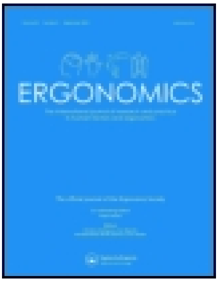

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The effect of overhead drilling position on shoulder moment and electromyography

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Keywords: Adult; human; biomechanics; working posture; arm elevation; occupational disorders; shoulder joint; myoelectric amplitude; myoelectric power spectrum.

The effect of overhead drilling tasks on electromyographic (EMG) activity and shoulder joint moment was examined in this study. Twenty subjects simulated an overhead drilling task using a close, middle and far reach position while standing on either a lower or a higher step of a stepladder. Root mean square amplitude (AMP) of EMG activity from the dominant side anterior deltoid, biceps brachii and triceps brachii muscles was used to determine muscular load. Digital video was used to determine shoulder joint moment using 2-dimensional static link segment modelling in the sagittal plane. The results demonstrated that, compared to the far reach position, using the close reach position significantly decreased anterior deltoid AMP and biceps brachii AMP and moment, but increased triceps brachii AMP. Compared to the lower step, using the higher step significantly decreased anterior deltoid AMP and triceps AMP and moment, while increasing biceps AMP in the close position. There was no significant change noted in EMG median frequency indicating that fatigue was minimized. Moment increased monotonically with AMP. The findings indicated that workers performing overhead tasks should work close to their body in order to minimize shoulder forces. The implications of this recommendation are discussed.

1. Introduction

Work-related musculoskeletal disorders of the shoulder are common in the construction and manufacturing trades. The prevalence of disorders such as shoulder tendonitis have been reported to be as high as 30 – 40% (Olson 1987, Holmström *et al.* 1992). Herberts *et al.* (1981) estimated an 18% prevalence for

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supraspinatus tendonitis in shipyard welders and an overall incidence rate of 15–20% for the welder population. Rosecrance *et al.* (1996) reported that 41% of a sample of construction workers in the pipe trades complained of work-related shoulder pain, with tasks performed in differing postures including directly overhead.

Construction workers often encounter work situations that require overhead hand positions while using tools. For example, sheet metal workers must manipulate drills or pliers with their hands extended overhead while hanging ducts. Work in overhead positions is potentially harmful to the structures of the shoulder girdle. Mechanical impingement of the bicipital and supraspinatus tendons in the subacromial region may occur, especially if shoulder elevation is in the 60 to 120° range or at the end range of motion (Flatow *et al.* 1994). Since the tendons in these regions have atypical vascularity (Lohr and Uhthoff 1990, Swiontkowski *et al.* 1990), repetitive shoulder motion in these ranges may lead to tendonitis or rupture.

Epidemiologic evidence also suggests that work in posture greater than 60° elevation is associated with disorders of the shoulder (Hagberg and Wegman 1987). Bjelle *et al.* (1981) reported that work with the hands above shoulder level increased workload and could lead to the development of shoulder disorders. Sakakibara *et al.* (1995) found that orchard workers who repetitively reached overhead had more complaints of shoulder stiffness and muscular tenderness than workers who used their shoulders at lesser angles. A dose-response relationship has been implied with overhead work and work-related musculoskeletal disorders of the shoulder or neck (Olson 1987, Holmström *et al.* 1992). Laboratory studies have shown that the greater the angle of shoulder elevation the higher the load on shoulder musculature (Jonsson and Hagberg 1974, Sigholm *et al.* 1984, Giroux and Lamontagne 1992, Sporrong and Styf 1999). However, there are few studies that have examined the effect of overhead work positions on shoulder load (Wiker *et al.* 1989, Haslegrave *et al.* 1997), and little is known about the changes in shoulder load with varied overhead arm positions.

Avoidance of overhead postures is usually not practical for sheet metal workers or others in construction trades. While performing overhead tasks on a ladder, many workers use an extended reach, which may precipitate a fall. In order to reduce the risk of injury, ergonomists often recommend that workers move closer to the task by repositioning the ladder. This solution has the apparent added benefit of reducing the shoulder load. However, there is no objective evidence that positioning closer to an overhead task reduces shoulder stress. Therefore, the purpose of this study was to determine the effect of moving closer to overhead work while performing simulated drilling tasks on a ladder. Various horizontal and vertical reach distances to the work surface were used in this study to determine the effect of these positions on shoulder electromyography (EMG) and joint moment.

