

Biomechanical Loads and Subjective Stress Exposure to Lumber Graders in Sawmill Industry

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The aim of this study was to determine biomechanical loads and subjective stresses on lumber graders and associated morbidity in a high risk and repetitive sawmill occupation. The exposures of all 29 male sawmill worker volunteers were recorded. Motion and posture were studied with electrogoniometers, muscle loads were recorded with surface electromyography, and psychophysical stresses were assessed with subjective responses. Fifty-nine percent of the participants reported greater than moderate discomfort in their task-dominant upper extremity. Job performance required an average range of motion of 44°, 21°, and 52° in flexion/extension, radial/ulnar deviations, and pronation/supination respectively. It also required an average of 9% maximum voluntary contraction force and was repeated an average of 34 times/min. This repetitive exertion over an 8-h shift was deemed to be a significant risk factor associated with prevalent upper extremity morbidity.

job analysis lumber graders wood product manufacturing repetitive strain
upper extremity physical and psychophysical stress

1. INTRODUCTION

Musculoskeletal injuries accounted for 1698 Workers' Compensation Board claims in the sawmill industry of Alberta, Canada, in 1997–2002 [1]. This represented 33% of the total cost of claims and 38% of the total time lost due to claim in the same period. Within the sawmill industry the lumber grader position was identified as a production position with a high risk of musculoskeletal injury (MSI) to the upper extremity [1, 2]. Incidence of recordable upper extremity MSI events in the lumber grader position ranged from 1.09 to 1.25 per person-year worked in this occupation.

Given the large human and financial burden imposed on industry by MSIs, prevention has become a priority of occupational health programs. A large evidence base establishing the role of exposures to postural and biomechanical loads in precipitation of MSIs is now present and a number of probable mechanisms of injury have been proposed [2, 3]. In most musculoskeletal conditions, it is the combined effect of physical exposures which are most highly related to the incidence of MSI [2]. Ergonomic risk assessments are based on models of MSI causation which consider the integrated role of biomechanical and physiological exposures.

The authors acknowledge the assistance of Edgar Vieira in the completion of data collection. Additionally the authors would like to acknowledge the assistance of the industry association/company representatives Lloyd Harman, Len Bourdin, Mike Schwirtz, and Al Caputo in the completion of this study.

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Calculation of ergonomic risk requires the evaluator to define the physical exposures required to perform the job. Traditionally, worksite exposure assessments have been performed based on observation. Multiple methods of defining the maximum posture used to describe the range of motion are available in the literature. Similarly, multiple methods of assessing the exertion required to perform a job task are also described. Three methods of defining the maximum posture used to circumscribe the range of motion include the peak posture observed in the plane of interest during any point in the job sample, the peak posture observed considering the primary task only (defined here as the repetition average posture), and the overall average posture considering all motions in the job. Similar to posture, exertion may be assessed with quantitative or subjective means in several ergonomic risk assessment methods [4, 5]. However, the equivalency of these definitions has not been examined. Only one study of the

equivalency of multiple definitions of posture and exertion has been published [2]. In fact, it has been suggested that the methods used to define end range posture and assess exertion required may not be equivalent [2, 6].

In this paper the physical exposures of posture, exertion, and frequency have been examined. Valid conclusions require accurate measures. For this reason, electrogoniometers and surface electromyography were used to record the physical exposures required to perform the lumber grader job. Definitions of the exposure variables examined have been chosen to reflect those used by worksite evaluators. These definitions also reflect those techniques required by different ergonomic risk assessment methods. The aim of the study was to determine the exposure profiles of lumber graders with respect to postural and biomechanical loads and the subjective stress felt by this professional group. Furthermore, the study also aimed to study morbidity in lumber grader occupation.



Figure 1. Lumber grader.

