

# Short-cycle overhead work and shoulder girdle muscle fatigue

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## Abstract

The objective of this research was to determine shoulder girdle fatigue for different combinations of weight of workpieces, weight of hand-tools, shoulder postures, arm up time and arm down time that are commonly used in automotive assembly operations. Both objective [surface electromyography (sEMG)] and subjective measures (ratings of perceived exertion, (RPE), fatigue and pain) were used to assess stress, fatigue and pain in the shoulder girdle. Ten healthy young female subjects participated in a laboratory experiment that consisted of a simulation of common automotive assembly job tasks. The simulation consisted of four tasks in a 1-min job-cycle. Each cycle was repeated 50 times. The four tasks were varied with different predetermined combinations of two weights ( $W_1$  signifying a workpiece and  $W_2$  signifying the hand-tool weight), three exertion times and three shoulder postures.  $W_1$  was either 1.36 or 2.73 kg (3 and 6 lb), and  $W_2$  was 0.45, 0.91 or 1.82 kg (1, 2 and 4 lb). Exertion time was with the arm up for 2 seconds and down for 2 s (2–2) for ten exertions per minute, arm 3 s up and 3 s down (3–3) for seven exertions/min, or arm 5 s up and 3 s down (5–3) for five exertions/min. Each cycle finished with an 8–10 s rest phase to complete a 1-min cycle time. The posture angles were shoulder flexion of 60°, 90° and 120° combined with an included elbow angle of 90°, 120° and 150°, respectively. Experimental combinations ( $n = 54$ ) were randomly selected. Response variables were recorded in the first minute and every 5 min thereafter for 50 min. The response variables included sEMG, RPE, fatigue and pain in the shoulder girdle.

All subjects were able to perform all combinations with the lowest weights; however, in the more extreme postures, a few subjects prematurely terminated the experiments due to fatigue and/or pain. RPEs, as compared to sEMG data, appeared more sensitive and consistent. An analysis of variance showed that all four variables (workpiece weight ( $W_1$ ), tool weight ( $W_2$ ), arm up and down time, exertion time and shoulder posture) were statistically significant ( $p \leq 0.01$ ), although the tool weight and workpiece weight were most predictive of capabilities. As expected, the RPE, fatigue and pain increased with an increase in the weights of the workpiece ( $W_1$ ) and hand tool ( $W_2$ ). Guidelines for acceptable workloads are provided.

## Relevance to industry

Combinations of weights, exertion time and shoulder posture that cause excessive fatigue are important for designing overhead work and hand-tools. The data reported provide a set of such data for female subjects.

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## 1. Introduction

There is a high prevalence of shoulder musculoskeletal disorders (MSDs) in the general population, with elevated risk reported particularly in those with jobs requiring overhead work (Hagberg and Wegman, 1987; Winkel and

Westgaard, 1992; Sommerich et al., 1993; Kuorinka and Forcier, 1995; NIOSH, 1997; BLS, 2004; Miranda et al., 2005). Shoulder MSDs also cause a large proportion of lost or restricted days (median = 12) (Kelsey, 1997; BLS, 2004) and are costly, reportedly having an average total direct cost of \$11,565 per shoulder claim and a reported cost of over \$24,626 per case of rotator cuff tendinitis in Washington State, 2004 (WL&I, 2004). There is a belief that overhead work is a risk factor for shoulder disorders

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(NIOSH, 1997); however, the elimination of overhead work tasks is frequently impossible (American Automobile Manufacturers Association, personal communication, 1999, (AAMA)). Further, recommendations for the design of overhead work tasks is also weak with rather limited reported experimental data. Thus, guidance for the design of overhead work tasks has largely relied upon expert opinion.

There are two primary theoretical biomechanical concerns from overhead work, mechanical compression and impaired blood supply. The compression of the supraspinatus tendon reportedly occurs between the humeral head and acromion process (mechanical impingement). The reduction in the blood supply, especially to the supraspinatus and infraspinatus muscles, is thought to occur due to an increase in intramuscular pressure (IMP) when the upper arm is elevated. Since the pathophysiology is unclear, there is resulting confusion regarding the actual mechanism (Hagberg, 1984; Hegmann and Moore, 1998). Järvholm et al. (1988, 1991b) reported that fatigue and shoulder muscle blood flow were affected at moderate shoulder abduction and without hand load. They hypothesized that recurrent sustained periods of ischemia trigger degenerative processes in poorly vascularized areas of the muscular compartments, thus potentially affecting the blood supply to the affected tendons.

Several studies using electromyography (EMG) have shown high activity in shoulder muscles (especially in the supraspinatus and infraspinatus muscles using intramuscular EMG) in elevated arm positions (Chaffin, 1973; Herberts and Kadefors, 1976; Herberts et al., 1980; Bjelle et al., 1981; Hagberg, 1981a,b; Sigholm et al., 1984; Christensen, 1986; Hagberg and Sundelin, 1986; Järvholm et al., 1988, 1991b; Takala and Viikari-Juntura, 1991; Jensen et al., 1993, 1999; Veiersted et al., 1993; Palmerud et al., 1995; Vasseljen and Westgaard, 1995). Some studies have suggested that the supraspinatus and/or infraspinatus are the most vulnerable muscles when working with the arms elevated (Herberts et al., 1980; Bjelle et al., 1981; Hagberg, 1981b; Sigholm et al., 1984; Järvholm et al., 1988, 1989, 1991b; Sporrang et al., 1996; Sporrang and Styf, 1999). However, EMG of the trapezius has often been used to study total shoulder muscle load (Hagberg, 1981a; Jonsson, 1982; Aaras et al., 1988; Westgaard and Aaras, 1984; Hagberg and Sundelin, 1986; Westgaard, 1988; Jensen et al., 1993, 1999; Veiersted et al., 1993; Vasseljen and Westgaard, 1995). Similarly, while the deltoid muscle has been extensively used to study shoulder muscle load, some studies have questioned the hand-load dependency of the three parts of the deltoid muscle (Hagberg, 1981a; Sigholm et al., 1984). Jensen et al., (1993) reported that current techniques for measuring shoulder muscle load using surface EMG are inadequate. Some researchers have used IMP to study shoulder muscle load and have reported higher IMPs in infraspinatus and supraspinatus muscles with elevated arm positions and/or with an increase in hand load (Sigholm et al., 1984; Järvholm et al., 1988,

1989, 1991b; Sporrang and Styf, 1999). For example, Järvholm et al. (1991b) concluded that prolonged work with elevated arms will impede muscle blood flow in the stabilizing muscles of the rotator cuff and this might lead to localized muscle fatigue. However, it is unclear how high the arms must be elevated (shoulder flexion or abduction), for how long a time and with what weights or forces in the hands before harmful effects may in theory result (NIOSH, 1997; Svendsen et al., 2004). Further according to Svendsen et al., (2004) “pain on elevation of the arm is a common symptom of various shoulder disorders and, consequently, work above shoulder level may provoke pain even if the exposure is neither casually nor prognostically related to any underlying disorder.” Whether EMG and intramuscular studies provide a metabolic explanation of muscle pain and work-related disability has not been validated (Järvholm et al., 1991b). Further these studies do not necessarily imply that it is not physiologic to work with elevated arms (Järvholm et al., 1991b). At present, there is no generally acceptable method to quantify shoulder muscle load in relation to shoulder pain, let alone the subsequent risk of shoulder impairment and disability (Sejersted and Westgaard, 1988; Westgaard, 1988; Järvholm et al., 1991b). The exact mechanism behind shoulder muscle pain remains unclear. The present lack of knowledge limits our ability to recommend guidelines to prevent work-related shoulder pain and shoulder disorders (Kilbom, 1999).

The objective of this research was to determine shoulder girdle fatigue for different experimental combinations to provide some guidance for design of overhead work. Experimental combinations were of weight of workpieces, weight of hand-tools, shoulder postures, arm up and down times that are commonly used in automotive assembly operations. Both, objective (surface EMG (SEMG)) and subjective measures (ratings of perceived exertion (RPE), fatigue and pain) were used to determine excessive stress, fatigue and pain in the shoulder girdle.

### 1.1. Epidemiological studies

Approximately 39 studies have been reported assessing relationships between ergonomic factors and shoulder disorders (Kuorinka and Forcier, 1995; NIOSH, 1997). Despite the relatively large number of studies, there were no job-related risk factors for shoulder disorders reported by NIOSH (1997) to have strong evidence, and most generic job physical risk factors were categorized as having “insufficient evidence” (NIOSH, 1997). Most epidemiological studies on work-related shoulder disorders suffer from methodological limitations (Riihimaki, 1999; Harkness et al., 2003). Major limitations include both job physical assessments and diagnoses of shoulder disorders (Riihimaki, 1999). Most studies are cross-sectional (assessing associated factors rather than true risk factors) and/or job physical demands are based on job titles (NIOSH, 1997; Riihimaki, 1999; van der Windt et al., 2000;

Harkness et al., 2003; Svendsen et al., 2004). Most studies have studied shoulder disorders in aggregate, and many studies did not separate shoulder and neck disorders. Svendsen et al. (2005) concluded that even task-based estimates of job physical exposure from a collective database could be very imprecise. They found that task-based estimates of physical exposure were only marginally superior to estimates based on occupation. While there is some evidence that rotator cuff (supraspinatus) tendinitis is related to job physical factors (NIOSH, 1997), muscle tension syndrome is thought to have a large contribution from psychosocial risk factors (Krantz et al., 2004; Dainoff et al., 2005). Results from a few more recent epidemiological studies are summarized below.