2. Material and methods

2.1. *Subjects*

Twenty healthy volunteers, twelve males and eight females, participated in the study. The subjects had a mean age of 31 years (SD = 8.1 years; range = 22–44 years), mean height of 173 cm (SD = 11.7 cm), mean weight of 76 Kg (SD = 15.5 kg), and all were right-handed. None of the subjects had a previous history of shoulder pathology in the right arm, arthritic disorders, or experience in the construction trades. All subjects were thoroughly informed of the experimental procedure and gave consent prior to participation. The Institutional Review Board at the University of Iowa approved this study.

2.2. *Experimental apparatus*
A 2.27 kg portable drill (DeWalt 3/8" VSR Cordless DW991, Hampstead, MD, USA) was fitted with a steel rod bit 6 cm long and 0.95 cm in diameter. The bit had a plate washer firmly attached to the chuck and a spring overlay. The oval-shaped drill handle had a circumference of 14.5 cm (4.8 cm front to back, 3.7 cm wide), was hard plastic near the trigger, and had a rubber anti-slip grip on the section that fitted in the palm. A battery pack was attached to the bottom of the handle, which balanced the drill in the palm when positioned vertically.

All simulated overhead drilling trials were performed on an overhead work apparatus consisting of a vertical upright beam, and a level, horizontal beam that was incrementally adjustable up or down according to the subject's reach. A 104 cm long board was placed under the horizontal beam of the apparatus. Three vertical holes spaced 25 cm apart were drilled in the board prior to the experiment, which determined fixed horizontal reach distances of close, middle, or far. Fixed horizontal distances were chosen since workers performing overhead tasks often do not determine where, for instance, a hole must be drilled. To simulate overhead drilling, the drill bit, attached to the drill, was placed in one of the three holes of the horizontal board, and by pressing upwards the spring on the drill bit was compressed (figure 1). A thick place washer was fixed to the bottom of each hole to ensure vertical alignment of the drill bit. At each hole, a battery-operated light switch was rigged to close upon contact from the plate washer on the drill bit to verify proper

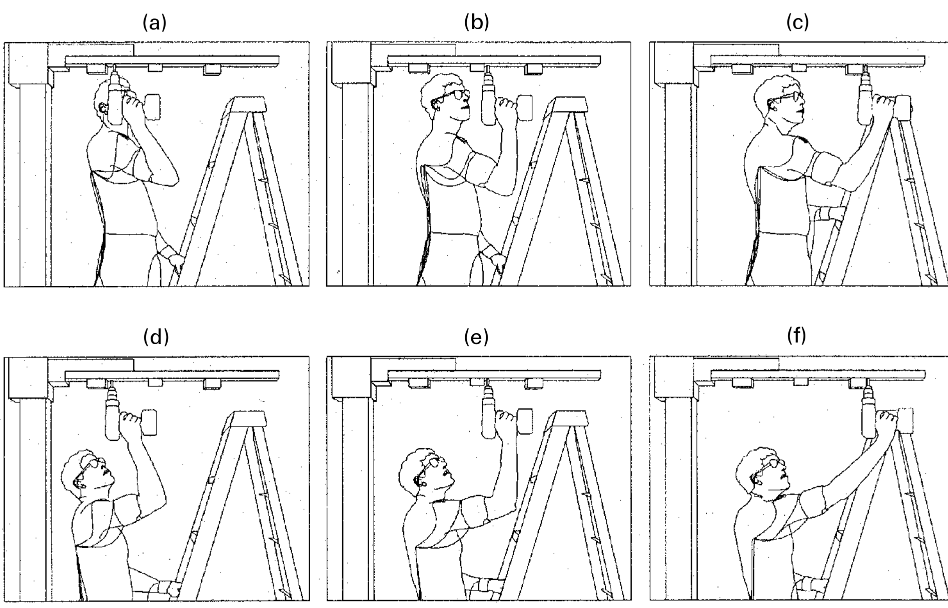

Figure 1. Posture of the overhead drilling task using a close, middle and far reach position while standing on the lower and higher step of a stepladder. (a) Close reach, high step; (b) Middle reach, high step; (c) Far reach, high step; (d) Close reach, low step; (e) Middle reach, low step; (f) Far reach, low step.

spring compression. The compression force necessary to trigger the switch was 22.3 N.