2. METHODS

2.1. Occupation Identification and Task Description

The occupational health records of sawmills were obtained to determine the musculoskeletal morbidity in the lumbar grader occupation. The lumber graders are responsible for assigning a product value grade to each piece of dimensional lumber leaving the sawmill. Board dimensions to be graded vary from 243.8 to 609.6 cm in length and 10.2–25.4 cm in width, all dimensional lumber assessed was 5.1 cm in depth. To assign a grade to a piece of dimensional lumber the lumber graders were required to inspect the four sides of a board. Inspecting all surfaces required the board to be turned with the task-dominant upper extremity. When a grade was chosen the lumber graders marked the board with the non-task-dominant upper extremity to enable automated sorting. Boards were observed to vary in weight from 2.27 to 22.7 kg dependent upon dimension, species of wood, and moisture content. Lumber graders were free to sit or stand during the grading activity. Whether the lumber grader was sitting or standing, the task-dominant upper extremity was positioned at $\sim 0^\circ$ of shoulder flexion and 90° of elbow flexion. The pace of grading required all workers to perform a standard work method. Figure 1 depicts the primary board turning task of the lumber grader.

2.2. Subject Selection and Job Description

Workers performing the lumber grader job ranging between ages of 18–65 years were recruited at the three sawmill facilities studied. The jobs and sample across the facilities were not significantly different. Injury to the upper extremity within the past 12 months, generalized arthropathies or neuropathies, or the inability to understand and follow instructions were used as exclusion criteria. The experimental protocol was approved by the University of Alberta Health Research Ethics Board. Twenty-nine of the 29 subjects of the all-male sample volunteered to take part in the study and gave their informed consent.

Mean duration of work experience of subjects at time of assessment was 4.4 years (*SD* 4.9).

2.3. Body Part Discomfort Survey

Each worker was asked to complete a body part discomfort rating survey prior to beginning data collection, during their work shift. The scale spanned from 1 (indicating *no discomfort*) to 10 indicating the body region was *very uncomfortable* [7]. Scores greater than 1 were taken to indicate discomfort.

2.4. Data Collection

2.4.1. Motion data acquisition

Motion at the wrist was assessed with two precalibrated electrogoniometers (Biometrics, USA) placed on the wrist and forearm reported by the subjects as used primarily to turn boards. Initial calibration of the electrogoniometers on uni-planar jigs revealed maximum errors of 2.33° , 3.67° , and 3.33° in the planes of wrist radial/ulnar deviation, flexion/extension, and pronation/supination respectively. Only the upper extremity used to turn boards (task-dominant upper extremity) was assessed. A Biometrics™ bi-axial SG-65 and uni-axial Q-150 electrogoniometers were applied to the task-dominant upper extremity [8]. Prior to beginning data collection the subjects were asked to position their elbow at 90° , their forearm in mid position (thumb positioned superiorly), and wrist in neutral position in the planes of flexion/extension and radial/ulnar deviation while the electrogoniometers were zeroed. A sample of 5 min was recorded during job performance. Angular displacement was recorded in 3 planes (x , y , z) with a bi-axial and uni-axial Biometrics™ electrogoniometer positioned appropriately at a sampling frequency of 200 Hz. Postures required to perform the job were derived from analysis of the recorded wave forms with the Biometrics™ Data link analysis software (for Windows XP).

2.4.2. Exertion data acquisition

Surface electromyography (EMG) was used to determine the muscle activity and its magnitude associated with maximum and job simulated exertions in static trials. Job simulated and maximum EMG trials were performed at a location removed from the production line. Only the upper extremity reported by the subjects as primarily used to turn boards (task-dominant upper extremity) was assessed. The flexor carpi radialis, flexor carpi ulnaris, and flexor digitorum superficialis were assessed for the flexion component and the pronator teres were evaluated for the pronation component of the board flip task. Electrode placement was determined by isolating the muscle in question with manual muscle testing performed by a physical therapist and placing the electrode in approximately the midpoint of the muscle belly. A Delsys Bagnoli 8 EMG system (Bagnoli, USA) was used to record the muscle activity of all muscles assessed in each trial. Single differential bipolar electrodes with parallel bar-shaped silver detection surfaces (1 cm in length $\times$ 1 mm in width) spaced 1 cm apart were used in the EMG trials and oriented perpendicular to the muscle fibers. The data acquisition system consisted of an analog-to-digital board with a 100-kHz sampling capacity. The four EMG channels were sampled at 1 kHz in real time with a high pass filter of 10 Hz and low pass filter of 500 Hz. The sampled signals were stored on a laptop computer. The EMG traces obtained during job simulated and maximum trials were full-wave rectified and linear envelope-detected. From those processed traces, peak EMG and average EMG were derived using custom software developed by the Ergonomics Research Laboratory at the University of Alberta. Data acquisition took place during a 9-s activity sample to cover the entire task cycle. Two seconds prior to the start of the task were used to record a baseline activity and 2 s following the 5-s test were used to allow the subject to return to baseline values. Experimental trials were administered in random order to allow differences observed to be attributed to differences in the experimental conditions and not the order of trials. A minimum