Punnett et al. (2000) conducted a case-referent study on 79 cases and 124 referents over a 10-month period in an automobile assembly plant. The authors concluded that severe shoulder flexion or abduction ( $>90^\circ$ ), especially for 10% or more of the work cycle, was predictive of chronic or recurrent shoulder disorders. Use of handheld tools increased the risk. However, mild flexion or abduction ( $46\text{--}90^\circ$ ) and peak shoulder torque were not associated with an increased risk of shoulder disorders.

These results appear to be in conflict with the laboratory studies by Järholm et al., (1988, 1991b), who reported that both EMG activity and the IMP increased with an increase in weight in the hand as well as with an increase in shoulder flexion and abduction angle up to  $90^\circ$ . EMG activity and IMP decreased with shoulder flexion and abduction angles greater than  $90^\circ$ .

Harkness et al. (2003) conducted a 2-year prospective study on newly employed workers ( $n = 803$  in the beginning and 476 at 24 months) from 12 diverse occupational settings to determine job physical factors and psychosocial factors that predicted onset of shoulder pain defined as lasting at least 24 h in the past month. The assessment of manual handling activities was based on a self-completed instrument designed to measure frequency, duration and weights of work related to mechanical tasks performed. In multivariate analyses, factors included in the final model were: lifting weights with one or two hands, pushing or pulling heavy weights, working with hands above shoulder level, monotonous work and other pain. However, 95% confidence intervals showed that only pushing and pulling weights  $\geq 31.8$  kg and monotonous work were statistically significant.

Svendsen et al. (2004) conducted a cross-sectional study in a historical cohort of 1886 males from three occupational groups. Exposure assessments were performed for four consecutive days in a random sample of 72 subjects. The prevalence of dominant sided shoulder complaints and disorders was twice as high among house painters as compared to those in car mechanics and machinists. They reported that arm elevations  $>90^\circ$  were related to shoulder disorders. While the prevalence of shoulder disorders increased with an increase in reported lifetime upper arm elevation, duration of employment was nega-

tively related to shoulder disorders (though not statistically significant).

Fredriksson et al. (2005) reported results from data on 256 subjects (75 chronic, 143 non-chronic and 38 dropouts) who were re-examined in 1993 and were given a second follow-up in 1997. The aim of the study was to identify work- and leisure-time-related conditions that contributed to chronic neck/shoulder pain. No associations were found among men. Among women, risk factors included poor coping strategies, time pressure at work and work with hands above shoulder level  $>0.5$  h per day. However, in multivariate analysis, only poor coping strategies was statistically significant.

From the above brief review of epidemiological studies, it appears that (i) there is a lack of consistency in results from different epidemiological studies on shoulder pain and shoulder disorders and (ii) the epidemiological results are not always consistent with biomechanical findings.

## 1.2. Job risk factors

Various researchers have reported “risk” factors for shoulder MSDs that included highly repetitive work, shoulder posture (especially shoulder flexion and/or abduction  $>60$  degrees, NIOSH, 1997); force (Herberts et al., 1981, 1984; Stenlund et al., 1992; Andersen and Gaardboe, 1993; Chiang et al., 1993; Wells et al., 1993) and cumulative load based on self-reported questionnaire data (Miranda et al., 2005).

Several studies have evaluated the effects of hand-tool weights and hand forces on muscle fatigue though not specifically on the shoulder. In general, these studies have shown an increase RPE, a shift in EMG median (or mean) frequency to a lower frequency or fewer EMG gaps and a decrease in maximum acceptable frequency with an increase in percent maximum voluntary contraction (%MVC) (Björkstén and Jonsson, 1997; Armstrong et al., 1989; Bystrom and Kilbom, 1990; Dahalan and Fernandez, 1993; Kim and Fernandez, 1993; Grant et al., 1994; Harber et al., 1994; Snook et al., 1995, 1997, 1999; Marley and Fernandez, 1995; Abu-Ali et al., 1996; Klein and Fernandez, 1997). Silverstein et al. (1987), Armstrong et al. (1987) and Chiang et al. (1993) found that a combination of high force and high repetition was a significant risk for carpal tunnel syndrome and hand/wrist tendinitis. Moore and Garg (1994) reported that the incidence rate for all distal upper extremity disorders grouped together was directly proportional to the applied hand force and inversely proportional to the recovery time.

The above studies are important because there may be an association between hand muscle activity and shoulder muscle activity. In this regard, Sporrang et al. (1996) studied the effect of handgrip force (30% and 50% MVC) in eight different arm positions on four shoulder muscles using intramuscular EMG. The authors reported that high static handgrip force, particularly in elevated arm positions, increased the load on some shoulder muscles.

Further, the stabilizing muscles (the rotator cuff muscles) were more influenced than the larger muscles (deltoid and trapezius).

Sigholm et al. (1984) studied the effects of hand-tool weight (0, 1 and 2 kg) and arm position (shoulder flexion/abduction of 0°, 45° and 90° with elbow flexed at 90° or 120°) on six shoulder muscles using intramuscular EMG. The study concluded that the degree of upper arm elevation was the most important variable in determining shoulder muscle load. The stabilizing infraspinatus muscle was found to be more hand load dependent than elevating shoulder muscles. Further, the upper arm rotation and elbow flexion were of little importance in determining shoulder muscle load. Järvholm et al. (1988, 1991b) reported that the IMP increased with an increase in shoulder flexion and abduction angle up to 90° and then it decreased. At 135° of shoulder flexion angle, IMP was lower than that measured at 30° shoulder flexion. At 135° of shoulder abduction angle, IMP was comparable to that measured at 60° shoulder abduction. The added hand load increased IMP in all positions except in shoulder flexion of 135°. This study suggests that shoulder flexion/abduction of 135° is less hazardous than shoulder flexion/abduction of 90°.

Järvholm et al. (1991a) evaluated the effect of arm support by a suspension device for jobs involving low load assembly type of work and welding tasks with high shoulder muscle load. They concluded that the IMP was high enough even with arm support to reduce muscle flow, and the prevention of work-related shoulder pain is problematic. Jensen et al. (1999) reported more continuous muscle activity on the mouse side but shoulder loads were unaffected by arm movement frequencies and work cycle times.

In short, risk factors for shoulder disorders are poorly understood due to a lack of large, robust cohort studies that include clearly defined health outcomes and objectively measured job physical exposures. As well, there is no comprehensive job analysis model for shoulder exposure. Thus, design and prevention strategies to be followed are also unclear.

## 2. Methods

### 2.1. Subjects

Ten volunteer females were chosen as subjects and compensated. Only females were enrolled as adding males would not gain information on what the acceptable population-based workloads are and would double the study's costs. An analysis of variance showed that we would have 80% power to detect significant effects ( $\alpha = 0.05$ ) of weights and postures on RPE. The subjects were all college students from 21 to 33 years of age. All 10 subjects were right-handed. All 10 subjects claimed to be in good physical health and stated they had never had any musculoskeletal or cardiovascular disorders. All the sub-

jects were informed of the experimental procedures and signed consents to participate. A number of anthropometric measurements were made on the 10 subjects to characterize the subject population. These measurements included age, height, shoulder height, body weight, upper arm length, lower arm length, hand length (wrist to the center of grip), active shoulder flexion range of motion and grip strength. These measurements are given in Table 1. All subjects had previously completed a training phase, and thus were not performing unaccustomed lifting tasks.

### 2.2. Procedure

Two of the investigators visited an assembly plant belonging to one of the members of the AAMA. Two meetings with the representatives of the AAMA members were held to design the protocol for laboratory simulation of short-cycle overhead work performed during automobile assembly operations. Based upon the plant visit and the two meetings, it was decided that the laboratory simulation should include the following: The cycle time should be 1 min as the automotive industry targets assembly of one car per minute. Each cycle should consist of the following four tasks (elements):

#### 2.2.1. Task 1

Task 1 represented lifting a workpiece with one hand from a workbench and carrying it to an overhead conveyor for use in assembly.  $T_1$  and  $W_1$  represented time and weight used in task 1. Task 1 was simulated in the laboratory by holding a dumbbell in one hand to one side of the subject (with the arm hanging down (arm down)).

#### 2.2.2. Task 2

Task 2 was lifting the workpiece with one hand, weighing  $W_1$ , above the shoulder (overhead work) and attaching it to

Table 1  
Summary of demographic and anthropometric data for the ten female subjects

Variable	Mean	SD	Range
Age (years)	25.8	4.3	21–33
Height (cm)	168.4	5.59	159.0–176.8
Shoulder height (cm)	136.9	4.32	127.5–143.3
Body weight (kg)	66.4	10.8	50.0–87.7
Upper-arm length (cm)	34.8	1.27	33.3–36.6
Lower-arm length (cm)	26.2	1.02	24.9–28.2
Hand length (wrist to cg) (cm)	5.8	0.76	5.1–7.1
Shoulder flexion range of motion (°)			
HR = 0; IEA = 180	159.5	11.9	141.0–178.0
HR = 0; IEA = 150	159.1	15.2	133.0–186.0
HR = 45; IEA = 180	158.4	14.9	140.0–186.0
HR = 90; IEA = 180	165.1	15.7	140.0–195.0
Grip strength (kg)	34.2	3.45	29.4–40.4

HR = shoulder horizontal rotation. IEA = included elbow angle.

the automobile chassis.  $T_2$  represented the time for task 2 in the laboratory simulation. This included the time for lifting the workpiece above the shoulder to a preselected posture (arm up) and holding it in that posture for sufficient time to accomplish the task.

