4.00	0.05	3.17	**0.017**
MVC * F/E	0.09	4.00	0.02	1.70	0.157
MVC * F/E * ET	0.12	4.00	0.03	2.24	0.071
P/S * F/E with GG	0.17	6.74	0.03	0.72	0.654
P/S * F/E * ET with GG	0.22	6.74	0.03	0.93	0.485
MVC * P/S * F/E with GG	0.22	6.05	0.04	0.88	0.511
MVC * P/S * F/E * ET with GG	0.24	6.05	0.04	0.97	0.445
Residual	42.51	1150	0.037		
Total	45.72	1249			

Table 4 Regression equations of TDS for combinations of wrist Flexion/Extension and forearm Pronation/ Supination

At 20% MVC repetitive wrist flexion task at 15 exertions per minute					
Equations at the levels of Wrist F/E (%ROM)*		R^2	Equations at the levels of Forearm Rotation (%ROM)*		R^2
E 55	TDS = 0.00002*PS^{2} + 0.00001*PS + 0.492	0.880	S 60	TDS = 0.00004*FE^{2} + 0.464	0.799
E 35	TDS = 0.00002*PS^{2} + 0.470	0.889	S 30	TDS = 0.00003*FE^{2} + 0.441	0.698
Neu	TDS = 0.000005*PS^{2} + 0.421	0.632	Neu	TDS = 0.00002*FE^{2} + 0.41	0.876
F 35	TDS = 0.00002*PS^{2} + 0.461	0.788	P 30	TDS = 0.00003*FE^{2} + 0.453	0.716
F 55	TDS = 0.00002*PS^{2} + 0.494	0.861	P 60	TDS = 0.00004*FE^{2} – 0.00005*FE + 0.460	0.693
At 10% MVC repetitive wrist flexion task at 15 exertions per minute					
E 55	TDS = 0.00003*PS^{2} + 0.370	0.821	S 60	TDS = 0.00003*FE^{2} + 0.00008*FE + 0.393	0.990
E 35	TDS = 0.00003*PS^{2} – 0.00001*PS + 0.357	0.747	S 30	TDS = 0.000008*FE^{2} + 0.379	0.369
Neu	TDS = 0.00002*PS^{2} + 0.317	0.838	Neu	TDS = 0.00003*FE^{2} + 0.318	0.773
F 35	TDS = 0.00001*PS^{2} + 0.389	0.854	P 30	TDS = 0.000007*FE^{2} + 0.355	0.239
F 55	TDS = 0.00003*PS^{2} + 0.00005*PS + 0.369	0.895	P 60	TDS = 0.00004*FE^{2} + 0.394	0.840

*P= Pronation (-ve), S=Supination (+ve), F = Flexion (-ve), E = Extension (+ve) each in % ROM

Table 5 Comparison of Standardised Discomfort Scores due to changes in wrist posture

Wrist			Remark	Reference
Flexion	Neutral	Extension		
3.4 (55%ROM)	1.9	3.4 (55%ROM)	10% MVC flexion at 15 exertions/min.	Present study
5.5	3.5	5.24	20% MVC flexion at 15 exertions/min.	
2.9 (55%ROM)	0.9	2.4 (55%ROM)	10%MVC flexion at 10 exertions/min.	Carey & Gallwey, (2002)
3.8	1.9	3.0	20%MVC flexion at 10 exertions/min.	
Forearm				
Prone	Neutral	Supine		
3.8 (60%ROM)	2.3	3.3 (60%ROM)	10% MVC flexion at 15 exertions/min.	Present study
5.4	3.8	5.3	20% MVC flexion at 15 exertions/min.	
2.8 (60%ROM)	1.8	4.1 (60%ROM)	10N flexion at 15 exertions/min, neutral wrist	Khan et al. (2008)
4.1 (60%ROM)	3.5	5.2 (60%ROM)	20%MVC supination torque at 15 exertions/min.	O'Sullivan and Gallwey (2005)
6.8	5.1	5.6	20%MVC pronation torque at 15 exertions/min.	