A 2.4 m long, type IA step ladder (136 kg load capacity, Werner 6208, Greenville, PA, USA) was positioned under the horizontal beam so that the lowest step was directly below the closest hole. The first step was approximately 29 cm from the floor and the second step was 57 cm from the floor. Each of the steps were 7.6 cm deep and had a serrated aluminium tread to reduce slippage. The lowest step was 57 cm wide with the second step was 53 cm wide. Thus, the sides of the ladder were not parallel. In order to ensure that all subjects were positioned similarly with respect to their height and the height of the overhead board, subjects stood on the lowest step, and the horizontal overhead board was positioned so that the subject could just reach a marker on the farthest hole with the head of their fifth metacarpal, while the arm was extended and maintaining an upright posture. The horizontal board was then kept in the same position for the respective subject's trials. Subjects were instructed to minimize trunk rotation during the experimental trials. The right arm of each subject served as the test arm.

2.3. *Electromyography*

Myoelectric activity of the right biceps brachii, triceps brachii, and anterior deltoid muscles was recorded using bipolar silver-silver chloride surface electrodes with on-site preamplification (Therapeutics Unlimited, Iowa City, IA, USA). The anterior deltoid muscle was sampled because it is a prime flexor of the shoulder (Kadefors *et al.* 1976) and is known to contract synchronously with the supraspinatus during this motion (Perry 1988). The biceps brachii is a humeral head stabilizer during overhead postures and auxiliary shoulder flexor (Perry 1988, Rodosky *et al.* 1994). Additionally, the bicipital tendon is commonly affected by impingement (Neer 1990). The triceps brachii muscle allows a comparison of antagonistic muscle actions during overhead work.

Before affixing electrodes, the skin was cleansed with alcohol. Positioning of the electrodes was based on a method suggested by Soderberg (1992). The electrodes were connected to a differential amplifier/processor module (EMG-67) with a bandwidth of 40 Hz to 4 kHz (two-pole Butterworth filter). The gain was adjusted to between 500 and 10 000 to prevent saturation of the signal during a maximal voluntary contraction (MVC) and was unchanged for each subject for the duration of their trials. The raw EMG signal was sampled at a rate of 1024 Hz for 2 s. The root mean square amplitude (AMP), with an averaging time constant of 50 ms, and median frequency from spectral analysis were calculated using a microcomputer data collection system. Normalization of AMP was the electrical activity from a reference voluntary contraction obtained when subjects stood on the lower step and pressed the drill bit upward into the closest hole position (% Reference Voluntary Exertion (RVE)). These contractions were performed before and after the experimental trials and the mean of these two tests was taken as the normalization factor.

2.4. *Biomechanical analysis*

A static, co-planar, link segment analysis of the shoulder, elbow and wrist joints in the sagittal plane was performed by examining single frames of digital video. Reflective tape markers were placed on the subject's right lateral acromion, lateral epicondyle, dorsal aspect of the lunate and distal aspect of the dorsal third metacarpal of the right arm. Anthropometric measurements of the subjects' upper arm, forearm and wrist/hand segment were taken. The mass of these segments, as well as the location of the centre of mass, were determined using anthropometric data from normative tables (Dempster 1990). A digital video camera (Sony DCR-VX1000, Sony Corporation, Tokyo, Japan) was positioned at 2 m lateral to the overhead apparatus to view all the markers simultaneously orthogonal to the sagittal plane of the subject's shoulder. The camera position and field of view were kept constant for all subjects. Shoulder flexion moments were calculated from measurements taken on a single still video frame of the third second, during each 4 s experimental trial.

