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BIOMEDICAL ENGINEERING | RESEARCH ARTICLE

Ranking the effects of cycle time parameters, shoulder posture and load, on shoulder discomfort in a single experiment using Taguchi methods

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Abstract: The purpose of this study was to use the Taguchi Design of Experiments approach to investigate the effects of five risk factors on ratings of shoulder discomfort in a single study. The development of shoulder MusculoSkeletal Disorders is complex as they are caused by several risk factors occurring simultaneously. In this study, five independent variables were tested (shoulder flexion, shoulder horizontal abduction, duty cycle regime, repetition rate, and load), each at four levels. Signal to noise ratio analysis was performed on the data to rank the magnitude of effects of the risk factors on shoulder discomfort. The results indicated repetition was first, with load second, flexion third, W/R regime fourth and abduction fifth. Therefore, the results indicated that repetition had the strongest effect on discomfort, while shoulder abduction had the least effect, for the combinations and levels of treatments studied.

Subjects: Ergonomics & Human Factors; Work Design - Ergonomics; Musculosketletal Disorders - Ergonomics

Keywords: shoulder; discomfort; taguchi; musculoskeletal disorders < health and safety

1. Introduction

MusculoSkeletal Disorders (MSDs) are the most common work-related health problem in Europe (OSHA, 2007). They are caused by a number of inflammatory and degenerative conditions, which may result in pain and functional impairment of neck, shoulders, elbows, forearms, wrists and hands (Hagberg et al., 1995). The neck/shoulder accounts for 25% of all upper limb MSDs (Kraker & Blatter, 2005). The shoulder girdle is the first part of a mechanical chain that links the shoulder through the

ABOUT THE AUTHORS

This research was undertaken at the Design Factors Research Group in the University of Limerick. Dr O'Sullivan is a senior lecturer in the group where he leads several research projects around work place ergonomics. A lot of their research focuses on work related musculoskeletal disorders. In recent years, they have work on research projects to study the use of novel technologies to assist workers perform their tasks so as to reduce musculoskeletal loading. This research includes a study of wearable sensors and robotics for physical augmentation of body activity.

PUBLIC INTEREST STATEMENT

People who perform manual physical work as part of their work are often at risk of sustaining injuries. For the shoulder, the scientific knowledge indicates that lifting heavy loads, holding the arms away from the body, and performing repetitive intensive work are established risk factors. These risk factors have been studied in many experiments but not all together. It is interesting to study them all together so that we can understand which risk factors have the higher impact on risk. This is helpful so that we can help prevent such injuries occurring in workplaces. The results of this study demonstrate the importance of these risk factors for injury of the shoulder. Further, we use a statistical approach in the study that enables this type of research to be performed with very pragmatic samples of test participants.

elbow and forearm to the fingers. MSD causation is complex, with generally several risk factors and their synergistic relationships causing the strain that results in injury onset (National Institute for Occupational Safety & Health [NIOSH], 1997). The pertinent risk factors for MSDs are task repetition, force of exertion, posture and rest/recovery (Keir & Brown, 2012; Malchaire, Cock, & Robert, 1996; Silverstein, Fine, & Armstrong, 1986).

1.1. Factors affecting shoulder MSDs

1.1.1. Load/exertion level

Load, or level of exertion, is an important risk factor for MSDs of many joints of the body, including the neck and shoulder (Ekberg et al., 1994), elbow and hand-wrist (NIOSH, 1997). It has been shown that exertion of forces even as low as 10% MVC, and lower, can lead to muscle pain and fatigue for the shoulder (El ahrache, Imbeau, & Farbos, 2006; Hagberg, 1981; Mathiassen & Winkel, 1990).

1.1.2. Posture

For the shoulder, repetitive shoulder deviations are associated with risk of injury (Putz-Anderson, 2010). Keir, Bach, and Rempel (1999) found that sustaining non-neutral postures can increase pressure in the tissues surrounding nerves which in turn increases perception of discomfort and risk of injury in the upper limb. NIOSH (1997) reported that the effects of shoulder deviations on risk of injury are pronounced when posture deviations are combined with high loads.

