Ergonomic interventions for the furniture manufacturing industry. Part II—Handtools

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Abstract

The objectives of this intervention research project were to develop and evaluate engineering controls for the reduction of the upper extremity injury risk in workers in the furniture manufacturing industry. The analysis of OSHA Form 200 logs and surveys of furniture workers revealed that upholsterers, workers who use random orbital sanders and workers who use spray guns are at higher levels of risk of illness than the rest of the working population. An on-site ergonomic analysis of these three jobs was performed and the following risk factors were identified for each of these three work groups: upholsterers—repetitive, high-force pinch grips; sanders—long-duration static grip forces; and sprayers—awkward postures (ulnar wrist deviations and wrist flexion). Engineering interventions in the form of new or modified handtools were then evaluated in the laboratory to assess their effectiveness in reducing exposure to these risk factors. For sanding, an interface was created that secured the hand to the sander with the intention of reducing the need for static grip forces during sanding. A new handtool was created for upholsterers that replaced the repetitive pinch grips with a power grip. Finally, a commercially available spray gun with ergonomic features was evaluated. Each of these modified tools/methods was compared with the standard methods typically used in industry. The results show that most of the intended beneficial effects were realized. The random orbital sander interface reduced extensor muscle activities by an average of 30%. The upholstery handtool reduced the intrinsic hand muscle activities by an average of 51%. The effects of the adapted spray gun were most prominent when working on horizontal surfaces and showed an average reduction of $40°$ of wrist flexion and $14°$ of ulnar deviation as compared to the standard pistol grip spray gun in this activity.

Relevance to industry

The ergonomic intervention research described in this report documents a reduction in exposure to risk factors for upper extremity cumulative trauma disorders for three work activities in the furniture manufacturing industry. © 2002 Published by Elsevier Science B.V.

Keywords: Cumulative trauma disorders; Upper extremity; Intervention research; Furniture industry; EMG

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1. Introduction

Cumulative trauma disorders of the upper extremity continue to be a problem for many in

the manufacturing sector. The statistics describing the incidence of carpal tunnel syndrome (CTS) and tendinitis show that the furniture manufacturing industry also has experienced these types of problems. On average, CTS incidence rates for the furniture manufacturing industry are 10.64/10,000 workers (as compared to 8.8 for the manufacturing industry and 4.36 for all private sector industries) and tendinitis incidence rates are 7.62/10,000 workers (as compared to 6.56 for the manufacturing industry and 2.88 for all private sector industries) (BLS, 1992–1996).

Furniture workers have exposure to many of the recognized occupational risk factors for upper extremity cumulative trauma disorders: overhead work, static shoulder postures, pinch grips, vibrating hand tools, awkward wrist postures (both radial/ulnar deviation and flexion/extension), high grip force, and repetitive hand/wrist motions (Bovenzi et al., 1991; Osorio et al., 1994; Silverstein et al., 1987; Sommerich et al., 1993; Tanaka et al., 1995). Unfortunately, there is little literature specifically related to work-related musculoskeletal injuries/illnesses among furniture industry jobs or related to interventions aimed towards the prevention of these disorders among these workers.

There are three control strategies at the disposal of practising ergonomists: engineering controls, work practice controls and administrative controls. The OSHA final rule (Federal Register, 2001) defines engineering controls as "… controls that physically change the job in a way that controls or reduces MSD hazards". It goes on to say that "work practice controls involve procedures and methods for safe work". Finally, the final rule states that "Administrative controls are work practices and policies implemented by the employer that are designed to reduce the magnitude, duration, and/or frequency of employee exposure to risk factors by changing the way work is assigned or scheduled (p. 68360)." Engineering controls include workstation modifications, changes to the tools or equipment, and altering production processes. Work practice controls include use of neutral positions or postures (keeping wrists straight, lifting close to the body) and team lifting. Administrative controls include employee rotation and job enlargement. The final rule goes on to say that "…engineering controls are the preferred method of controlling MSD hazards in cases where these controls are feasible. In contrast to administrative and work practice controls or personal protective equipment (PPE), which traditionally have occupied lower tiers of the hierarchy, engineering controls fix the problem once and for all (p. 68360)." This is not to say that work practice and administrative controls do not have their place. In some instances, this is the only reasonable/feasible solution. But what it does say is that, given the choice, engineering controls are preferred since they have the ability to reduce stress at the source instead of reducing levels of exposure or relying on the individual operator to monitor the ergonomics of their activity. With these principles in mind, the specific objectives of this intervention research project were to develop and evaluate engineering controls for the reduction of upper extremity injury risk in workers in the furniture manufacturing industry.