2.5. *Experimental procedure*

An experimental trial consisted of a subject simulating overhead drilling into one of the three holes that defined reach positions, while standing on either the first or second step of the ladder (figure 1). Each subject was allowed to practise holding the drill at all reach and step positions prior to the trials, and was given a 2 min rest period before the trials. The order of the step and reach position trials was randomized for each subject.

During a trial, the subjects stood on one of the two steps in an upright posture with knees extended, and grasped the ladder with the left hand keeping the left elbow tucked against their side. Subjects stood on the ladder in a self-selected, comfortable position, but were not allowed to brace their feet against the rails of the step ladder. In order to avoid fatigue effects, an investigator positioned the drill so that the bit entered one of the randomly chosen holes in the horizontal overhead board. Subjects then grasped the drill handle with their right hand and pressed upward until the pre-set spring tension was achieved. Subjects maintained this position for 4 s with EMG sampled during the middle two seconds. The subjects followed the same procedure for all six combinations of a reach-step trial, and subjects were given a 2 min rest after each trial. Subjects then repeated the entire process a second time. While standing on the ladder, the subject's right acromion was under the horizontal overhead board. Thus, each simulated drilling trial was performed in the sagittal plane of the shoulder.

2.6. *Statistical analysis*

Paired *t*-tests were used to test for differences between the first and last median frequency during the normalization trials. The primary statistical analysis was a 2-factor repeated measures analysis of variance to test for significant changes in AMP and moment due to reach (horizontal) and ladder step (vertical) position variables. Both repetitions for each of the six reach-step combinations were entered into the repeated measures analysis; the values were not averaged. Follow-up pairwise comparisons were performed using Tukey's test. A random coefficients model was used to determine the relationship between moment and AMP (PROC MIXED, SAS Institute, Cary, NC, USA). An α level of 0.05 was used as the significance level of all analyses.

3. Results

3.1. *Fatigue and main effects*

There was no significant difference noted between the first and the last median frequency values (table 1), suggesting that fatigue was not a factor in this study. Figure 2 displays the mean values of AMP and moment for each reach position on the two steps. Since the interaction between reach position and step was found to be

Table 1. Pretest to post-test median frequency (Hz).

	N	Mean difference	Standard error	t statistic	p
Anterior deltoid	20	−0.28	1.39	−0.20	0.8448
Biceps brachii	20	1.89	2.03	0.93	0.3636
Triceps brachii	20	−0.78	1.19	−0.65	0.5223