2.2.3. Task 3

Task 3 represented overhead work without supporting a workpiece, such as attaching grommets or using a small nut runner. This included lifting a hand-tool, weighing  $W_2$ , with one hand to a specified shoulder posture, using the hand-tool in that posture (arm up), lowering the hand-tool to the side of the worker and holding it at the side (arm down). Task 3 was repetitive and performed several times in a minute. In the laboratory simulation,  $T_3$  represented time for task 3.  $T_3$  had two components: arm up time and arm down time. Arm up time included the time to lift the hand-tool to a specified overhead posture and hold the hand-tool in that posture. Arm down time included lowering the hand-tool (dumbbell) to the side of the subject and holding it at the side.

2.2.4. Task 4

Task 4 was rest without any weight in the hand. In the laboratory simulation, the subjects placed the dumbbell on a stool on their right side and next to them, and stood there without any weight in the hand.  $T_4$  represented the time for task 4.

Fig. 1 shows the laboratory simulation of short-cycle overhead work. The subjects picked up workpiece weight  $W_1$  (1.36 or 2.73 kg) and held it at their right side for time  $T_1$  (5 s). They then lifted weight  $W_1$  and held it in a specified overhead posture for time  $T_2$  (5 s). The subjects then lowered weight  $W_1$ , placed it on a stool next to them, picked up hand-tool weight  $W_2$  (0.45, 0.91 or 1.82 kg) and held it to their right side (arm down, part of task 3). Next,

the subject lifted weight  $W_2$  and held it in a specified overhead posture (arm up, part of task 3). The subject repeated lifting and lowering weight  $W_2$  several times each minute (5 times in 1 min in the example shown in Fig. 1). Lastly, the subject placed the weight  $W_2$  on the stool next to them and stood with no weights in their hands for time  $T_4$  (8 or 10 s). The subject then repeated the aforementioned cycle every minute for 50 minutes.

The following combinations of arm up times, arm down times, shoulder postures, workpiece weights and hand-tool weights were used to simulate the overhead work. There were two levels of workpiece weight,  $W_1$  (1.36 or 2.73 kg) and three levels of hand-tool weight,  $W_2$  (0.45, 0.91 or 1.82 kg). There were three postures: 60/90 (shoulder forward flexion of 60° and included elbow angle of 90°), 90/120 and 120/150. The subjects were allowed to rotate their shoulder horizontally to a posture, which they found to be the most comfortable. Usually, the shoulder horizontal angle ranged between 20° and 30°. Times for  $T_1$  and  $T_2$  were fixed at 5 s each.  $T_3$  had three combinations of arm up time and arm down time. These were 2–2 (arm up for 2 s and down for 2 s), 3–3 and 5–3. The weights for workpiece ( $W_1$ ) and hand-tool ( $W_2$ ), shoulder postures, and times for carrying the workpiece ( $T_1$ ), attaching the workpiece ( $T_2$ ), and times for hand-tool use ( $T_3$  and  $T_4$ , arm up and down times) were selected to represent the most commonly used workpiece and hand-tool weights, most commonly used overhead postures, and most commonly used times for carrying and attaching the workpiece and hand-tools in automotive assembly.

Each subject performed a total of 54 combinations (two levels of weight  $W_1 \times$  three levels of weight  $W_2 \times$  three levels of time  $T_3 \times$  three overhead postures). A total of 500 h of data were collected (54 h/subject  $\times$  10 subjects), as only seven of the 10 subjects were able to complete all 54 combinations. Among the remaining three subjects, one

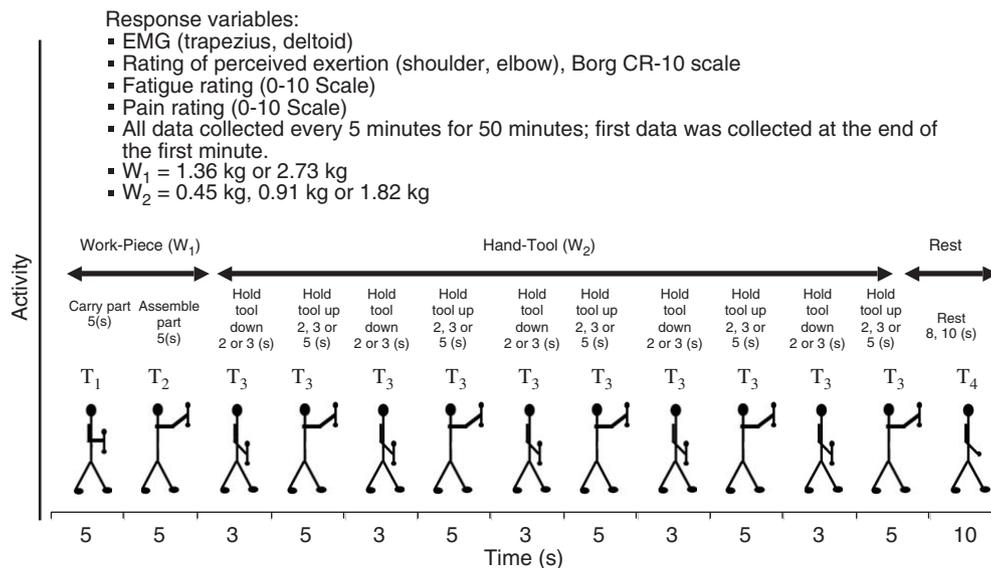


Fig. 1. One-handed, short-cycle overhead work activity sequence (the example shown is for arm up for 5 s and arm down for 3 s).

completed 47 combinations, one completed 28 combinations and one completed 21 combinations.

One of the 54 combinations of weight  $W_1$ , weight  $W_2$ , time  $T_3$  and posture P was randomly selected. For a given 50-min experimental setting, weight  $W_1$ , weight  $W_2$ , time  $T_3$  and posture P were kept fixed. Each of the 10 subjects performed a randomly selected combination of weight  $W_1$ , weight  $W_2$ , time  $T_3$  and posture P for 50 min. Subjects participated once per day and 3–5 times per week for the vast majority of data collected. In a few cases (<3% of data), the subjects participated once in the morning and once in the evening. In these cases, a minimum of 8 h of rest was provided between two successive experiments conducted in a given day. Surface EMG, RPE for the shoulder and the elbow, and fatigue and pain ratings for the shoulder girdle were recorded every 5 min for 50 min. In addition, data were collected during the first minute to provide the baseline data. All subjective data were collected during the last 20 s of each 5 min segment when the arm was up with weight  $W_2$ .

At the end of each experiment, the subjects were asked to estimate the total number of hours per day they felt they could perform the given combination of weight  $W_1$ , weight  $W_2$ , time  $T_3$  and posture P.

The temperature and humidity were normal room temperature and humidity. The room was centrally heated during the winter months and air-conditioned during the summer. The room temperature varied between 20.0 and 22.3 °C and the humidity between 30% and 45%.

### 2.3. Subject positioning

A 1.25 m × 1.25 m plastic platform, with the center marked to place the right great toe of the subject, served as the standing surface for the subject. A tennis ball hung by an adjustable string from a moveable pole marked the target for the dominant hand (right hand) to achieve the specified shoulder forward flexion and elbow angles. The subject was instructed to touch the bottom of the tennis ball with the knuckles of the right hand and the tennis ball was adjusted laterally to the subject's desired posture for horizontal rotation. A manual goniometer was used to measure shoulder flexion, shoulder horizontal rotation (0° = arm and elbow are directly in front of the body, completely in the sagittal plane, and 90° = arm and elbow are directly to the side of the body, completely in the coronal plane), and included elbow angles (180° = elbow is completely extended and 30° = elbow is near complete flexion). Dumbbells, with weight adjustments in increments of 0.1 lb, were used to simulate hand-tool weights.

### 2.4. Surface EMG

Muscle activity was monitored for the upper trapezius and mid-deltoid muscles, as overhead work is reportedly primarily supported by these muscles (Luttgens and Wells, 1989). Importantly, the horizontal rotation of the shoulder

was not fixed for these experiments and this meant that we would not necessarily assess each muscle's likely area of maximal activity with the electrodes despite uniform positioning. The myoelectric activity was recorded using bi-polar, silver/silver-chloride, surface electrodes, 1 cm in diameter detection surfaces, spaced 2 cm apart on center. The electrode on the deltoid was placed at a point halfway between the lateral aspect of the acromion process and the insertion of the deltoid on the deltoid tubercle. The electrode on the upper trapezius muscle was placed at the mid-point between the C<sub>7</sub> spinous process and the posterior aspect of the acromion process. On a pilot basis, we placed the electrodes on different areas of the upper trapezius muscle to determine where the muscle had the maximum sEMG signal. These pilot tests were conducted on two subjects while they lifted weights in three different postures. The mid-point on the trapezius was selected as it resulted in the maximum sEMG signal intensity. The electrodes and ground were connected to a Therapeutics Unlimited (Model #544) EMG monitoring system. Here, the EMG signals were further amplified and conditioned by a high-pass filter set at 20 Hz. The signal was then digitized using a 12-bit A/D data acquisition card and stored in the data acquisition computer.

### 2.5. Subjective rating scales

Posters of subjective rating scales were hung on a wall in front of the subjects. These scales included:

1. An RPE scale (Borg CR-10 scale; Borg, 1982),
2. An 11-point fatigue scale (0 = no fatigue, 10 = cannot continue any longer) and
3. An 11-point pain scale (0 = no pain, 10 = the worst pain ever).

When using the Borg CR-10 scale, the subjects were asked to provide ratings on how hard the physical exertion was on the shoulder girdle (shoulder rating) as well as on the elbow (elbow rating). When using the 11-point fatigue scale, the subjects were asked to rate the degree of fatigue in the shoulder girdle. When using the 11-point pain scale, the subjects were asked to rate the degree of pain, if any, in the shoulder girdle.