of a 2-min rest was given to subjects between trials to prevent fatigue. Two trials were performed for each condition with the second trial being recorded to allow the subject to become familiar with the task.

2.4.3. Maximum voluntary contraction trial

During the MVC trials the subjects were seated with the task-dominant upper extremity positioned at the side and the elbow bent to 90°. An isometric exertion in either a flexion or rotational direction on a handle made from a piece of dimensional lumber connected to an immobile base with a steel cable was performed dependent upon the trial (wrist flexion or pronation). During flexion trials the steel cable was connected to the middle of the handle and the subject was instructed to perform a static flexion exertion. During the pronation trial an alternate handle to which the steel cable was attached to the outside edge was used and the subjects were instructed to exert a static rotational exertion on the handle. During MVC trials the subjects were instructed as follows: "When I say go, I want you to bring your force up to your maximum level over 2 s and hold for 3 s or until I say stop."

2.4.4. Job simulated trial

Job simulated trials were performed in a location removed from the industrial process within the facility. Job simulated muscle activity was determined by having the subject hold a representative board (5.1 cm deep $\times$ 20.3 cm wide $\times$ 488 cm long) in a job simulated standardized static position while muscle activity was recorded. This dimension was selected as representative because it was produced in all facilities and shifts examined and was reported by most subjects as most demanding. The subjects were tested in standing posture with the wrist in neutral flexion/extension and supinated position (job simulated flexion) or slightly pronated from full supination position (job simulated pronation). The height of the test table was adjusted such that the subject maintained the board at an angle of $\sim 3^\circ$ from the horizontal plane

and 90° of elbow flexion. During job simulated trials the weight of the representative board was supported by the experimenter until the trial was begun. After the trial was begun, the weight of the representative board was given to the subject who maintained the hold for 5 s.

2.4.5. Subjective measure of exertion

Following motion data collection, immediately after task performance, the workers were asked whether during the cycle there were job actions that required muscular effort of the upper limbs. The workers were then asked to rate the actions on a scale of 1–10 using the Borg CR-10 scale [9]. The workers were also asked to rate the strength demand required to turn the boards and the overall job demand on a 10-cm visual analog scale (VAS) [10].

2.5. Data Analysis

2.5.1. Comparisons

Three types of comparisons were made in this study. First, it was determined if the different methods commonly used by worksite evaluators to define end range posture resulted in a significantly different range of motion values. The Friedman test ($\alpha = .05$) was used to test whether significant differences existed between posture variable definitions (peak, repetition average, overall average). Second, several ergonomic risk assessment methods allowed exertion to be assessed using either psychophysical measures (e.g., VAS or Borg score) or quantified measures such as surface EMG. Correlations between exertion variables (%MVC, Borg, VAS) were tested with the Spearman's ρ rank correlation test ($\alpha = .05$). Lastly, meaningfully different incidence rates in the lumber grader position were reported between companies. As physical demands of the job are known to be related to incidence of MSI, differences in the exposure profiles of lumber graders between facilities were examined. The non-parametric Kruskal–Wallis H test ($\alpha = .05$) was used to determine if significant differences existed between companies on the exposure variables recorded (range of motion, %MVC,

Borg scores, VAS scores, body part discomfort scores).