1.1.3. Repetitiveness

Repetitiveness generally refers to performing stereotyped cyclical motions with little variation. Repetitiveness has been identified as an important MSD risk factor for shoulder injuries on its own (Latko et al., 1999). But again, there is a synergistic effect when combined with other risk factors, notably high force exertions and deviated postures (Kilbom, 1994).

1.1.4. Work/rest regime

There are a number of different Work/Rest (WR) allowance models in the literature, most of which relate to static or intermittent static contractions (El ahrache & Imbeau, 2009). Rest allowance models developed by Rohmert (1973) and Byström and Fransson-Hall (1994) suggest that negligible fatigue occurs in a muscle when the force exerted does not exceed 15% (MVC). In fact, fatigue can occur well below 15% MVC. It has been found shown that that static loads as low as 1% MVC can lead to indications of muscle fatigue.

The pathology of MSDs are complex with more than one risk factor present at any given time (Kumar, 2001). The effect of individual factors on MSD development (task repetition, force, posture and rest/recovery) depends on the level of exposure as well as the relationship between the factors themselves. However, the order of importance of the risk factors for risk of shoulder injury remains largely unstudied.

1.2. Taguchi Design of Experiments

The Taguchi Design of Experiments (DOE) approach is a statistical method that can be used to study multiple independent variables in a single manageable study (Antony, 2006). A benefit of Taguchi DOE is that it provides a standardized approach for planning, designing and analysing data, while reducing the number of permeations of treatments to a practical number reasonable to simulated in a laboratory experiment. Another benefit of a Taguchi DOE is the option to perform Signal to Noise Ratio (SNR) analysis on the data (Roy, 2010). The SNR is a function of two quantities, the standard deviation and the mean, the combination of both which offers a powerful way to study the importance of effects of individual factors on the dependent variable (Roy, 2010). The general principle behind SNR analysis is that the greater the ratio the smaller the product (outcome variable) variance around the target value.

The aim of this experiment was to use a Taguchi DOE to A., design an experiment of five independent variables considered risk factors for shoulder discomfort in a single laboratory experiment, and B. to use SNR to rank the effects of the five variables on discomfort.

2. Method

2.1. Basis of the experiment

The five risk factors for shoulder MSDs studied were: posture in the sagittal (shoulder flexion) and coronal (shoulder abduction) planes, duty cycle regime, repetition rate, and load. A full factorial experimental of these five factors at four levels would give 1,024 combination treatments per person, which is not practical, and certainly questionable on ethical grounds. The Taguchi DOE reduces this to 16 treatments per participant.

2.2. Design of experiment

The traditional design of experiments limits the options to test multiple levels of independent factors. However, the Taguchi approach gives an opportunity to test more than two factor levels at a time as well as study variability using SNR. Using a Taguchi DOE, five independent variables at four levels ($L4^5$) gives 16 unique experiment conditions per participant.

The five independent variables and their levels were;

(1) Shoulder flexio.n: 30°, 60°, 90°, 120°;
(2) Shoulder horizontal abduction: 0°, 30°, 60°, 90°;
(3) Duty cycle regime: 1/4, 1/2, 2/1, 4/1;
(4) Repetition rate: 4, 8, 12, 16/min);
(5) Loads lifted: 0.5, 1, 1.5 and 2 kg.

Design-Expert software (Stat-Ease, version 8.0.4) was used to generate the treatments combinations and orders for each participant (Table 1).

Shoulder flexion from 30° to 120° combined with shoulder abduction 0 to 90° was observed by in a mix of industrial jobs by Browne (2011). The W/R regimes were based on previous research by Moore and Wells (2005). The repetition rates were intended to represent very low through very high frequency of shoulder movement. The loads were considered representative of tasks in industry, including work with tools and lifting parts on assembly lines.

The dependent variable was shoulder discomfort rated on a 100 mm Visual Scale. The scale ranged from 0 (no discomfort) to 10 (extreme discomfort). Discomfort scores were standardised to accommodate for possible discomfort threshold differences between participants (Gescheider, 1988; Equation (1)). This scale and standardisation procedure has been used in a number of experiments previously in the University (Khan, O'Sullivan, & Gallwey, 2009a, 2009b, 2010; Mukhopadhyay, O'Sullivan, & Gallwey, 2007a, 2007b, 2009; O'Sullivan & Gallwey, 2002, 2005).