2. Methods

Analysis of the industry-provided OSHA Form 200 logs and surveys of industrial participants (details appearing in Mirka et al., 2002) revealed that upholsterers, users of random orbital sanders and users of spray guns were at elevated risk for hand and wrist problems. Biomechanical analysis, both on-site and videotape, of these tasks revealed the specific risk factors for each job type. The principle risk factors for hand/wrist stress in upholsterers were the repetitive (up to 40 pinches/min), forceful (up to 65 N of pinch force) and static pinch grip exertions performed by the operators' non-dominant hand (Fig. 1a). Specifically, the operators would pull the fabric to a specified tension with their non-dominant hand using a pinch grip between their thumb and index finger and then would secure the fabric using staple gun held in their dominant hand. The operators would then release the grip on the fabric and move their hand down to ∼5 cm and repeat the process. Each one of these grips required a forceful pinch grip
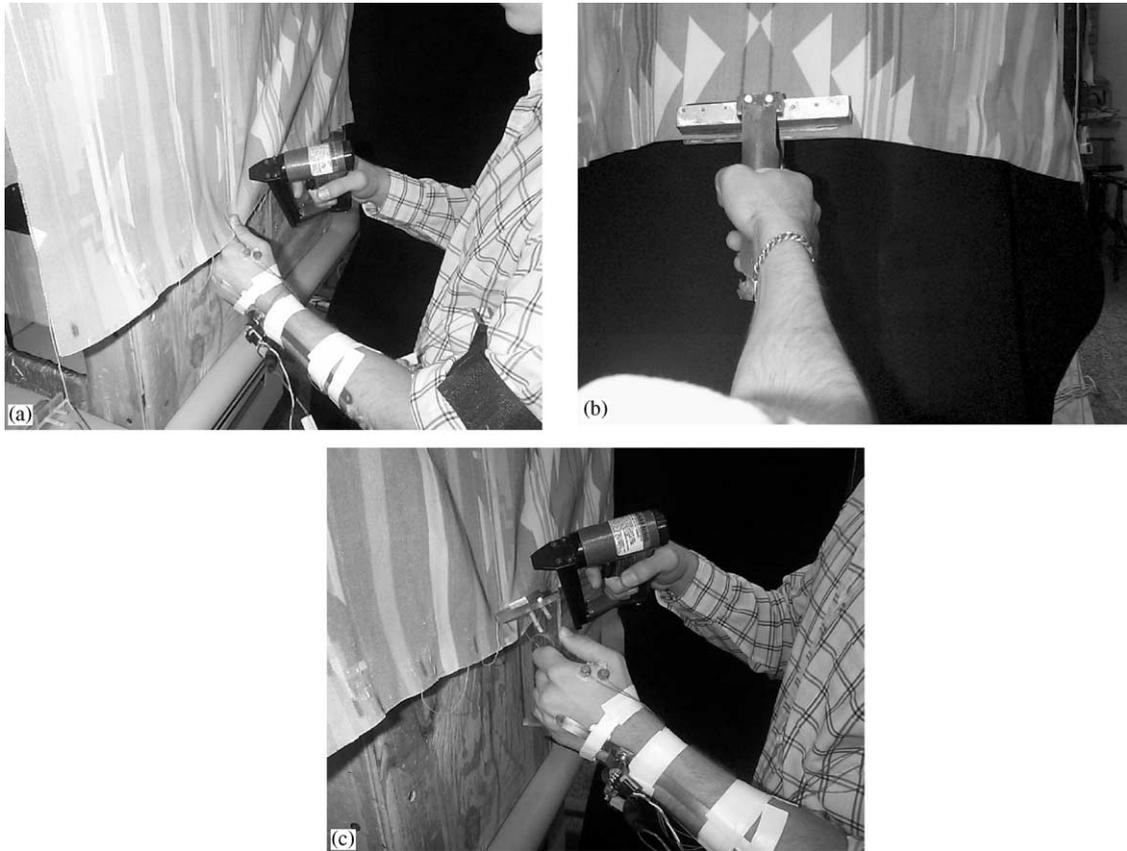
Fig. 1. Upholstery fabric-pulling techniques: (a) standard pinch grip technique, (b) prototype 1 (spring-loaded clamping mechanism), and (c) prototype 2 (fabric snagging tool).

and the repetition rates often exceeded 2 grips/s. The operators complained of pain in the fingers, wrists and forearm of the fabric-pulling hand.