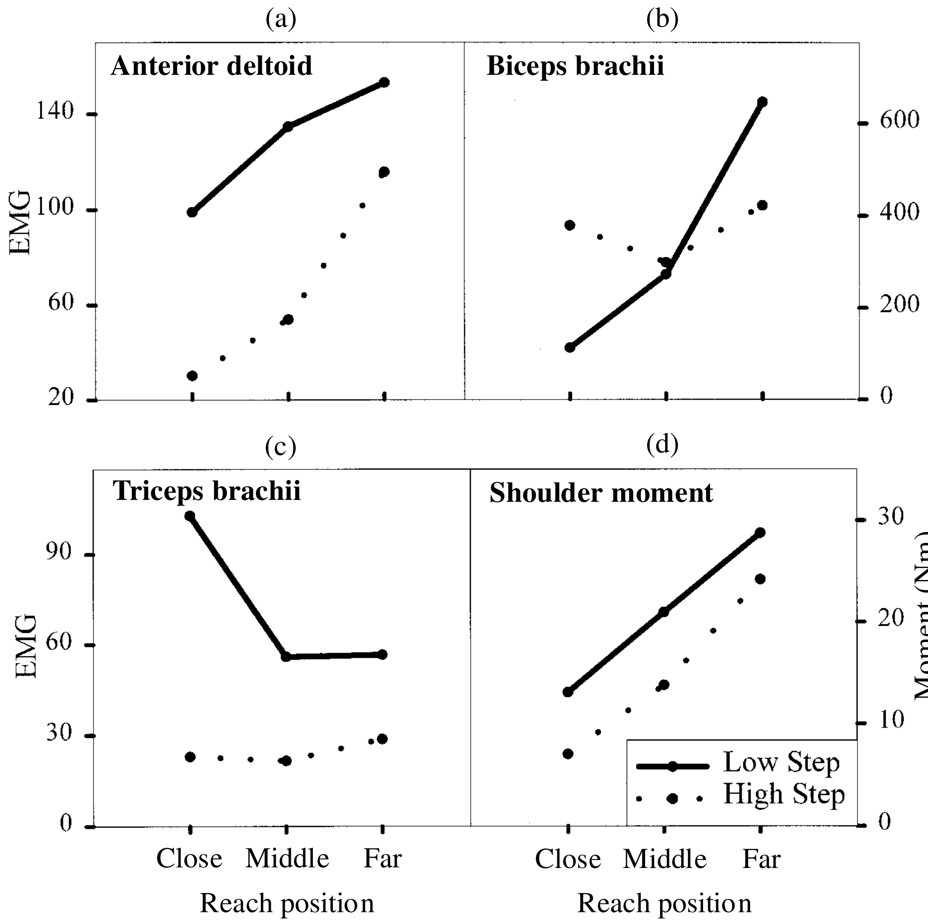

Figure 2. Mean RMS amplitudes of EMG and shoulder joint moment by reach position and step height (EMG = percentage normalized EMG). (a) Anterior deltoid; (b) Biceps brachii; (c) Triceps brachii; (d) Shoulder moment.

significant for all AMPs and for moment ($p < 0.001$), the simple effects of reach position and step were evaluated separately.

3.2. *Effect of reach position*

In regard to the effect of reach position, the anterior deltoid muscle AMP and shoulder joint moment presented an overall significant trend of increasing values with a farther reach as opposed to a closer one ($p<0.001$; figure 2). All pairwise comparisons for the deltoid AMP and moment were significant except for the deltoid AMP middle reach and far reach on the lower step (table 2). A similar trend of increasing values with a farther reach was seen with the biceps brachii AMP on the lower step ($p<0.001$) and the triceps brachii AMP on the higher step ($p = 0.009$). However, the only significantly different pairwise comparisons were the far reaches from the middle or close reach positions. In contrast, triceps AMP was significantly higher in the close reach position on the lower step compared to the middle or far reach positions. For the biceps, the only significant pairwise comparison on the higher step was between the far and the middle reach position.

3.3. *Effect of step*

In regard to the simple effect of step, moving up a step had the effect of significantly reducing deltoid AMP, triceps AMP, and moment at all reach positions ($p<0.001$), as well as reducing biceps AMP at the far position ($p<0.001$). In contrast, biceps AMP significantly increased in the close position ($p<0.001$) and did not change in the middle position by moving up a step. Mean coefficient of variation of EMG signal for the trials was 10.8% for the anterior deltoid, 21.7% for the biceps brachii, and 16.3% for the triceps brachii muscles.

3.4. *Moment-EMG relationship*

The slope for the relationship between moment and deltoid AMP was significantly different than zero ($p<0.0004$) as was the relationship between moment and biceps AMP ($p<0.0001$). Using the random coefficients model, the relationship between shoulder moment and deltoid AMP indicated that for every Nm of moment, AMP increased by approximately 5% (figure 3). Biceps AMP increased by 14% for every Nm of moment (figure 4). There was no consistent relationship noted between triceps AMP and moment.

4. Discussion

Fatigue was minimized during this study since all subjects were able to maintain the appropriate force on the spring during each trial. Additionally, there was no significant reduction in median frequency for the first to the last trial. As in this

Table 2. Mean RMS amplitudes (% normalized EMG) and shoulder joint moment (Nm) by reach position and step height.

		Close reach		Middle reach		Far reach	
	Step	Mean	SE	Mean	SE	Mean	SE
Anterior deltoid	High	30.18	2.41	53.88	2.98	115.77	3.89
	Low	98.91	3.17	134.73	4.85	153.11	8.14
Biceps brachii	High	379.07	12.61	298.96	30.96	422.31	44.10
	Low	112.98	49.82	272.90	21.91	645.82	65.07
Triceps brachii	High	22.93	2.11	21.55	1.64	28.71	2.11
	Low	102.67	4.41	55.92	3.19	56.64	4.19
Shoulder joint moment	High	7.03	0.42	13.78	0.408	24.18	0.554
	Low	13.07	0.493	20.95	0.583	28.74	0.612

SE = standard error.