Equation (1): Discomfort standardization equation (Gescheider, 1988)

$$\text{SDS} = \left(\frac{\text{raw value} - \text{minimum value}}{\text{maximum value} - \text{minimum value}}\right) \times 10$$

SDS: Standardised Discomfort Score.

Table 1. List of 16 experiment conditions

Combination No.	Main factors				
	Flexion [°]	Abduction [°]	Work/rest regime	Repetition rate (per min)	Load [kg]
1	30	30	1/2	8	1
2	30	0	1/4	4	0.5
3	30	90	4/1	16	2
4	30	60	2/1	12	1.5
5	60	0	1/2	12	2
6	60	60	4/1	4	1
7	60	90	2/1	8	0.5
8	60	30	1/4	16	1.5
9	90	30	4/1	12	0.5
10	90	60	1/4	8	2
11	90	90	1/2	4	1.5
12	90	0	2/1	16	1
13	120	30	2/1	4	2
14	120	60	1/2	16	0.5
15	120	90	1/4	12	1
16	120	0	4/1	8	1.5

2.3. Participants and ethics
A total of 32 participants (24 males and 8 females, average age 22.3 years, SD = 5) took part in the experiment.

The study and procedure was approved by the Research Ethics Committee of the University of Limerick.

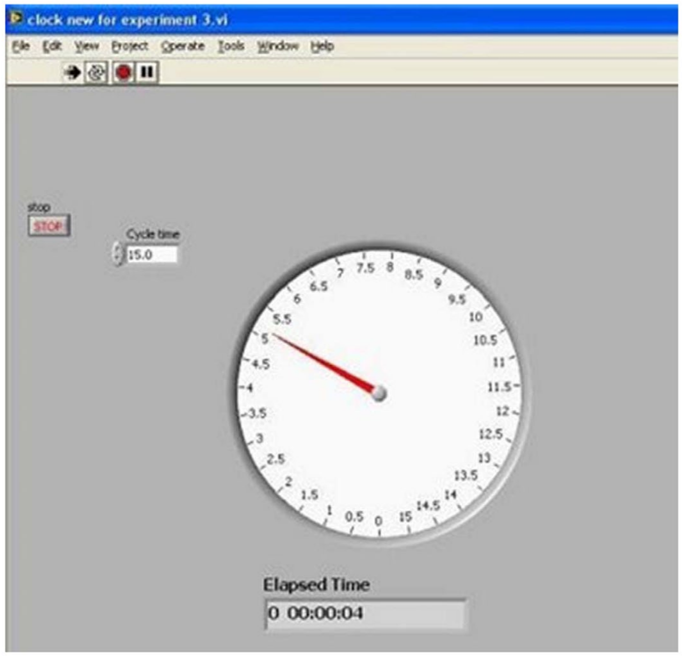
2.4. Repetitive shoulder movement task and equipment
The task performed during the experiment simulated an assembly line task, requiring an operator to pick up elements from their elbow height and place them on a higher shelf. Two shelves with adjusted height were positioned in front of the participant. To the right of the shelves on a computer screen a clock was presented to visualize work and rest periods in the cycle times for each of the experiment conditions. On the screen, depending on the combination of W/R regime and repetition rate, the value of cycle time was adjusted (LabView, version 8.5, Figure 1). This was reflected on the clock viewed by the participant on the screen. After the test time passed, the clocked stopped and a rest time of five minutes started, which was shown in the "Elapsed Time" cell on the screen.

A set of four pairs of dumbbells weighing 0.5, 1, 1.5 and 2 kg were used as the loads lifted. The loads were lifted by both hands simultaneously, with one dumbbell in each hand to ensure equal biomechanical loading on both sides of the participant's body.

2.5. Procedure
The participant was briefed on the nature of the experiment. They read the experiment description and gave their informed consent. Participants were excluded from the experiment if they had experienced musculoskeletal complaints of symptoms during the past twelve months.

The participant stood directly in front of the adjustable shelving mounted to a wall. One shelf was set to waist height and the other according to the shoulder postures of the experimental condition

Figure 1. Visual feedback of cycle time and W/R regime.