### 2.6. Experiment control

An Allen-Bradley SLC-500 programmable logic controller (PLC), with four distinctly colored lights (blue, yellow, red and green) and buzzers, was connected to a DataQ DI-200 PGH eight-channel data acquisition card. The data acquisition system and the PLC were used in conjunction to control cycle times during the short-cycle overhead work simulation phase of the study. Cyclic timers activated colored lights and buzzers to pace the subject. The lights and buzzers prompted the subject to perform specific tasks within a given cycle.

### 3. Results

All subjects were able to perform all combinations of weight  $W_1$ , weight  $W_2$  and time  $T_3$  in the 60/90 posture for 50 min. In the 90/120 and 120/150 postures, a few subjects terminated the experiments earlier than 50 min due to unbearable stresses, fatigue and/or pain in the shoulder girdle. The earlier terminations in the above two postures occurred for tasks with  $W_1 = 2.73$  kg,  $W_2 = 1.82$  kg and  $T_3 = 2-2$  (2 s arm up time–2 s arm down time) or 5–3 s. In the 90/120 posture, two subjects did not finish the experiments with  $T_3 = 2-2$  s and one subject with  $T_3 = 5-3$  s. In the 150/180 posture, three subjects did not finish the experiments with  $T_3 = 2-2$  s and one with  $T_3 = 5-3$  s. In addition, one subject terminated the experiment earlier than 50 min in the 150/180 posture for the task with  $W_1 = 1.36$  kg,  $W_2 = 1.82$  kg and  $T_3 = 2-2$  s. Thus, it appears that these subjects found the 90/120 and the 120/150 postures with  $W_1 = 2.73$  kg,  $W_2 = 1.82$  kg, and  $T_3 = 2-2$  s the most difficult.

#### 3.1. RPE, fatigue and pain

The average RPE, fatigue and pain in the shoulder girdle at the end of 50 min or the final ratings if the experiments were terminated earlier than 50-min duration are given in Table 2. Since RPE for the shoulder girdle were consistently higher than those for the elbow, the latter are not presented. Among the three ratings for the shoulder girdle, the perceived exertion ratings were the highest, followed by the fatigue ratings, and the pain ratings were the lowest (Table 2). The average ratings increased with an increase in the weight of the hand-tool,  $W_2$ . The ratings were the highest for  $W_2 = 1.82$  kg. The ratings were higher for the weight of the workpiece weight of  $W_1 = 2.73$  kg than for  $W_1 = 1.36$  kg. The ratings for the 90/120 and the 120/150 postures were higher than those for the 60/90 posture. In general, the arm up times and arm down times ( $T_3$ ) of 2–2 and 5–3 produced higher ratings than the  $T_3$  of 3–3 s. In particular,  $T_3 = 2-2$  appears to be the most stressful and fatiguing. An analysis of variance (two levels of  $W_1 \times$  three levels of  $W_2 \times$  three levels of  $T_3 \times$  three postures  $\times$  10 subjects) showed that all four variables ( $W_1$ ,  $W_2$ ,  $T_3$  and posture) had significant effects on RPE, fatigue and pain ( $p \leq 0.01$ ).

#### 3.2. sEMG

There was a small decrease in the median power frequencies (MPFs) for the upper trapezius and mid-deltoid muscles at the end of 50 min. On the average, the MPF decreased by 4.3% (range = 0–28%) for the trapezius and 2% (range = 0–20%) for the deltoid. There was a large between-subject-variability in the MPF at the end of 50 min. The trapezius showed fatigue for four out of 54 tasks and the mid-deltoid for one task. More importantly, there was no relationship between the MPF and job

physical demands. The RMS values were significantly higher ( $p \leq 0.05$ ) at the end of 50 min for the 13 out of 54 task combinations for the trapezius muscle and for eight task combinations for the deltoid. However, there was no consistent pattern. Some of the less physically demanding tasks were found to be fatiguing while more physically demanding tasks were found non-fatiguing.

#### 3.3. Estimated hours

The number of hours that the subjects estimated that they could perform the various combinations of weight of workpiece ( $W_1$ ), weight of hand-tool ( $W_2$ ), posture, arm up time and arm down time are summarized in Table 3. The subjects estimated that they could perform the overhead work for 7.7 h or more if the weight of the hand-tool was 0.45 kg. If the weight of the hand-tool was 0.91 kg, they estimated they could perform the overhead work for at least 7 h with the exception of the arm up time and down time of 3–3, workpiece weight  $W_1 = 2.73$  kg and posture 120/150 combination. A hand-tool weight of 1.82 kg resulted in significantly lower estimates (Table 3). The worst combination was the heaviest workpiece and hand-tool weights (workpiece weight of 2.73 kg, hand-tool weight of 1.82 kg), arm up time of 2 s and arm down time of 2 s in the 90/120 and 120/150 overhead postures (Table 3). Under these conditions, the subjects believed they could not perform the job for more than 2 h.

## 4. Discussions

#### 4.1. Suggested acceptable rating levels for perceived exertion, fatigue and pain

Since in most work situations fatigue is not a binary decision (fatigue versus no fatigue), one issue of interest is what levels of perceived exertion, fatigue and pain are acceptable and/or “safe”. In other words, what levels of perceived stresses, fatigue and/or pain would significantly increase the risk of shoulder MSDs? Psychophysical methods are one of the methods used to determine acceptable workloads (Snook and Ciriello, 1991). These studies suggest that, when given control of the weight of the load, applied force or frequency of exertion, subjects select workloads resulting in ratings ranging from “light” to “hard” on the Borg RPE scale (Garg and Saxena, 1982; Garg and Badger, 1986; Garg and Banaag, 1988; Garg, 1989; Garg et al., 1999; Garg and Hegmann, 2003). Further, these studies show that the more stressful the task, the higher the rating of perceived exertion for the workload selected by the subjects (Garg and Saxena, 1982; Garg, 1983; Garg and Badger, 1986; Garg and Banaag, 1988; Garg, 1989; Garg et al., 1999; Garg and Hegmann, 2003).

Based on the above reported prior studies, a mean rating of 3.5 or less on the Borg CR-10 scale (between “moderate” and “somewhat hard”) is suggested as an acceptable level of perceived stresses to the shoulder girdle.

Table 2  
Mean, standard deviation and range for the ratings of perceived exertion, fatigue and pain for different workpiece weights, handtool weights, shoulder postures, and arm up and down times