An analysis of the jobs requiring use of the spray guns revealed that these spraying activities often generated extreme wrist flexion (up to $40°$ of flexion) and ulnar deviation (up to $20°$ of ulnar deviation). This was particularly problematic when these workers were spraying on the large horizontal surfaces (like the tops of desk, tables, conference tables, etc.) (Fig. 2a). In addition to these postural risk factors for the wrist, repetitive trigger activations and significant shoulder forces to support the weight of the spray guns and the hoses (~ 15–20 N) were noted. In most cases, this is the only task that the workers perform, indicating an extended exposure to these risk factors.

An analysis of jobs requiring the continuous use of the random orbital sander highlighted two principle risk factors for hand/wrist/forearm fatigue and discomfort: static grip force and exposure to vibration. When using the sander, the operator would use significant hand-grip force for extended periods of time (up to 30 min of continuous gripping) as they sanded the piece (Fig. 3a). Further, due to the non-symmetrical nature of the rotation of a random orbital sander, significant vibration exposure exists. In many cases, this is the only task that the workers perform throughout the workday, indicating an extended exposure.
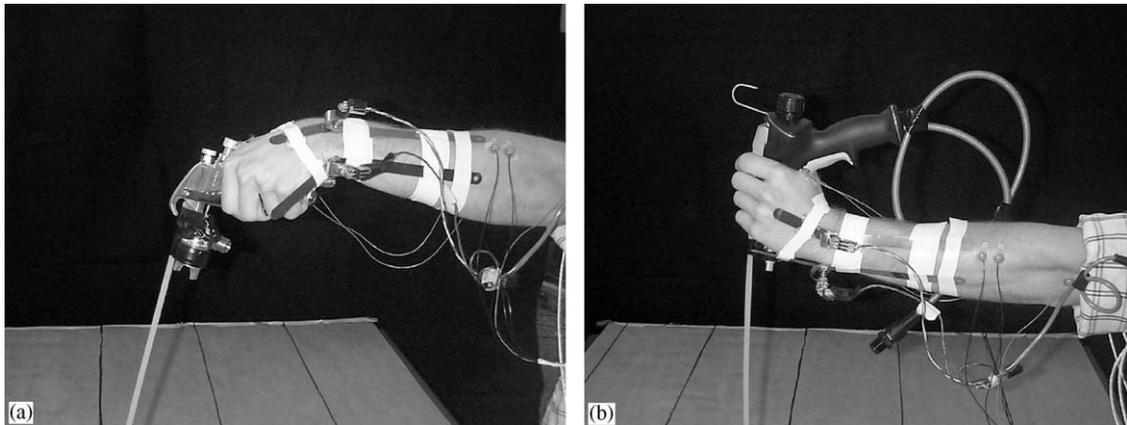
Fig. 2. Spray gun techniques: (a) standard pistol grip spray gun posture when spraying a large horizontal surface (such as a desktop) and (b) in-line spray gun posture (when spraying the same surface).
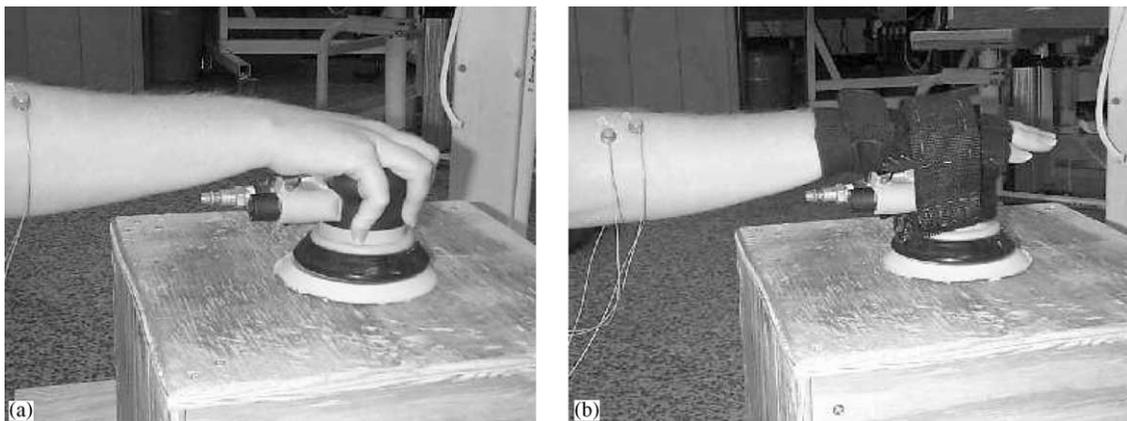