(abduction and flexion). The positions were determined and marked on the wall at the start of the experiment and then set as appropriate at the start of each experimental condition.

The participant was advised of how to identify possible feelings of discomfort in the shoulder region. Participants were advised that symptoms of discomfort include fatigue, soreness, warmth, cramping, pulling, numbness, tenderness, pressing, or pain.

Participants were then given a demonstration of the task. A cycle was considered a movement in one direction (from the bottom shelf to the top shelf or from the top shelf to the bottom shelf). The W/R regime dictated how much time was allowed after each lift for rest. Each experimental condition lasted 5 min after which the participant rated their perceived discomfort in the shoulders, as per O'Sullivan and Clancy (2007), O'Sullivan and Gallwey (2002, 2005). There was a break of at minimum 5 min, or until the participant experienced no residual discomfort before commencement of the next experimental condition.

2.6. Data analysis

All analysis was performed in Mini Tab software (version 16). The general idea behind the SNR is that the greater the ratio is the smaller the product (outcome variable) variance around the target value.

Equation (2): Mean Square Difference of the Signal to Noise Ratio S/N = $-10\log_{10}$

The purpose of the log transformation is to linearise any nonlinear behaviour of the factors. When log transformed SNR is used for analysis, the optimum estimated performance is more likely to be reproducible (Roy, 2010). Out of three SNR analysis options (the smaller the better, nominal best, the larger the better), the smaller the better rule was used. That is, the smaller discomfort score is reported after performing the work the better.

For the-smaller-the-better rule the formula for the mean square deviation is given as

$$\text{Mean Square Difference} = \frac{(y_1^2 + y_2^2 + y_3^2 + \ldots + y_{n-1}^2 + y_n^2)}{n}$$

where y is a trial score, n is number of observations.

3. Results

3.1. Study of main effects on discomfort

Table 2 resents the results of ANOVA on the SDS data. Four out of five main factors had significantly positive effects on discomfort. These factors were flexion (DF 3, F 8.02, $p < 0.0001$), work/rest regime (DF 3, F 5.07, $p < 0.01$), repetition rate (DF 3, F 18.2, $p < 0.0001$) and load (DF 3, F 11.2, $p < 0.0001$). Abduction did not have a significant effect on discomfort (DF 3, F 1.31, $p = 0.27$).

Figures 2–6 present plots of the average SDS data (+/− 1 standard deviations) for each of the five main effects separately. For flexion, W/R regime, repetition rate and load, each had a near linear effect on discomfort. For abduction, however, discomfort was flat between 0° and 60° and then it decreased slightly for 90°. The higher levels of the main factors recorded less variability between participants for all the factors with the exception of abduction. The plots also indicate large standard deviations in the data, but in spite of this, the ANOVA indicated significant differences as already reported.

3.2. Signal-to-Noise ratio analysis

The standardised discomfort data were studied with the SNR analysis (Table 3). Repetition rate was first, with load second, flexion third, W/R regime fourth with abduction fifth. For all the factors except for the abduction, the SNR decreased at a steady rate (Figure 7). However, for abduction, the SNR decreased from the first to the third level, and at the fourth level it increased to nearly the same value as in level 1.

Table 2. ANOVA of standardised discomfort scores for five main factors

Source	DF	*F*	Sig.
Flexion	3	8.02	0.0001*
Abduction	3	1.31	0.27
Work/rest regime	3	5.07	0.002*
Repetition rate	3	18.20	0.0001*
Load	3	11.20	0.0001*

*Significant at $p < 0.01$.

Figure 2. Mean standardised discomfort scores (±1 SD) for shoulder flexion.