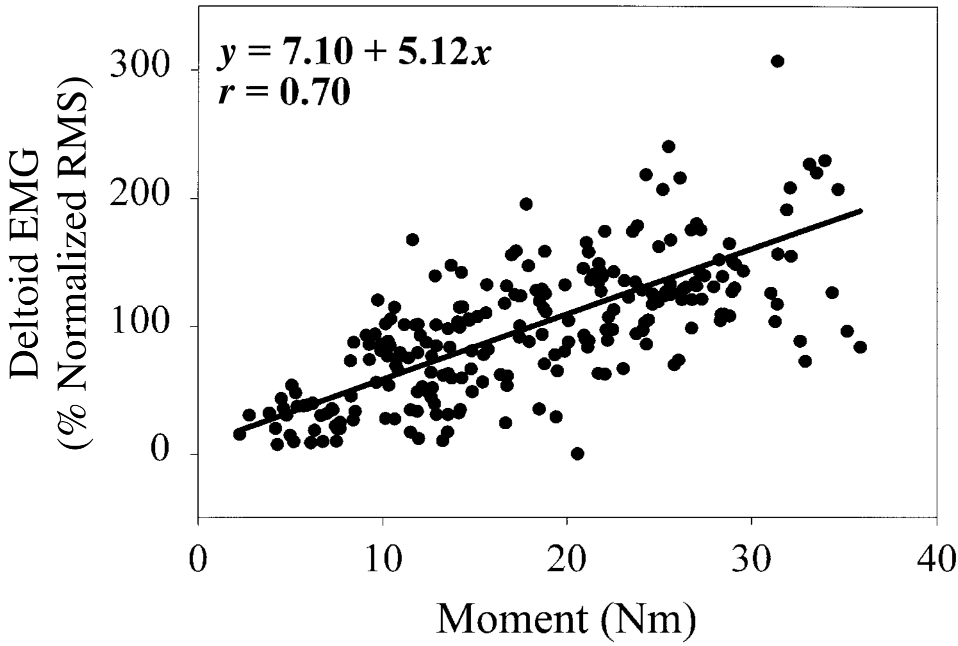

Figure 3. Relationship between the anterior deltoid percentage normalized RMS amplitude and shoulder joint moment. Solid regression line through the data points was determined using a randomized coefficients model.

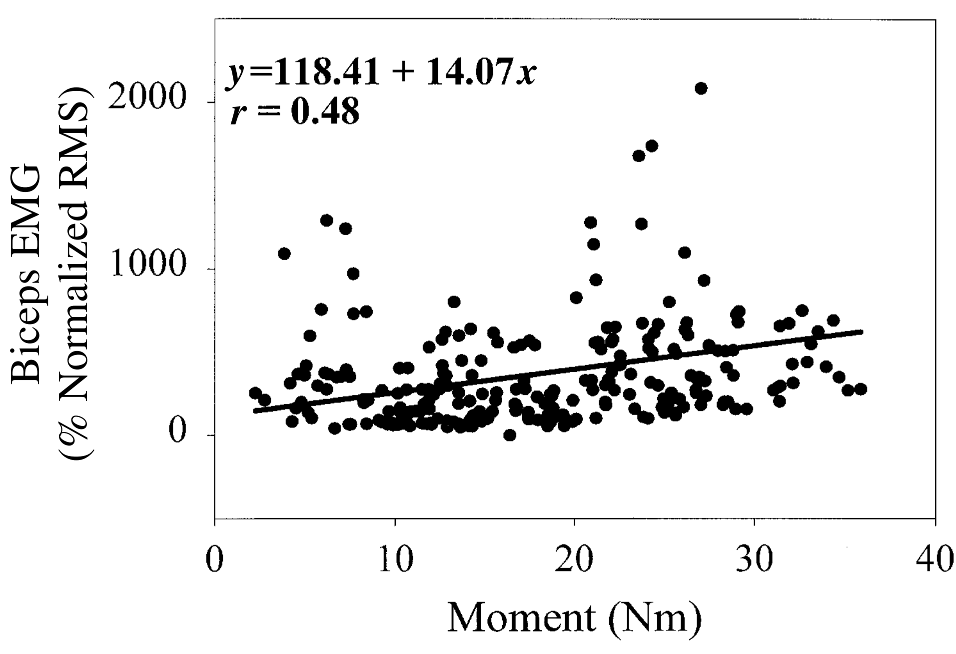

Figure 4. Relationship between the biceps brachii percentage normalized RMS amplitude and shoulder joint moment. Solid regression line through the data points was determined using a randomized coefficients model.

study, others have found no significant changes in median frequency with brief isometric contractions (Jørgensen *et al*. 1988).