Rating scale <sup>a</sup>	Weight (kg)	Posture <sup>b</sup> and time sequence <sup>c</sup>									
		60/90			90/120						
		W <sub>1</sub>	W <sub>2</sub>	W <sub>3</sub>	2-2	3-3	5-3				
Perceived Exertion	1.36	0.45	1.56 ± 1.74 (0-4)	1 ± 1.25 (0-3)	1.25 ± 1.83 (0-5)	1.5 ± 1.2 (0-3)	1.63 ± 1.51 (0-4)	2.88 ± 2.7 (0-9)	2.5 ± 1.51 (0-5)	2.5 ± 1.51 (0-5)	1.88 ± 1.55 (0-4)
	1.36	0.91	2.2 ± 1.14 (0-4)	1.33 ± 1.22 (0-4)	1.38 ± 1.19 (0-3)	1.88 ± 1.46 (0-4)	2.5 ± 1.2 (0-4)	3.44 ± 2.3 (1-9)	3.78 ± 1.72 (1-7)	2.44 ± 1.59 (0-6)	2.56 ± 1.33 (0-4)
	1.36	1.82	<b>3.78 ± 1.2 (2-5)</b>	3.22 ± 1.92 (0-6)	<b>4 ± 1.33 (2-6)</b>	<b>5.5 ± 1.85 (3-8)</b>	<b>6 ± 3.08 (2-10)</b>	<b>4.75 ± 2.05 (2-8)</b>	<b>7 ± 2.69 (3-10)</b>	<b>5.33 ± 3.08 (1-9)</b>	<b>5.88 ± 2.85 (2-10)</b>
	2.73	0.45	1.89 ± 0.93 (0-3)	1.56 ± 1.13 (0-3)	1.7 ± 1.34 (0-4)	3.3 ± 1.64 (0-6)	2.88 ± 2.36 (0-8)	2.13 ± 1.46 (0-4)	3 ± 1.49 (1-5)	2 ± 1.66 (0-4)	2.5 ± 2.14 (0-5)
	2.73	0.91	2.33 ± 1 (1-4)	3.11 ± 2.15 (0-6)	2.67 ± 1.87 (0-6)	<b>3.78 ± 1.3 (2-6)</b>	3 ± 2.12 (0-6)	3.22 ± 1.48 (0-5)	<b>3.67 ± 2.45 (0-8)</b>	<b>3.89 ± 2.71 (1-9)</b>	<b>3.5 ± 1.31 (1-5)</b>
	2.73	1.82	<b>4.11 ± 1.83 (1-6)</b>	3.33 ± 1.5 (0-5)	<b>5.22 ± 2.77 (1-10)</b>	<b>8 ± 2.88 (3-10)</b>	<b>5.57 ± 2.88 (2-10)</b>	<b>6.38 ± 3.07 (2-10)</b>	<b>7.78 ± 2.77 (3-10)</b>	<b>5.78 ± 2.49 (3-10)</b>	<b>5.63 ± 2.45 (3-10)</b>
Fatigue	1.36	0.45	1.44 ± 1.59 (0-4)	0.9 ± 0.99 (0-3)	0.88 ± 1.46 (0-4)	1.13 ± 1.25 (0-3)	1.25 ± 1.39 (0-4)	2.5 ± 2.88 (0-9)	2 ± 1.51 (0-4)	1.9 ± 1.52 (0-5)	1.25 ± 1.75 (0-4)
	1.36	0.91	1.5 ± 1.08 (0-3)	1.11 ± 1.27 (0-4)	1.13 ± 1.25 (0-3)	1.5 ± 1.51 (0-4)	2 ± 1.41 (0-4)	2.89 ± 2.37 (0-8)	3.22 ± 1.56 (1-5)	2 ± 1.58 (0-5)	2.33 ± 1.22 (0-4)
	1.36	1.82	3.22 ± 1.39 (1-5)	2.89 ± 1.76 (0-6)	3.4 ± 1.51 (1-6)	<b>5.25 ± 2.55 (1-9)</b>	<b>5.56 ± 3.13 (2-10)</b>	<b>4 ± 2.33 (1-7)</b>	<b>6.44 ± 3.4 (1-10)</b>	<b>4.89 ± 3.55 (1-9)</b>	<b>5.25 ± 3.24 (2-10)</b>
	2.73	0.45	1.56 ± 1.24 (0-3)	0.89 ± 1.27 (0-3)	1.3 ± 1.42 (0-4)	2.8 ± 1.87 (0-6)	2.25 ± 2.55 (0-8)	1.63 ± 1.3 (0-3)	2.7 ± 1.57 (0-5)	1.67 ± 1.32 (0-4)	1.75 ± 1.83 (0-5)
	2.73	0.91	2.11 ± 1.27 (0-4)	2.89 ± 2.32 (0-7)	2.44 ± 1.67 (0-5)	3.22 ± 1.39 (2-5)	2.78 ± 2.28 (0-6)	2.44 ± 1.67 (0-4)	3.33 ± 2.24 (0-7)	3.67 ± 3 (0-10)	3.25 ± 1.28 (1-5)
	2.73	1.82	3.44 ± 2.3 (1-7)	3.22 ± 1.2 (1-5)	<b>4.89 ± 3.06 (1-10)</b>	<b>7.5 ± 3.25 (2-10)</b>	<b>4.86 ± 3.44 (1-10)</b>	<b>6 ± 3.3 (1-10)</b>	<b>7.44 ± 2.92 (3-10)</b>	<b>5.33 ± 2.4 (3-9)</b>	<b>4.5 ± 3.16 (1-10)</b>
Pain	1.36	0.45	0.67 ± 1.12 (0-3)	0.4 ± 0.7 (0-2)	0.75 ± 1.49 (0-4)	0.63 ± 1.06 (0-3)	0.5 ± 1.07 (0-3)	1.5 ± 2.73 (0-8)	0.88 ± 1.13 (0-3)	1.2 ± 1.48 (0-4)	0.63 ± 1.06 (0-3)
	1.36	0.91	0.9 ± 1.1 (0-3)	0.89 ± 1.05 (0-3)	0.75 ± 1.16 (0-3)	1.38 ± 1.6 (0-4)	0.63 ± 1.06 (0-3)	1.89 ± 2.57 (0-8)	2 ± 2.18 (0-5)	1.56 ± 1.94 (0-6)	1.33 ± 1.32 (0-3)
	1.36	1.82	2.11 ± 1.76 (0-4)	1.78 ± 1.86 (0-5)	2.4 ± 1.96 (0-5)	<b>3.5 ± 1.69 (1-6)</b>	<b>3.78 ± 3.9 (0-9)</b>	<b>2.63 ± 3.02 (0-7)</b>	<b>4.44 ± 3.28 (0-9)</b>	<b>3.56 ± 3.5 (0-9)</b>	<b>4 ± 3.7 (0-9)</b>
	2.73	0.45	1.22 ± 1.09 (0-3)	0.44 ± 1.01 (0-3)	1 ± 1.49 (0-4)	2 ± 1.89 (0-6)	1.5 ± 1.51 (0-4)	0.63 ± 0.92 (0-2)	1.7 ± 1.77 (0-4)	0.67 ± 1 (0-3)	1.13 ± 1.64 (0-4)
	2.73	0.91	1 ± 1.32 (0-3)	1.78 ± 1.79 (0-5)	1.22 ± 2.05 (0-6)	2 ± 1.87 (0-5)	1.78 ± 2.17 (0-6)	2 ± 2 (0-5)	2.22 ± 2.22 (0-7)	2.22 ± 2.05 (0-5)	2 ± 1.77 (0-4)
	2.73	1.82	<b>2.56 ± 2.65 (0-6)</b>	1.78 ± 2.05 (0-5)	<b>4.44 ± 3 (0-8)</b>	<b>5.5 ± 4.24 (0-10)</b>	<b>4 ± 3.37 (0-9)</b>	<b>4.13 ± 3.6 (0-9)</b>	<b>5.56 ± 4 (0-10)</b>	<b>4 ± 3.5 (0-9)</b>	<b>3.63 ± 3.5 (0-9)</b>

Notes:

Bold Italic numbers based on:

- average rating of perceived exertion > 3.5
- average fatigue rating of > 3.5
- average pain rating > 2.5.

<sup>a</sup> At the end of 50 min or the final rating if the experiment was terminated before 50 min.

<sup>b</sup> Posture: shoulder flexion/elbow included angle.

<sup>c</sup> Time sequence: arm up time (seconds) – arm down time (seconds).

**Table 3**  
Number of hours estimated by the subjects that they could work per day for different combinations of workpiece weights, hand-tool weights, shoulder postures, and arm up and down times

Weight (kg)	Hours for Posture <sup>a</sup> and time sequence <sup>b</sup>									
	60/90		90/120		120/150					
$W_1$	$W_2$	2-2	3-3	5-3	2-2	3-3	5-3			
1.36	0.45	10.44 ± 1.24 (9–10)	10.1 ± 1.79 (8–10)	9.88 ± 3.14 (3–10)	10.25 ± 1.28 (8–10)	9.38 ± 2.07 (6–10)	9.13 ± 2.23 (6–10)	8.5 ± 2.62 (3–10)	9.4 ± 3.17 (2–10)	9.22 ± 2.22 (4–10)
1.36	0.91	10.5 ± 1.72 (8–10)	10.38 ± 1.51 (8–10)	9.57 ± 1.99 (6–10)	9.38 ± 2.45 (6–10)	8.63 ± 2.77 (4–10)	8.44 ± 2.74 (5–10)	<b>7.44 ± 2.24 (4–10)</b>	7.94 ± 2.98 (2.5–10)	8.89 ± 1.17 (7–10)
1.36	1.82	<b>5.69 ± 2.89 (2.5–10)</b>	8.11 ± 2.98 (3–10)	<b>7.11 ± 2.52 (2–10)</b>	<b>4.44 ± 1.95 (1.5–8)</b>	<b>5.33 ± 2.55 (1–8)</b>	<b>5.06 ± 2.48 (2–8)</b>	<b>3.42 ± 3.56 (0.5–9)</b>	<b>6.47 ± 3.11 (1.25–10)</b>	<b>5.56 ± 3.31 (1–10)</b>
2.73	0.45	9.17 ± 2.62 (3.5–10)	10 ± 1.8 (7–10)	9.8 ± 2.04 (6–10)	7.9 ± 1.91 (4–10)	8.25 ± 2.66 (3–10)	9 ± 2.29 (6–10)	8 ± 2.24 (5–10)	9.11 ± 2.76 (4–10)	7.75 ± 3.01 (3–10)
2.73	0.91	9.33 ± 1.87 (6–10)	7.56 ± 2.35 (4–9)	8.44 ± 2.13 (6–10)	<b>7.11 ± 2.47 (3–8)</b>	8.11 ± 2.89 (3–10)	7.56 ± 2.74 (3–10)	<b>7 ± 3.08 (2–10)</b>	<b>6.61 ± 4.17 (1.5–10)</b>	<b>7.22 ± 2.39 (3–10)</b>
2.73	1.82	<b>6.56 ± 2.7 (2–10)</b>	7.67 ± 1.8 (4–10)	<b>5.56 ± 3.09 (1–10)</b>	<b>1.94 ± 2.03 (0.25–6)</b>	<b>5.57 ± 2.95 (1.5–9)</b>	<b>3.66 ± 2.93 (0.25–8)</b>	<b>1.84 ± 1.45 (0.125–4)</b>	<b>4.03 ± 2.36 (1–8)</b>	<b>4.56 ± 2.85 (1–8)</b>

Notes:

Bold Italic numbers based on: hours < 7.5.

<sup>a</sup>Posture: shoulder flexion/elbow included angle.

<sup>b</sup>Time sequence: arm up time (seconds)–arm down time (seconds).

It is acknowledged that some researchers may consider a mean Borg CR-10 rating of 3.5 as too high while others may prefer a higher rating for the allowable workloads. Similarly, a mean rating of 3.5 or less on the fatigue scale, corresponding to the bottom-third of the fatigue scale, is suggested as an acceptable level of fatigue in the shoulder girdle. This recommendation is consistent with the observed mean fatigue ratings of 0.8–3.6 for the same subjects when they selected the maximum frequencies acceptable to them for an 8-h workday for the three different weights and six different shoulder postures (Garg and Hegmann, 2003). It is believed that this would not cause excessive fatigue in the shoulder girdle. In clinical settings or during functional capacity evaluations of injured workers, a pain rating of 3 or less is considered as “low pain” (Blankenship, 1986). In the maximum acceptable frequency determination phase of this series of experiments, the mean pain ratings for the same subjects ranged from 0.4 to 2.2 depending upon the weight and overhead posture involved (Garg et al., 1999). It is believed that a mean pain rating of 2.5 or less is an acceptable level of pain in the shoulder girdle and workloads at this level of pain would not expose workers to an increased risk of MSDs. In this regard, Gerr et al. (2002) in their prospective cohort study of office computer users defined a case for non-specific disorders of distal upper extremity and shoulder girdle if the peak intensity of reported pain in these body parts was  $\geq 6$  on the pain scale during any 1-week period. Thus, a recommendation for a pain intensity of  $\leq 2.5$  as an acceptable level of pain is well below the cut-off level used in prospective cohort studies to define a case with non-specific disorders.