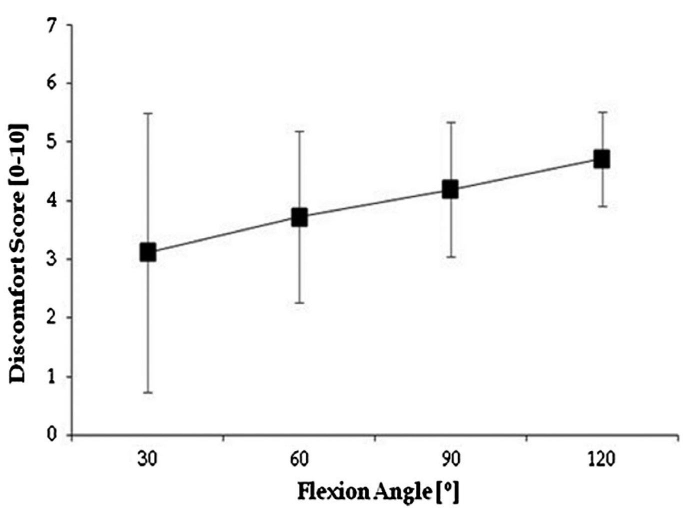


Figure 3. Mean standardised discomfort scores (±1 SD) for shoulder abduction.

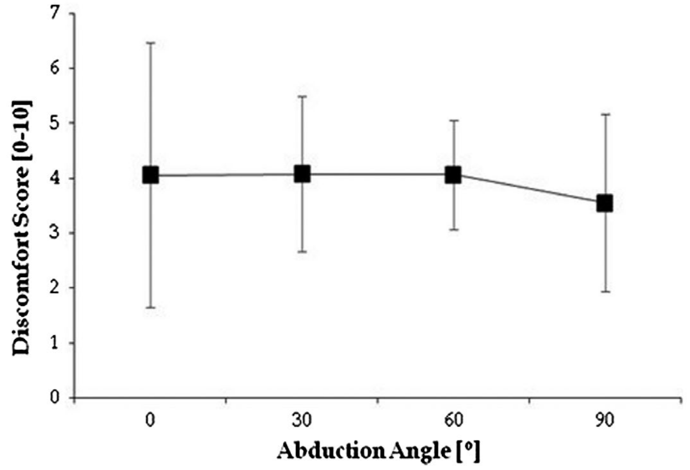


Figure 4. Mean standardised discomfort scores (±1 SD) for W/R regime.

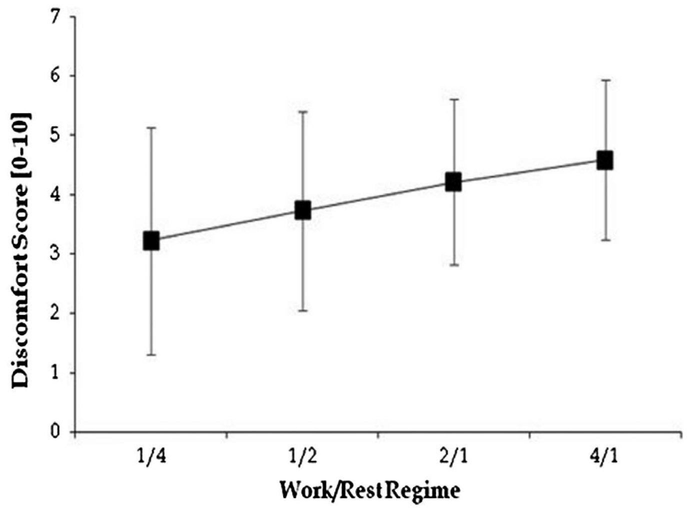


Figure 5. Mean standardised discomfort scores (±1 SD) for repetition rate.

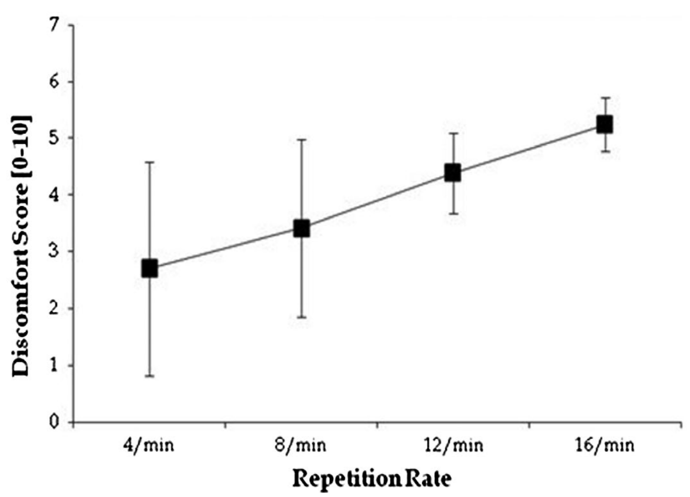


Figure 6. Mean standardised discomfort scores (±1 SD) for load lifted.