2.5.2. Motion

2.5.2.1. Posture. Postures required to perform the lumber grader's work were defined on the basis of three criteria. The peak excursion was defined as the maximum excursion observed during the entire task in the respective plane of motion (e.g., flexion or extension). The peak excursion represented the maximum excursion observed and may not have taken place during a repetition of the primary task (turning boards). The repetition average posture was defined by randomly selecting 10 repetitions (board turns), recording the maximum deviation in the plane of interest (e.g., radial and ulnar deviation), and calculating the mean values in each subject. Finally, the overall average excursion was calculated considering all motions in the plane of interest for the entire sample. Overall average posture reflects the average value observed considering all motion taking place in the defined plane of motion during the sample.

2.5.2.2. Duty cycle. The percentage of the sample where subjects were active, as opposed to resting, was determined by defining rest periods as those periods with more than 1.2 s during which there was less than a 5° change in posture in each of the 3 planes assessed concurrently and no force application. Rest periods were recorded, summed, and divided by total cycle time to arrive at percentage of sample performing the primary task (turning boards). Rest periods were defined using these criteria as currently there are no standardized criteria for defining a rest period.

2.5.2.3. Frequency. Repetitions of the primary task performed during the sample were determined by defining a repetition as indicated by a change in direction of motion of at least 18° at the proximal radio-ulnar joint. Pronation/supination was used to define repetition due to its cyclical nature in performance of the job (board turning) and clear repeated trace as recorded by the analysis system used. A change in direction of 18° was selected by inspecting both the electrogoniometer output and simultaneous video

of the job being performed and subjectively selecting the cut-point which differentiated between cycles of the primary task. Every time a motion exceeded the threshold value it was counted. The sum of these numbers over the sample time provided the frequency variable.

2.5.2.4. Velocity and acceleration. The angular excursion and time of motion was recorded for 5 samples of the supination pronation excursion and was taken to be representative of flipping a board for 3 subjects at each facility assessed and used to calculate average velocity and acceleration values. Only half of the cycle was considered, as it was assumed that after the board reached the midpoint gravity will take over to complete the flip. Angular excursion was divided by the time necessary to reach the midpoint of the cycle to arrive at the average velocity. Single and double differentiating the displacement versus time was used to calculate velocity and acceleration respectively.

2.5.3. Exertion

2.5.3.1. Electromyography: %MVC. A sample of ~2 s of consistent activity from the 5-s trial was selected by reviewing the processed EMG signal of the primary agonist (flexor carpi radialis—flexion, pronator teres—pronation).

The mean values resulting from the EMG recording of each muscle assessed during the job simulated flexion trial and the job simulated pronation trial were divided by the peak EMG values obtained on the MVC comparisons to arrive at %MVC required to perform the flexion and pronation components of the task.

2.5.3.2. Dynamic force applied. Dynamic force required to turn the representative board was calculated assuming the boards were of uniform density and the axis of rotation was along the edge of the board. The inertial component of the force required was calculated using the average acceleration as described in section 2.5.2.4. Figure 2 describes the methods and equations used to calculate dynamic force required to perform the primary task.

3. RESULTS

3.1. Incidence of Upper Extremity Musculoskeletal Injury

A review of the Alberta Workers' Compensation Board data set revealed that an average of 148 successful claims were incurred annually across the 6 years examined (1997–2002) in the occupation groups containing the lumber grader position.