4.1. *Effect of reach position*

The results of this study indicate that a closer reach may be more advantageous while performing overhead work (table 2). Although there are few studies on overhead work, the results support those noted by other investigators (Haslegrave *et al*. 1997), who determined that subjects performing a vertical overhead task were able to exert more force when in a close reach position than when reaching to the side. Similarly, the present study indicates that less EMG is required in the close reach position than in a far reach position. Although the methods employed in the present study differed from those used by Haslegrave *et al*. (1997), both studies suggest that working with the arm away from the body (far reach or out to the side) increases the potential for shoulder injury. Thus, if an overhead task requires the exertion of substantial force, a closer reach should be used.

On the lower step, shoulder joint moment increased by 120%, anterior deltoid AMP by 55% and biceps AMP by 472% if a far reach was used relative to the closest one. On the higher step, use of a far reach increased the shoulder joint moment by 244%, deltoid AMP by 283%, and triceps AMP by 25% compared to the closest position, but there was no consistent change in biceps AMP. This study reinforces the often used ergonomic recommendation of moving closer to the task. It is important to note that moving up a step is not preferable to reducing the horizontal reach distance, as evidenced by the greater changes on the higher step. Dramatic percentage changes such as these may be helpful for instructors to emphasize during ergonomic awareness training in order to motivate workers to move closer to the task.

Reduced deltoid and biceps AMP in the close position while on the lower step can be partially attributed to the decreased moment at the shoulder joint present with a decrease in reaching distance. Arborelius *et al*. (1986) reported similar findings during a task that required lifting a box off the ground and placing it on a table. The loading moment at the shoulder was reduced if the subject stepped forward towards the table during the lift. The authors emphasized the importance of limiting the horizontal distance when manipulating a load in front of the body. Increased moments have the potential for causing fatigue or acute strain. If it can be assumed that muscular fatigue is one aetiological factor in cumulative trauma disorders, minimizing the horizontal reach or using lighter tools may be one method of reducing these disorders. A backpack to hold the power tool batteries is one practical method of making tools lighter. Various tool supports have also been recommended (Wos *et al*. 1992).

4.2. *Effect of step*

Moving up a step on the ladder had the effect of reducing shoulder joint moment by 86% and deltoid AMP by 228% in the close position (table 2). The reduction was smaller in the far reach position while moving up a step. Biceps AMP decreased by 11% in the far reach position on the high step compared to the low one. However, biceps AMP increased by 70% when the subject moved up a step with a close reach. The length-tension relationship of the biceps suggests that there is less ability to generate tension at the extremes of elbow flexion, such as occurs at the close position. The constrained position of the upper arm may have required greater biceps myoelectric activity to maintain the drill in position. On the lower step, the biceps are in a better length-tension relation since the elbow is flexed to around 90°. Higher triceps AMP correlated with positions that required greater muscle activity to counteract a flexing moment at the elbow. Moving up a step while using a closer reach also decreased the shoulder flexion angle from an average of 77° to 17°. Since repeated shoulder elevation between 60° and 120° has the potential for creating impingement, it may be beneficial for workers to limit the use of their shoulder in these ranges (Flatow *et al.* 1994). Even though biceps AMP is greater on the higher step, it is likely that the shoulder flexion angle has a more important effect on bicipital tendonitis. Thus, moving closer to overhead work in a vertical direction may be a practical method of avoiding impingement syndromes.