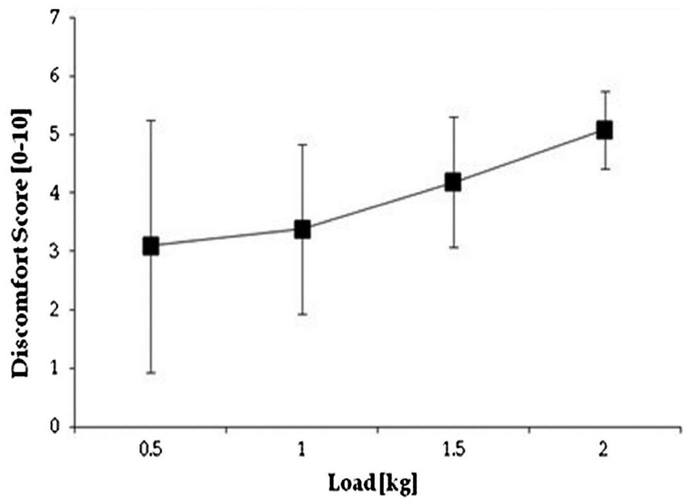
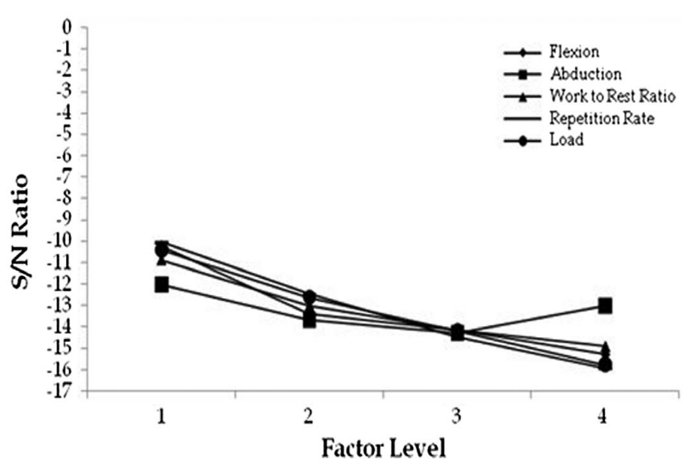


Table 3. SNR data with ranks of experiment main effects on SDS

Level	Repetition rate		Load		Flexion		Work/rest regime		Abduction	
1	4/min	−10.0	0.5 kg	−10.4	30°	−10.2	1/4	−10.9	0°	−12.0
2	8/min	−12.5	1 kg	−12.6	60°	−13.4	1/2	−13.0	30°	−13.7
3	12/min	−14.5	1.5 kg	−14.2	90°	−14.1	2/1	−14.2	60°	−14.3
4	16/min	−15.9	2 kg	−15.8	120°	−15.3	4/1	−14.9	90°	−13.0
Rank	1		2		3		4		5	

Figure 7. S/N ratios for five experiment factors for "the smaller the better" criterion for standardised discomfort scores.



4. Discussion

4.1. Posture effects on discomfort

The National Institute for Occupational Safety and Health (1997) indicated that there was evidence that posture was a risk factor for shoulder MSDs. In the current study, shoulder flexion affected discomfort ($p < 0.0001$, SNR rank third) but abduction did not ($p > 0.05$, SNR rank fifth). Some previous studies have shown that shoulder deviation in the frontal plane results in higher shoulder muscle electrical activity than during deviation in the sagittal plane (Forsman, Birch, Zhang, & Kadefors, 2001; Jensen & Westgaard, 1995, 1997). The experiment involved dynamic movements of the shoulder, and as such, there was the possibility of negligible static loading (with the exception of high W/R regime conditions) which is of key concern for fatigue of the upper limb musculature. More research is needed to explain this finding further.