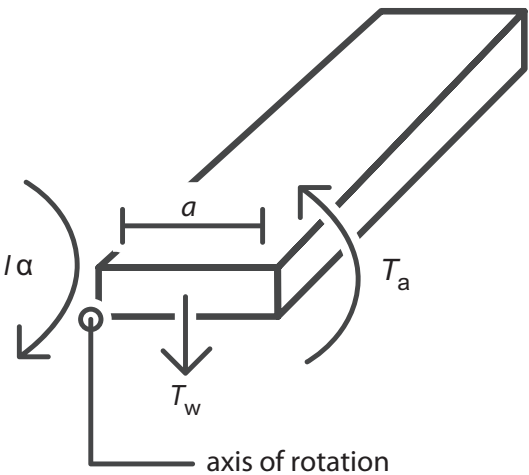


Figure 2. Methods and equations used to derive dynamic force required to perform the primary task.
Notes. Torque applied to rotate on rectangular plane with axis along edge. $T_a = T_w + I\alpha$, where $T_w = F a/2$, $I\alpha = 1/3 M a^2 \cdot \text{rad/s}^2$. Force applied with edge hand hold, force = torque/distance, force = T_a/a .

3.2. Body Part Discomfort Survey Scores

Fifty-nine percent of the subjects evaluated reported greater than moderate discomfort (greater than 4 on a scale of 1–10) in the task-

dominant upper extremity. Table 1 describes reported body region discomfort. No significant differences in reported discomfort were found between facilities in any body region assessed. Figure 3 illustrates percentage of the study population reporting discomfort (greater than 1 on a scale of 0–10).

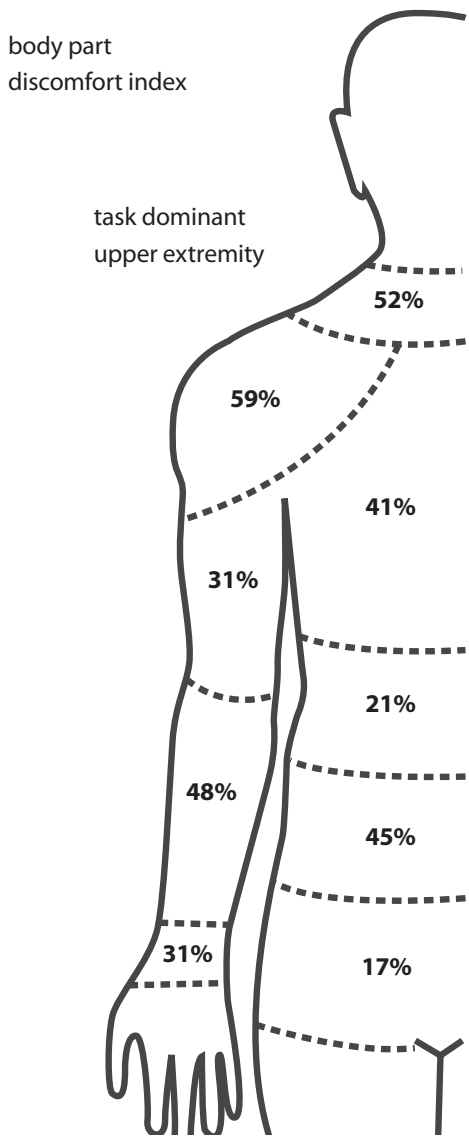


Figure 3. Percentage of the study population reporting discomfort by body region.

3.3. Motion Required

3.3.1. Posture/joint excursion

Table 2 lists peak, repetition average, and overall average ranges of motion observed in the recorded sample by plane of motion. Maximum mean angular differences between individuals with respect to the measures of forearm supination were 9.8° (peak) and 8.7° (repetition average) respectively. Maximum mean angular differences between subjects in peak extension were 18.4°. With respect to the total range of motion (ROM), only wrist flexion/extension, defined by peak postures, differed significantly between subjects assessed ($p < .01$). Maximum mean angular difference between subjects in total peak flexion/extension range of motion was 25.5°.

The effect of posture variable definition on ROM was assessed by comparing ROM values resulting from using peak postures to delineate endpoints to ROM values resulting from using repetition average values to delineate endpoints. Defining task ROM values by peak postures as opposed to repetition average endpoints resulted in significantly different ROM in all planes of motion assessed ($p < .001$). In terms of motion used to circumscribe the task ROM in the planes of radial/ulnar deviation, flexion/extension and pronation/supination were 44.6, 50.0, and 69.3% respectively.