The suggested limits for the average rating of perceived exertion  $\leq 3.5$ , the average fatigue rating  $\leq 3.5$  and the average pain rating  $\leq 2.5$  are provided as guidelines for job analysis and design based on current ergonomics literature. It is also possible to raise or lower these limits to determine acceptable workloads. In Table 2, numbers in bold italic represent those combinations of workpiece weight ( $W_1$ ), hand-tool weight ( $W_2$ ), shoulder posture, and arm up time and arm down time that exceed the average perceived exertion rating of 3.5, fatigue rating of 3.5 or pain rating of 2.5. These are believed to be the combinations that may cause excessive fatigue over an 8-h workday or expose female workers to an increased risk of shoulder MSDs. It is interesting to note from Table 2 that the limit of 3.5 for the mean RPE is more restrictive than the limits of 3.5 and 2.5 for the mean ratings of fatigue and pain, respectively. However, there is consistency among the three ratings in identifying acceptable and unacceptable exposure levels. For example, all three ratings indicate that using a hand-tool with a 1.81 kg weight ( $W_2 = 1.81$  kg) in the 90/120 and 120/150 postures would produce high stress, fatigue and pain in the shoulder girdle (Table 2). All three ratings show that a hand-tool weight of 0.45 kg in all three postures and for all combinations of workpiece weight ( $W_1$ ) and arm up times and arm down times ( $T_3$ ) does not exceed acceptable

exposure levels. The average RPE show that the combination of  $W_2 = 0.91$  kg and  $T_3 = 2-2$  in the 120/150 posture would be unacceptable. Neither the fatigue nor the pain ratings support this. It should also be noted that the weight of the workpiece ( $W_1$ ) had only small effects in determining the acceptable and unacceptable workloads.

#### 4.2. Effect of weight of workpiece ( $W_1$ ) on subjective ratings

Figs. 2–4 show the effect of workpiece weight ( $W_1$ ) on the RPE, fatigue and pain, respectively, in the shoulder girdle. As expected, the average ratings were higher for the 2.73 kg weight than those for the 1.36 kg weight (Figs. 2–4). However, the differences in RPE, fatigue and pain for the two weights are fairly small (Figs. 2–4). On the other hand, a hand-tool weight ( $W_2$ ) of 1.82 kg always exceeded the acceptable level for ratings of perceived exertion irrespective of whether the weight of the workpiece ( $W_1$ ) was 1.36 kg or 2.73 kg (Fig. 2). However, when  $W_1$  was increased from 1.36 to 2.73 kg, a 0.91 kg handtool weight ( $W_2$ ) exceeded the acceptable level for RPE in the 90/120 and the 120/150 postures (Fig. 2). Fatigue ratings followed almost the same trend as the RPE (Fig. 3). However, in general, the fatigue ratings were slightly lower than the RPE (Figs. 2 and 3). Pain ratings were the lowest and followed the same trend as RPE and fatigue (Fig. 4). Pain ratings were the highest for the hand-tool weight of 1.82 kg, particularly when the workpiece weight was 2.73 kg (Fig. 4).

#### 4.3. Effect of hand tool weight ( $W_2$ ) and posture on subjective ratings

Figs. 2–4 also show the effects of hand-tool weight,  $W_2$ , and overhead posture on RPE, fatigue and pain in the

shoulder girdle. All three ratings increased with an increase in the weight of the hand-tool. Increasing the hand-tool weight ( $W_2$ ) from 0.91 to 1.82 kg had much greater effects on all three ratings than increasing the weight from 0.45 to 0.91 kg. In particular, the hand-tool weight of 1.82 kg in the 90/120 and 120/150 postures resulted in substantial increases in the RPE, fatigue and pain (Figs. 2–4).

The 90/120 and the 120/150 postures were much more stressful, fatiguing and painful than the 60/90 posture (Figs. 2–4). In general, the perceived exertion, fatigue and pain ratings for the 90/120 and 120/150 postures were about the same (Figs. 2–4) and the differences in the ratings between the two postures were not statistically significant ( $p > 0.05$ ).

#### 4.4. Effect of arm up times and arm down times on subjective ratings

Figs. 5–7 show the effects of the arm up time and arm down time combinations on RPE, fatigue and pain in the shoulder girdle. On the average, quick motions involving the arm up for 2 s (including the time it took to raise the weight to the specified posture, usually less than a second) and arm down for 2 s (including the time it took to lower the weight to right side, usually less than a second) were the most stressful, fatiguing and painful to the shoulder girdle when compared to the other two arm up time and down time combinations (Figs. 5–7). The 2–2 combination was found to be more stressful, fatiguing and painful than the 5–3 combination, even though the latter required more static exertion. Among the three combinations studied, the combination of keeping the arm up for 3 s and down for 3 s was the least stressful, fatiguing and painful (Figs. 5–7). This indicates that at least 3 s of rest (including the time it

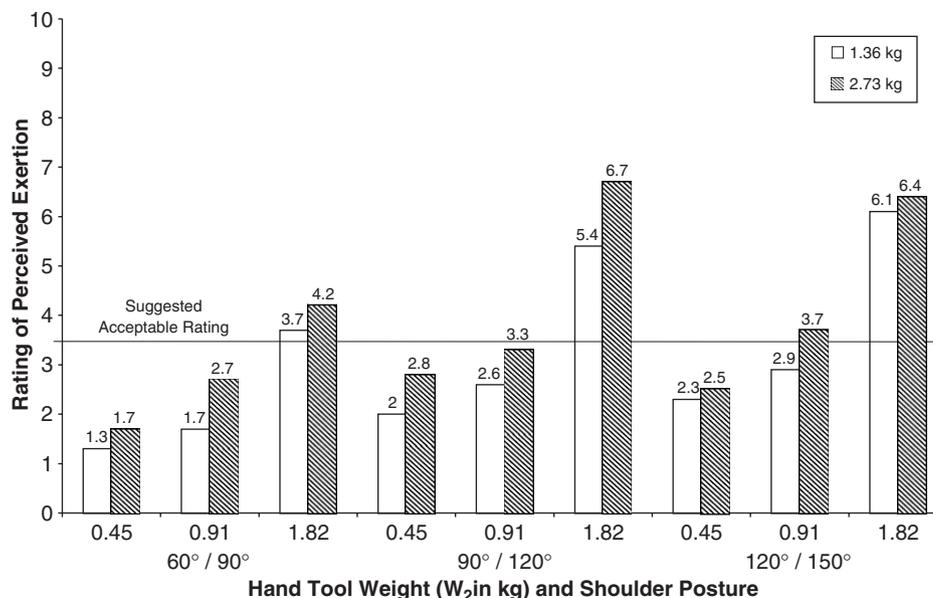


Fig. 2. Effects of workpiece weight ( $W_1$ ), hand-tool weight ( $W_2$ ) and overhead posture on rating of perceived exertion (the ratings are averaged for the three combinations of arm up and down times).

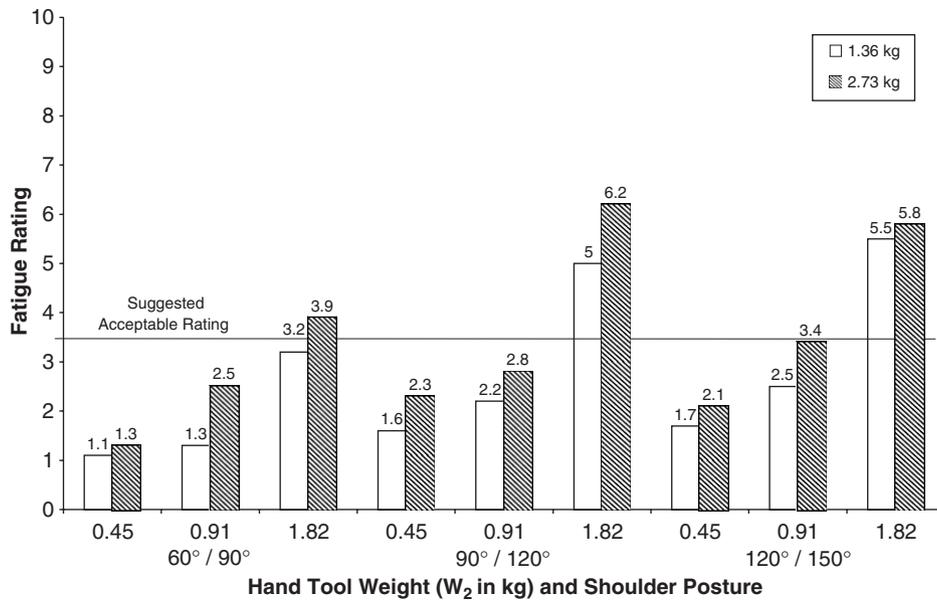


Fig. 3. Effects of workpiece weight ( $W_1$ ), hand-tool weight ( $W_2$ ) and overhead posture on fatigue rating (the ratings are averaged for the three combinations of arm up and down times).