Fig. 3. Random orbital sander techniques: (a) standard grip technique and (b) interface harness to reduce long duration static grip force.

2.1. Engineering design of prototypes

The research and design team employed an iterative prototyping process wherein each ergonomic intervention prototype was subjectively evaluated in the lab by the research team and in the field by furniture workers and the results of these assessments were used to improve on the design of the intervention. In the case of the upholstery operation, it was decided that the goal of the intervention would be to change the repetitive pinch grips to less frequent power grips. The first prototype of this intervention utilized a spring-loaded clamping mechanism with a 6 in wide nose plate (Fig. 1b). Preliminary field analyses of this prototype revealed that the size of the tool made it too cumbersome to be practical in many upholstery activities and a second-level prototype that overcame that limitation was developed (Fig. 1c). The concept behind this design is that the operator snags the fabric with the tool and then uses the large muscles of the arm to generate the fabric-pull force. The benefits of this design are that it changes the pinch grip to a power grip, eliminates the prolonged static exertion of the intrinsic hand muscles by utilizing a

passive holding mechanism, decreases repetition by covering more linear distance per exertion, and transfers the necessary grip and pull forces from the small intrinsic muscles of the hand to the larger, more powerful muscles of the arm and shoulder.

The principle risk factors for hand and wrist problems to be addressed in the spraying operations were the awkward hand/wrist postures (wrist flexion and ulnar deviation) and the repetitive and high trigger forces. A commercially available spray gun (OMX model, DeVilbiss) appeared to address these issues. This model is made of a light-weight composite and has an activation trigger for both a pistol grip and in-line grip operation (Fig. 2b). This particular spray gun has been evaluated for different applications in a previous report (Lee et al., 1997).

In the development of the intervention for the random orbital sander, the goal was to reduce the necessity for the prolonged static grip force required to hold onto the sander and reduce the exposure to vibration. During the prototyping process, different materials were evaluated to assess their ability to reduce the subjective levels of vibration in the hand/wrist. Viscolas material was found to be the best over 20 min of continuous sanding and was therefore chosen as the material to be sewn into the palm and proximal phlanges of a glove. To reduce the need for prolonged static gripping forces, a harness was fabricated to secure the hand to the sander (Fig. 3b). The harness is secured to the circumference of the handle of the sander. From this harness, two Velcro straps wrap over the top of the operator's hand and are secured to a piece of Velcro that is sewn into the back of the glove. This design allows for good control of the sander without the operator griping the tool.

2.2. Laboratory evaluation

2.2.1. Subjects

Eleven subjects (six men and five women) were recruited from the university population and provided written consent before participation. All subjects were in good health and had no serious musculoskeletal problems. Mean (standard devia-

tion) of some pertinent anthropometric variables are as follows: forearm circumference—26.9 cm (2.54), hand length—18.3 cm (1.27), hand breadth—8.4 cm (0.82), hand circumference—20.7 cm (1.87), and elbow to finger tip—45.4 cm (2.70).

2.2.2. Apparatus

Electromyography and goniometry were used to capture the biomechanical performance variables as the subject performed the experimental tasks. The time-dependent (100 Hz) wrist posture was captured using two electrogoniometers that were secured to the subject's right wrist: one to capture the time-dependent radial/ulnar position and the other to capture the flexion/extension position (Marras and Schoenmarklin, 1993). Integrated electromyography (IEMG) was used to measure muscle activity of the flexor digitorum, extensor digitorum, generalized thenar group, and the first dorsal interosseous. The processed (amplified, filtered (10–1000 Hz), rectified and smoothed (100 ms moving average)) IEMG data were collected at 100 Hz for the duration of each work activity. In all three experimental tasks, a standard stopwatch was used to mark the end of the experimental trial.