TABLE 1. Reported Discomfort by Body Region on Corlett and Bishop's Scale of 1–10 [8]

Discomfort	Neck	Shoulder	Upper Arm	Forearm	Wrist	Midback	Upper Lumbar Spine	Lower Lumbar Spine	Pelvis
Average	3	3	1	2	2	2	1	2	0
SD	3.13	3.05	2.42	2.58	2.53	3.36	1.66	2.57	0.76
Range	0–10	0–10	0–8	0–8	0–8	0–9	0–5	0–9	0–3

3.3.2. Frequency of movements (board turning)

Table 3 provides descriptions of the observed mean task duration and mean frequencies of movement. Mean repetitions performed per minute (34.2 reps/min) did not vary significantly between subjects. However, hours spent performing the lumber grader job varied significantly between subjects ($p < .01$). Maximum mean difference with respect to hours spent per day performing the lumber grader job was 3.7 h per day and ranged from 3.5 to 7.2. Significant differences in hours spent per day resulted in significantly different total repetitions per day as well as between individuals ($p < .001$). Finally, the duty cycle, velocity, and acceleration percentage of the sample active (duty cycle) varied significantly also. Maximum mean difference in the percentage of the cycle active was 12%. Duty

cycle values observed between subjects ranged from 33 to 45%. Mean velocity and acceleration employed to turn the boards were 125.4°/s (SD 32.6) and 293.5°/s² (SD 102.8) respectively. No significant differences were found between subjects with respect to the mean velocities or accelerations applied to turn boards.

3.3.3. Exertion required

A mean force of 9% MVC (SD 4) was required to turn a representative board (5.1 × 10.2 × 243.8 cm). Representative board weights upon which the job simulated MVC testing was performed varied from 3.2 to 3.9 kg. No significant differences were observed between subjects with respect to %MVC required to perform the primary job task. Table 4 gives %MVC specific to muscle assessed.

TABLE 2. Total Range of Motion Values by Motion Type

Motion	Radial Deviation		Ulnar Deviation		OA
	Peak	RA	Peak	RA	
Average	13	3	−34	−18	−7
SD	6.77	8.63	9.44	10.64	8.86
Range	1–27	−11.6–16	−50–−17	−41.4–1.7	−24.2–8.7

Motion	Flexion		Extension		OA
	Peak	RA	Peak	RA	
Average	28	1	−60	−43	−17
SD	14.60	10.64	15.86	14.07	11.63
Range	−2–62	−21.6–20.2	−106–−35	−74.7–−20.4	−46.5–0.5

Motion	Pronation		Supination		OA
	Peak	RA	Peak	RA	
Average	44	33	−31	−19	6
SD	11.45	12.23	9.35	7.51	8.63
Range	28–73	15.7–62.8	−52–−13	−37.1–−5.71	−13.1–24.2

Notes. RA—repetition average, OA—overall average. Negative values indicate end range of motion in ulnar deviation, extension, or supination.

TABLE 3. Frequency Variables Recorded

Frequency	Duty Cycle (%)	Reps/min	h/Day	Reps/Day	Total Exposure (h)
Average	38	34.2	5.7	11743.6	2.2
SD	8	6.17	2.14	4754.05	0.96
Range	18–56	18–46	0.9–9.75	953–19866.62	0.16–3.79

Notes. Reps—repetitions.

TABLE 4. Percentage of Maximum Voluntary Contraction (%MVC) by Muscle for the Task

Effort	Muscle Activity (%)				Component Values (%)		Task Average (%)
	FCR	FCU	FDS	PT	Flexion	Pronation	
Average	11	7	10	9	9	9	9
SD	5	3	6	6	3	6	4
Range	3–25	2–14	3–24	3–28	3–17	3–28	3–23

Notes. FCR—flexor carpi radialis, FCU—flexor carpi ulnaris, FDS—flexor digitorum superficialis, PT—pronator teres.