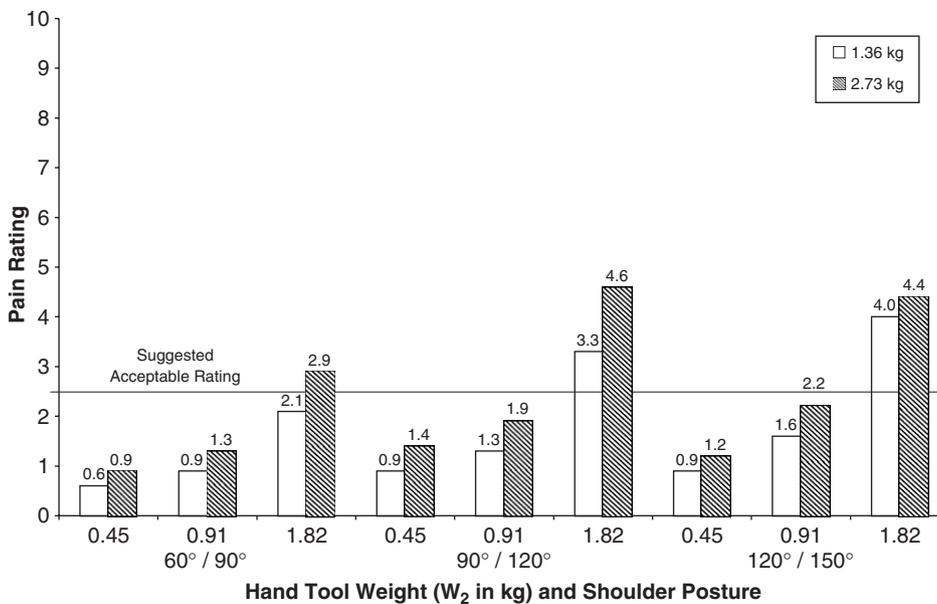


Fig. 4. Effects of workpiece weight ( $W_1$ ), hand-tool weight ( $W_2$ ) and overhead posture on pain rating (the ratings are averaged for the three combinations of arm up and down times).

takes to bring the arm down) should be provided each time the arm is brought down during repetitive cycling.

#### 4.5. Percent capable females

Subjective ratings of perceived exertion, fatigue and pain at the end of 50 min (or the final ratings if the experiments were terminated earlier) were analyzed for each subject, posture, weights  $W_1$  and  $W_2$ , arm up time and arm down time ( $T_3$ ). If the *individual subject's rating* of perceived

exertion was  $\leq 4$ , corresponding to “somewhat hard”, it was assumed that the subject could perform the overhead work without adverse health effects and was classified as capable of performing the given task. If the rating of perceived exertion was  $> 4$ , it was assumed that the subject could not perform the given overhead work without adverse health effects. The assumed “safe” level of  $\leq 4$  is based on past research (Garg and Saxena, 1982; Garg, 1983; Garg and Badger, 1986; Garg and Banaag, 1988; Garg, 1989; Garg et al., 1999; Garg and Hegmann, 2003).

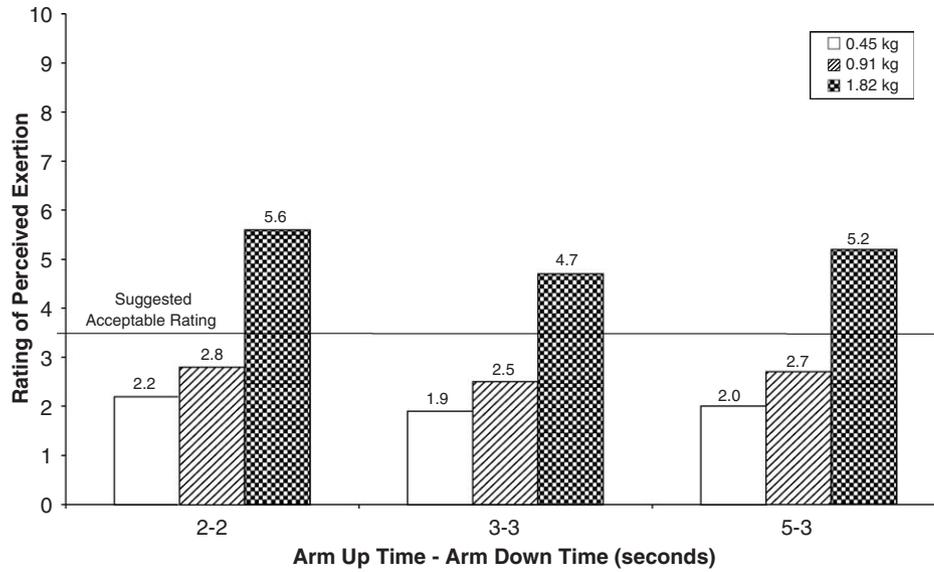


Fig. 5. Effects of arm up and down times on rating of perceived exertion. Data are averaged over the two weights of workpiece and the three overhead postures.

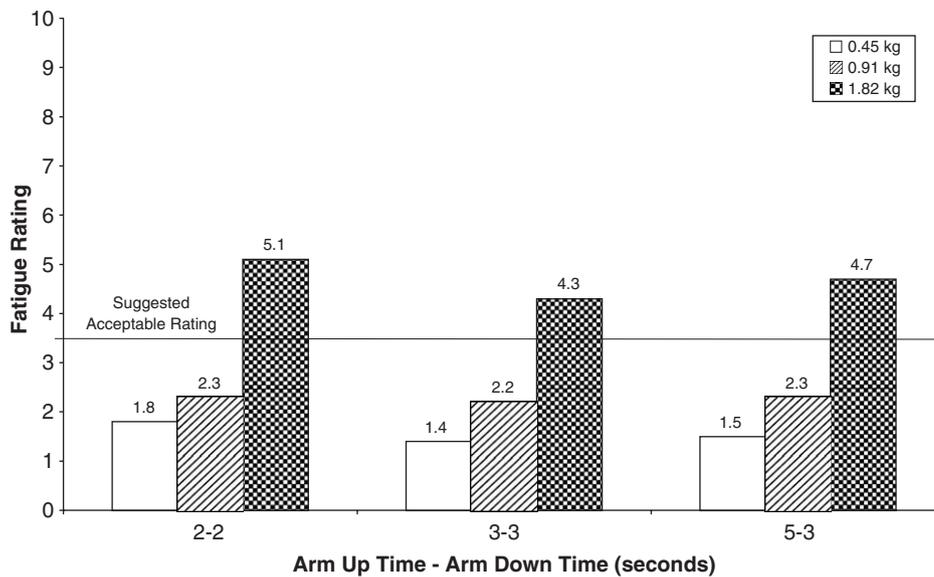


Fig. 6. Effects of arm up and down times on fatigue rating. Data are averaged over the two weights of workpiece and the three overhead postures.

It is recognized that it is not supported by any epidemiological studies of shoulder disorders. The number of subjects with the final perceived exertion ratings of  $\leq 4$  was divided by the total number of subjects who participated for a given combination of weights  $W_1$  and  $W_2$ , posture and time ( $T_3$ ). The above ratio was multiplied by 100 to obtain a percentage of females capable of performing the task. The same procedure was repeated using the fatigue and pain ratings, except the qualification for percent capable of performing a task was set at  $\leq 4$  for the fatigue rating and  $\leq 3$  for the pain rating.

The ratings from *individual subjects* used to determine the percent capable females are higher by 0.5 as compared

to the mean ratings used earlier to determine the acceptable tasks. There are two reasons for applying higher rating limits on individual subjects. First, all the subjects gave ratings as whole numbers rather than as fractions. For example, if a subject felt an exertion level of more than 3 but less than 4, she most likely gave a rating of 4 (personal communications with subjects). Thus, a rating limit of 3 on individual subjects would result in significantly lower allowable exposure levels as compared to a mean rating of 3.5. Secondly, several studies have shown that when given control over work pace or workload, different subjects like to work at different RPE, ranging from “very light” to “hard” on the Borg CR-10 scale (Garg and

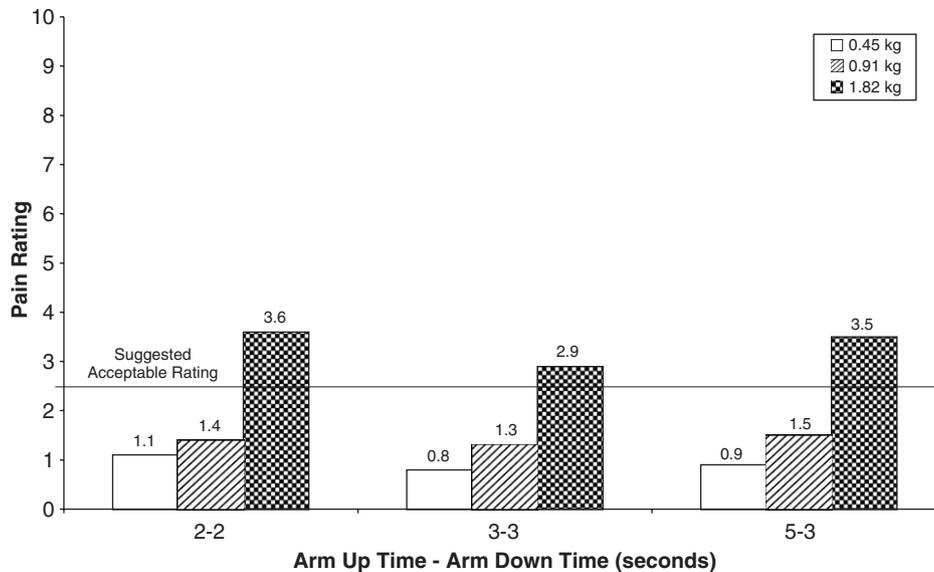


Fig. 7. Effects of arm up and down times on pain rating. Data are averaged over the two weights of workpiece and the three overhead postures.