Lin, Wang, Drury, and Chen (2010) studied perceived discomfort for repetitive arm reaching at low movement frequencies. Shoulder flexion, reaching frequency, weight and lifting duration had significant effects on discomfort ratings. Using biomechanical analysis, they found that the joint moment for the shoulder flexion at 60° and 120° was equal to, or smaller, than the peak joint moment for the shoulder at 90°. However, discomfort ratings for the shoulder at 120° were greater than those of other angles. This was not necessarily the case in the current study. While discomfort increased from 90° to 120° the magnitude was negligible. Higher discomfort ratings at increased upper arm elevation might be caused by increased intramuscular pressure and decreased blood flow impairing muscle metabolism, causing increasing metabolic accumulation, thereby leading to local muscle fatigue (Lin et al., 2010).

Shoulder flexion had a highly significant effect on discomfort. Mathiassen and Winkel (1990) performed an EMG study of the shoulder loading based on load lifted and posture (arm flexion and abduction). In the current shoulder discomfort study, load was ranked second ahead of shoulder flexion which was ranked third.

4.2. Repetition rate effects on discomfort

NIOSH (1997) indicated that there was evidence that repetition was a risk factor on its own for shoulder MSDs. In the current study, repetition was ranked first for effect on discomfort, although it was just marginally higher than the effect for load. Repetition is a factor that is most often mentioned as a key risk for MSD development (Andersen et al., 2003; Hansson et al., 2009).

4.3. Duty cycle regimes effects on discomfort

The W/R ratio was ranked fourth for effect on discomfort. As the work content increased and rest content decreased, discomfort increased. This corroborates the general ergonomics advice that dynamic work is more favourable than static work, especially for the shoulder region. This finding is in line with previous work on recovery times and W/R regimes (Konz, 1998).

Despite the fact that EMG recordings were not made during the experiment, it is believed, based on some previous work (Jensen, Finsen, Hansen, & Christensen, 1999), that EMG gaps would have been expected during all four W/R regimes, providing some relaxation for the shoulder muscles. It may be that the high repetition rate combined with some of the W/R regimes would influence the number of EMG gaps recorded, in that higher repetition rates would result in a smaller number of the gaps.

4.4. Load effect on discomfort scores

Load was ranked second for effect on discomfort. Given that load and repetition were ranked the top two for effect on discomfort, it is expected that there might well be an interaction effect, as observed by Silverstein et al. (1986) for the wrist. However, interactions effects were not tested in this experiment design so more studies are needed to test if an expected two interaction for this is present for the shoulder. In the NIOSH review (NIOSH, 1997) there was insufficient evidence to indicate that force was a risk factor on its own for shoulder MSDs. There is a growing body of research highlighting the importance of muscle activity parameters aside from load on risk of injury, notably the effects of long duration low contractions without rest (Iridiastadi & Nussbaum, 2006; Veiersted, Forsman, Hansson, & Mathiassen, 2013).

4.5. Limitations

An important limitation of the study design was the chosen duration of the experimental conditions (5 min). It may be argued that this is not sufficient time to induce fatigue in the shoulder muscles. However, in studies of muscle fibre conduction velocity it has been shown that fatigue can occur in the muscle during the first minute of a manual task (Bosch, de Looze, Kingma, Visser, & van Dieën, 2009).

Interactions between risk factors are recognised as important for risk of injury (Gallagher & Heberger, 2013; NIOSH, 1997). Interactions between the main factors were not analysed in this experiment. This is a recognised limitation of Taguchi experimental design and this is also a limitation of the current study.

5. Conclusions

In this experiment, the experimental conditions resulting in lowest discomfort were shoulder flexion at 30°, horizontal abduction at 0°, W/R regime of 1/4, repetition rate of 4/min and load of 0.5 kg. The highest standardized discomfort was recorded for the shoulder flexed 120°, the W/R regime 4/1, load of 2 kg and repetition rate of 16/min.

The ANOVA indicated the following variables had significant effects on Discomfort: Flexion, Repetition, Load (each $p < 0.0001$), and Work/Rest Regime ($p < 0.01$). Shoulder Abduction did not ($p = 0.27$). Repetition was ranked as having the greatest effect on the development of discomfort in the shoulder region, followed by load, shoulder flexion, and Work/Rest Regime. It must be stated that the findings of this study are limited to the range of levels of the current combinations of experimental condition tested.

The Taguchi design of experiments used here illustrates how large numbers of risk factors for musculoskeletal disorder development can be studied in single laboratory studies.

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