2.2.3. Experimental task 1

A simulated upholstery workstation was developed to create a basic representation of the task of pulling fabric to a designated tension and then securing the fabric to a wooden frame (Fig. 4). Marks were drawn at specific locations along the length of the fabric to indicate where the subject was to pull the fabric. Three different weights were suspended in the fabric on the back side of the workstation to simulate a range of pull force requirements (light (20 N), medium (40 N), and heavy (50 N)) for different fabrics and spring constants experienced by upholsterers. Subjects were asked to pull the fabric against this resistance through a distance of 3–4 cm and then simulate the stapling activity.

There were two independent variables in this study: type of grip (pinch grip vs. upholstery tool) and level of resistance (light, medium and heavy). There were four dependent variables in this

Fig. 4. Experimental apparatus to test the upholstery handtool.

study—the average normalized IEMG (NIEMG) of the (1) flexor digitorum, (2) extensor digitorum, (3) generalized thenar group, and (4) the first dorsal interosseous.

2.2.4. Experimental task 2

A tubular steel frame (1.4 m × 1 m × 1.2 m) was built and covered with paper to replicate the large work pieces encountered by sprayers in the furniture manufacturing industry (Fig. 5). Using a technique similar to that employed by Lee et al. (1997), the subjects were asked to follow a specific path on four surfaces of the piece. Before beginning the experiment, the subjects viewed a videotape that showed sprayers in the furniture industry performing their work task. The subjects were instructed to hold the gun approximately 0.75 m from the work surface and as close to perpendicular as possible. The spray path used by the subject to simulate spraying the whole surface was illustrated by lines on the work surfaces. The

path on the top and front surfaces were horizontal while those on the sides were vertical. Each trial was performed two times.

The independent variables in this study were the type of spray gun (OMX vs. standard), the vertical position of the piece, and the surface to be sprayed. The position of the frame had two levels: low (resting on the floor) and high (lifted 27 cm off the floor). The surface to be sprayed had four levels: 1—the top horizontal surface, 2—the right side vertical surface, 3—the front vertical surface, and 4—the left side vertical surface. The dependent variables in this study were: (1) the peak ulnar deviation of the wrist and (2) the peak wrist flexion.

2.2.5. Experimental task 3

To simulate the conditions of operators using orbital sanders in the furniture manufacturing industry, a wooden box was placed on a workstation. The subjects were instructed to sand with
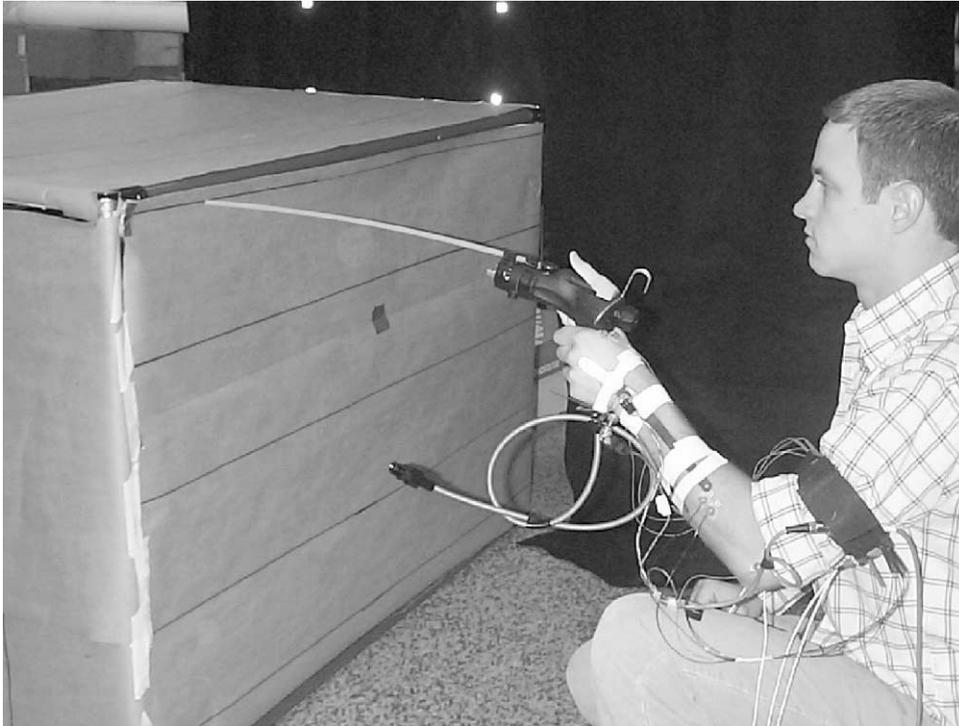
Fig. 5. Experimental apparatus to test the spray guns.