3.3.4. Subjective stress

Significant differences between subjects were observed ($p < .05$) in the Borg rating of exertion. The maximum mean difference in Borg score attributed to the turning of boards was 2.3 points and mean values ranged from 4.0 to 6.3. Borg score was significantly correlated to both the VAS measure of strength demands and the VAS measure of overall demand, however ($p < .001$, $r^2 = .47$ and $p < .001$, $r^2 = .44$ respectively).

With respect to the subjective measures of stress of the task a mean Borg scale score of 4.7 (SD 1.6) was obtained for discomfort in turning the lumber boards. The VAS for the stress on the job was 5.2 (SD 1.9) and the VAS for the overall demand of the task was 5.8 (SD 1.7). Thus the subjective stress on the task was moderate.

4. DISCUSSION

Biomechanical exposures are frequently used to evaluate injury/morbidity risk potential in industrial work. They include external load, postural load, motion involved, and frequency and duration of the industrial activities. It has been advocated and demonstrated that it is not only heavy activities that constitute injury risk but lower and modest levels of loading are also associated with significant injury and morbidity potential [3, 11, 12, 13, 14, 15, 16, 17, 18, 19]. Bernard published an extensive review of literature load and injury relationship describing their relationship [20]. Whereas it is concluded that the peak load is a hazard in itself and each tissue has ultimate failure strength, it is also emphasized that the cumulative load will have a significant effect on tissue tolerance and its vulnerability to injury [12, 17, 18].

The results of the current study demonstrate that lumber graders handled a relatively light load requiring a mean force of 9% MVC. This force may result in a relatively light exposure. However, when this force is exerted through 50% of range of flexion/extension, 44.6% of radial/ulnar deviation, and 69.3% of pronation/supination the impact of the light load is significantly amplified. As one continues the same exertion progressively at greater ranges of motion there is a continuing and exponential increase in the internal effort required to carry out that activity, significantly increasing the tissue load. The situation is further compounded when the activity is repeated frequently adding to the cumulative load [3, 12, 16, 17]. The experimental sample (100% of all workers on the job in those sawmills) performed this lumber grading activity to a mean of 11 743 times per day resulting in a mean repetition of 34.2 times/min. In terms of total duration for which this load was borne by the upper extremity and its tissues, it was 38% of the total time worked. This means that the workers' upper extremities and their tissues were loaded for 3 h of each 8-h shift. Such extensive exposure in relatively young work force (mean age 29.9–37.1 years) with a mean work experience of only 4.4 years resulted in significant morbidity. The study found that 59% of the workers had greater than moderate discomfort in task-dominant upper extremity. Such morbidity and injury profile associated with seemingly light work lets us conclude that the job of lumber grader has significant risk of injury and morbidity though the amount of load handled is light.

Limitations

Measurement error in posture and motion assessment due to simultaneous multi-planar motion was not assessed in this study. Additionally, only 5 min of job performance was recorded with electrogoniometers and assumed to be representative of the task. The repetitive nature of the job assessed, which allowed ~170 repetitions of the primary task to be assessed, supports the representativeness of the sample used, however. While motion and posture information was recorded during actual job performance, a static EMG assessment was used to assess the muscle activity required to perform a dynamic task. The small samples used to make the evaluation of the assumptions upon which parametric statistics are based may not be representative for the entire lumber grader occupation and thus require the use of nonparametric procedures. The power of the tests to detect differences and examine associations is therefore reduced. The limited ability of the compensation data set to identify incidence rates within the lumber grader position and unique surveillance systems in use are also important limitations of this study. The sample studied does represent the entire population of workers in this occupation of the facilities studied; hence these results have internal validity.

5. CONCLUSIONS

The use of electromyography and electrogoniometry in the assessment of workplace biomechanical and postural exposures has enabled a quantification of exposure variables and their association with morbidity. The lumber graders exerted a mean force of 9% MVC, 34.2 times/min to a total mean daily repetition of 11743.6 times per day with a mean daily exposure of 3 h for each 8-h shift. Fifty-nine percent of the work force reported a greater than moderate discomfort in their task-dominant upper extremity. The findings of this study indicate that even seemingly light jobs can result in significant cumulative load resulting in injury and morbidity.

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