A disadvantage of moving up a step is the increased potential for a fall from the ladder, which is a serious work-site problem. In Sweden, approximately 2% of all industrial accidents involve ladders, and in the USA ladders account for 20% of all construction-related disabling falls (Bureau of Labor Statistics 1994). Cohen and Lin (1991a) found that the highest percentage of ladder accidents occurred from overreaching. These authors noted that overreaching was often related to working in an awkward posture (Cohen and Lin 1991b). Although moving up a step on the ladder may reduce the reach and minimize physical requirements, the increased height of the worker's centre of gravity raises the potential that it will fall outside of the ladder's base of support. Reaching sideways on a higher step of a stepladder can also precariously shift the centre of gravity, and falls due to this activity are common in industrial settings (Björnstig and Johnsson 1992). Standing on the top rung of a ladder was found to be another factor in causing falls, often because the ladder was not high enough thus causing an excessive reach. Since falls from ladders account for a significant amount of lost work-time in the construction trades, it is important to develop safer habits when working on ladders (National Safety Council 1999). Another disadvantage of the use of a drill while on a higher step is that other safety hazards may occur from the close proximity of the drill bit to the worker's face. For example, there is the possibility of auditory damage or facial laceration when operating a drill in a close reach position. Obviously, safety goggles are essential with any use of a drill close to the face. However, the use of an elevated platform or lift is one practical solution to reduce the risk of shoulder injury while still maintaining a safe work-site.

A final issue is the effect of a change in reach distance or step height on the posture of other parts of the body. Although not specifically measured in this study, it was clear from the analysis that a closer reach position on the lower step tended to cause cervical extension, compared to drilling on the higher step which required greater cervical rotation. Since cervical facet joint and foraminal encroachment may occur with either posture (Edwards 1994), i.e. the right cervical facets are extended with right cervical rotation or cervical extension, it is difficult to predict which motion is more strenuous. Lumbar posture appeared to be unaffected by either position, although drilling overhead with a far reach will probably increase the activity of the lumbar musculature. With the drill used in this study, there were minimal differences in wrist posture during a close reach while standing on the lower step, compared to the higher step. Nevertheless, it is important to consider other consequences that changing a work task posture may have on the rest of the body.

4.3. *Limitations*

A limitation of this study is the use of static 2-dimensional biomechanical analysis. Dynamic or static 3-dimensional studies may more accurately evaluate true work posture while using a drill, but it is unlikely that the results of shoulder joint moment would be different from those reported here. Total shoulder loads for the entire task of overhead drilling would increase in a dynamic model and may better represent actual work conditions in the construction trades. Future studies may also benefit from multi-planar evaluation since sagittal plane motion cannot be generalized to all overhead tasks. However, studies examining multi-planar overhead motion have shown that workers use different methods to accomplish a similar task (Hammarskjöld *et al.* 1990). Since workers in the construction trades often find themselves in constrained positions due to the proximity of ducts or other structures, this sagittal plane analysis may be appropriate.

Although normalization by MVC is commonly used in EMG studies, %RVE of a task may be more appropriate for and has been used in ergonomic studies (Armstrong *et al.* 1979, Cook *et al.* 1998). Pilot data for this study using normalization by MVC revealed no differences in the primary results when compared to normalization by position. In addition, normalization by task was used since relative changes in EMG were of more interest than actual values.

There are inherent limitations in simulation studies. In the present study, the force exerted vertically was selected by the investigators, the drill was not operating during the trials, none of the subjects were construction workers, and fatigue was purposefully minimized. Therefore, generalization of this data to actual work conditions should be undertaken cautiously. For example, construction workers may be required to drill overhead into concrete surfaces, which will undoubtedly increase the moment and myoelectric activity at the shoulder to greater levels than seen in this study. However, this study was designed to provide important baseline information on simple overhead drilling tasks. This study is part of a larger project designed to determine the effect of ergonomic interventions on overhead work among construction workers.

5. Conclusions

The findings of this study demonstrate that it is more advantageous to perform work directly overhead positioned close to the body, regardless of step height, than to use an extended reach. Stress on the shoulder can be decreased by moving closer to the task, and this may reduce the risk of injury. Platform lifts are one practical intervention that would allow workers to move closer to the task. Future research should be performed at construction sites to more accurately estimate the effect of overhead work on the shoulder in a less controlled environment.

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