the orbital sander using their dominant hand and move it in a circular motion on the top of the box and then onto the side of the box (Fig. 6). The subjects performed this activity using both the standard technique (no interface) and using the new sander interface.

The independent variables in this study were the type of grip used to hold the sander (standard vs. interface) and the worksurface orientation (horizontal and vertical). The dependent variables in this study were the NIEMG of the flexor digitorum and the extensor digitorum muscle groups.

2.2.6. Complete experimental procedure

The subjects completed all experimental procedures within a 2-h period. The subject was informed of the experimental procedures and given written informed consent before participation. The subject's skin was then prepared for electrode placement over the four muscle groups to be sampled and the electrodes were then placed. Two electrogoniometers were then attached to the subject's wrist using a hypoallergenic, flexible surgical tape.

The data-collection phase of the experiment began with the subjects seated and resting their forearm on a platform that placed the right wrist in a neutral posture (both planes) and all hand and forearm muscles relaxed. Data were collected in this condition and formed the baseline resting (IEMG) and neutral (goniometers) condition. Four maximal voluntary exertions (MVE) were then performed to get a maximum contraction from each sampled muscle group for normalization purposes. The subject was instructed on how to perform each MVE and then made to practice each one. The subject was then asked to perform each MVE for 2 s and then made to rest 1 min before performing the next MVE. The MVE for the flexor digitorum was achieved as the subjects made a fist with their right hand, turned
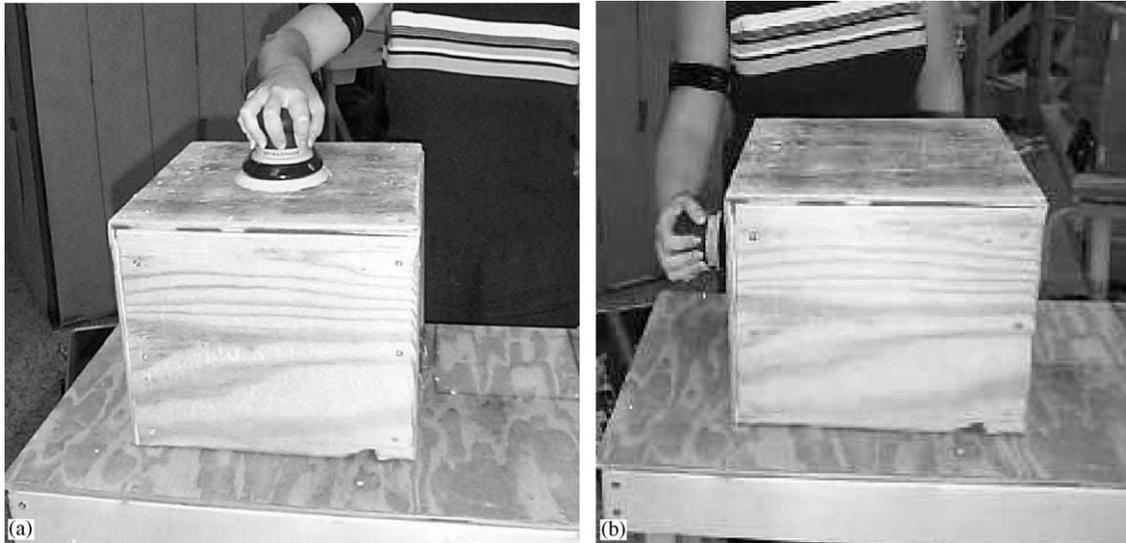
Fig. 6. Experimental apparatus to test the random orbital sander: (a) horizontal orientation and (b) vertical orientation.