Saxena, 1982; Garg, 1983; Garg and Badger, 1986; Garg and Banaag, 1988; Garg, 1989; Garg et al., 1999; Garg and Hegmann, 2003).

The percent capable females based on the RPE  $\leq 4$ , fatigue ratings  $\leq 4$ , and pain ratings  $\leq 3$  are given in Table 4. It is believed that the percentages of females listed in Table 4 can perform the various overhead tasks without excessive stress, fatigue or pain in the shoulder girdle. In general, practically all females can perform the overhead tasks studied if the weight of the hand-tool is 0.45 kg. On the other hand, 50% or fewer females can perform the overhead work in the 90/120 and 120/150 postures if the weight of the hand-tool is 1.82 kg.

In ergonomics, it is generally accepted that manual materials handling jobs should be designed so that they are within the physical capabilities of at least 75% of the workers. The higher the percentage of workers capable of performing the work, the lower are the reported incidence and severity rates (Snook et al., 1978; Herrin et al., 1986). For example, Snook et al. (1978) reported that a worker was 3 times more susceptible to low back injury if performing a job that less than 75% of the population could perform without overexertion.

#### 4.6. Surface EMG

In retrospect it may have been more appropriate to study the anterior deltoid than the mid-deltoid. The overhead tasks studied were dynamic in nature and the electromyographic signal may not have stabilized during the recording for 2, 3 and 5 s including the time it took to lift the weights, usually 1 s. Small changes in the subject's posture might have transferred the load to some other shoulder girdle muscles (infraspinatus, supraspinatus, anterior deltoid or lower trapezius). In this regard, Palmerud et al. (1995) have

shown that subjects have an ability to reduce EMG activity voluntarily in the trapezius muscle and increase EMG activity in other shoulder muscles, particularly the infraspinatus, without changing the load in the hand. This study was potentially susceptible to this influence, as we did not fix the horizontal location, as workers are not so similarly constrained to accomplish a job. Other possible problems may include small movement of electrodes during the 50-min exertion and rise in muscle temperature. In retrospect, it may have been appropriate to collect surface EMG signals under static conditions by asking the subjects to hold loads in a specific posture at different times during the experiment.

Oberg et al. (1994) reported a significant correlation between the MPF and the psychophysical rating at high load levels ( $r = -0.46$ ), but at low load levels the MPF did not change, resulting in no correlation. This study found that the MPF did not seem to work as a valid estimator of shoulder muscle fatigue at low load levels. Similar conclusions were drawn by Wiker et al. (1989). Malmquist et al. (1981) studied EMG from four different shoulder muscles (anterior deltoid, mid-deltoid, trapezius and supraspinatus) using wire electrodes. The building tasks believed to be strenuous by the workers included nailing, screwing boards, drilling and hand plastering. The mean values of frequency (Hz) at spectral maximum for fatigue incidence during 1-h recordings decreased by 2–12%. None of these decreases were found to be significant ( $p > 0.05$ ). Similarly, Hagberg (1981a) reported no correlation between workload in repetitive arm elevations and EMG of the deltoid. Sigholm et al. (1984) reported that hand-load dependency of the three parts of the deltoid was found to be low.

It is clear from the EMG literature that the rotator cuff muscles, particularly the supraspinatus and infraspinatus,

Table 4

Percentage of females (%) capable of completing various combinations of weight, posture and time sequencing based on ratings of perceived exertion, fatigue and pain

Rating Scale	Weight (kg)		Percent capable for Posture <sup>a</sup> and Time Sequence <sup>b</sup>								
	W1	W2	60/90			90/120			120/150		
			2–2	3–3	5–3	2–2	3–3	5–3	2–2	3–3	5–3
Perceived Exertion	1.36	0.45	100%	100%	88%	100%	100%	88%	88%	90%	100%
	1.36	0.91	100%	100%	100%	100%	100%	89%	67%	89%	100%
	1.36	1.82	67%	78%	70%	<b>25%</b>	<b>33%</b>	<b>38%</b>	<b>33%</b>	<b>44%</b>	<b>38%</b>
	2.73	0.45	100%	100%	100%	90%	88%	100%	80%	100%	88%
	2.73	0.91	100%	67%	89%	67%	67%	89%	56%	56%	75%
	2.73	1.82	56%	78%	56%	<b>25%</b>	<b>43%</b>	<b>38%</b>	<b>22%</b>	<b>33%</b>	<b>50%</b>
Fatigue	1.36	0.45	100%	100%	100%	100%	100%	88%	100%	90%	100%
	1.36	0.91	100%	100%	100%	100%	100%	89%	67%	89%	100%
	1.36	1.82	78%	89%	80%	<b>38%</b>	<b>44%</b>	<b>50%</b>	<b>33%</b>	<b>44%</b>	<b>50%</b>
	2.73	0.45	100%	100%	100%	90%	88%	100%	90%	100%	88%
	2.73	0.91	100%	67%	89%	67%	78%	100%	67%	56%	88%
	2.73	1.82	67%	89%	56%	<b>25%</b>	57%	<b>38%</b>	<b>33%</b>	<b>44%</b>	63%
Pain	1.36	0.45	100%	100%	88%	100%	100%	88%	100%	90%	100%
	1.36	0.91	100%	100%	100%	88%	100%	89%	67%	89%	100%
	1.36	1.82	67%	89%	70%	63%	56%	63%	<b>44%</b>	56%	<b>50%</b>
	2.73	0.45	100%	100%	90%	90%	88%	100%	70%	100%	88%
	2.73	0.91	100%	78%	89%	78%	78%	78%	78%	56%	75%
	2.73	1.82	56%	67%	<b>33%</b>	<b>38%</b>	57%	<b>50%</b>	<b>44%</b>	<b>33%</b>	<b>50%</b>

#### Notes:

Percent capable based on:

- Borg CR–10 rating  $\leq 4$
- Fatigue rating  $\leq 4$
- Pain rating  $\leq 4$
- Bold italic numbers correspond to % capable  $\leq 50\%$ .

<sup>a</sup>Posture: shoulder flexion/elbow included angle.

<sup>b</sup>Time sequence: arm up time (seconds)—arm down time (seconds).

appear to be significantly affected by overhead work. However, with the exception of a few studies (for example Sporrang and Styf, 1999), most studies have used intramuscular electrodes to study muscle load in these muscles. Unfortunately, due to the Institutional Review Board for the Protection of Human Subjects' concerns at our institution, it was not possible to use IMP. EMG and IMP studies have clearly shown that the local load in the supraspinatus and infraspinatus muscles increases both with an increase in shoulder flexion and abduction angles up to 90° and then there is a decrease in these variables with further shoulder flexion or abduction of greater than 90°. However, epidemiological studies have reported arm elevations greater than 90° to be an associated factor, though not necessarily statistically significant (Punnett et al., 2000; Harkness et al., 2003; Svendsen et al., 2004; Fredriksson et al., 2005). Similarly, results from epidemiological studies on weight in hands are inconsistent with biomechanical findings (NIOSH, 1997; Harkness et al., 2003; Svendsen et al., 2005).

## 5. Conclusions

1. This phase of the research simulated short-cycle overhead work tasks. The response variables included: surface electromyographic signals from the mid-deltoid/upper trapezius muscles, ratings of perceived exertion, fatigue ratings and ratings of pain in the shoulder girdle.
2. A few subjects were unable to finish the 50 min duration of the experiments in the 90/120 and 120/150 overhead postures for the combinations of work-piece weight = 2.73 kg, hand-tool weight = 1.82 kg, arm up time = 2 s and arm down time = 2 s due to the development of fatigue and/or under stress.
3. Analysis of the median power frequency did not show fatigue either in the trapezius or the deltoid muscles for most of the tasks studied.
4. The subjective ratings of perceived exertion, fatigue and pain were higher with the 2.73 kg workpiece weight than with the 1.36 kg workpiece weight. However, the

differences in the subjective ratings for the two weights were relatively small in comparison to the other task variables.

5. The weight of the hand-tool had a profound effect on the subjective ratings. A weight of 1.82 resulted in significantly higher perceived exertion, fatigue and pain ratings. This effect appears greater than the effect of posture, although the results suggest some reduction in MSDs may be expected if postural issues are able to be addressed in the design of the work.
6. All three subjective ratings were significantly higher for the 90/120 and 120/150 overhead postures than for the 60/90 posture. There were no significant differences between the 90/120 and 120/150 postures.
7. The arm up time and arm down time combination of 2–2 s was the most stressful, fatiguing and painful, followed by 5–3, and the 3–3 combination was the least stressful, fatiguing and painful.
8. Most subjects believed that they could perform the overhead work for 8 h with the hand-tool weight of 0.45 kg. They believed that they could not last for more than 2 h in the 90/120 and 120/150 postures for the combination of arm up time and down time of = 2–2 s, workpiece weight = 2.73 kg, and hand-tool weight = 0.91 kg.
9. The overhead tasks (combinations of workpiece weight, hand-tool weight, shoulder posture, and arm up time and arm down time) are identified that most females can perform for 8 h without excessive perceived stress, fatigue or pain in the shoulder girdle. These recommendations are based on the mean perceived exertion rating  $\leq 3.5$ , mean fatigue rating  $\leq 3.5$  and mean pain rating  $\leq 2.5$ .
10. The percentage of females that are capable of performing the overhead tasks for 8 h without excessive perceived stress, fatigue or pain in the shoulder girdle are provided. These percentages are determined using individual subject's perceived exertion rating  $\leq 4$ , fatigue rating  $\leq 4$  and pain rating  $\leq 3$ .

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