their arm to the fully supinated position, and attempted to roll their fist upward against resistance provided by the other hand. The MVE for the extensor digitorum was achieved when the subjects made a fist with their right hand, turned their arm to a fully pronated position, and attempted to roll their wrist upward against static resistance provided by the other hand. The MVE for the generalized thenar group was achieved by having the subjects attempt to pull their thumb across their palm against static resistance provided by the other hand. The MVE for the first dorsal interosseous was achieved by having the subjects attempt to abduct the index finger against the static resistance provided by the other finger. After the MVE exertions were completed, the subjects moved to the mock upholstery workstation and performed the simulated upholstery operation as outlined above. Upon completion of this task, the subjects rested for a period of 5 min. They then moved to the spray gun activity and performed each trial as outlined above followed by another 5 min rest period, after which they moved to the sander operation and performed it as outlined above, to complete the experiment.

2.2.7. Data reduction and statistical analysis

The first step in data reduction was to take each individual file containing the EMG and goniometer data and eliminate those points in time wherein the subject was not performing the designated task. The stopwatch data were used to demark these endpoints. All remaining IEMG values collected during the experimental trials were averaged and then normalized with respect to the muscle-specific maximum values. All remaining goniometric readings were normalized relative to the neutral wrist position and returned, through simple linear regression equations, the two-dimensional deviations of the wrist from neutral. Each data file was further reduced to the dependent measures as described in each section above.

ANOVA procedures were performed on this reduced dataset to identify any significant effect of the independent variables. In each case above, the design was that of a mixed-effects model and the derivation of the appropriate F-statistic was calculated from the expected mean squares (see Appendix A). The analysis used "subject" as a blocking variable to control for the differences between individuals.

Table 1
ANOVA for the ergonomic handtool interventions

ANOVA for Upholstery Handtool Experiment (Experiment 1)

	Pull force	Tool type	Interaction
Average ext EMG	$F(2, 20) = 1.8$ NS	$F(1, 10) = 1.34$ NS	$F(2, 20) = 0.64$ NS
Average flex EMG	$F(2, 20) = 0.77$ NS	$F(1, 10) = 1.64$ NS	$F(2, 20) = 2.54$ NS
Average thenar EMG	$F(2, 20) = 1.69$ NS	$F(1, 10) = 39.9^a$	$F(2, 20) = 0.22$ NS
Average FDI EMG	$F(2, 20) = 9.1^a$	$F(1, 10) = 48.3^a$	$F(2, 20) = 0.48$ NS

ANOVA for the Spray Gun Experiment (Experiment 2)

	Surface location	Gun type	Height	Surface × gun	Gun × height
Peak ulnar deviation	$F(3, 175) = 3.15^b$	$F(1, 175) = 83^a$	$F(1, 175) = 1.31$ NS	$F(3, 175) = 29^a$	$F(1, 175) = 7.47^a$
Peak wrist flexion	$F(3, 175) = 229^a$	$F(1, 175) = 190^a$	$F(1, 175) = 1.87$ NS	$F(3, 175) = 166^a$	$F(1, 175) = 0.72$ NS
	Surface × height	Gun × surface × height			
Peak ulnar deviation	$F(3, 175) = 3.71^b$	$F(3, 175) = 2.16$ NS			
Peak wrist flexion	$F(3, 175) = 14^a$	$F(3, 175) = 7.91^a$			

ANOVA for the Sander Interface Experiment (Experiment 3)

	Surface orientation	Interface type	Interaction
Average ext EMG	$F(1, 10) = 4.48$ NS	$F(1, 10) = 7.26^b$	$F(1, 10) = 0.24$ NS
Average flex EMG	$F(1, 10) = 6.34^b$	$F(1, 10) = 0.12$ NS	$F(1, 10) = 0.24$ NS

[a] Significant at $p = 0.01$ level.
[b] Significant at $p = 0.05$ level.
NS—not significant.

3. Results

The results of the statistical analysis of the data from all three experiments are shown in Table 1. These results indicate that each of the ergonomic interventions had the intended effect on muscle activity or wrist posture. The results of the analysis of the upholstery hand tool data revealed a significant reduction ($\sim 51\%$) in the NIEMG activity of the intrinsic muscles of the hand (Fig. 7) when the new hand tool was used, but no significant effect of the tool on extrinsic muscle activities. The effects of the OMX spray gun were slightly more complicated in that there were statistically significant interactions in this analysis. The interpretation of these interactions shows that the OMX spray gun was particularly effective in reducing wrist flexion (Fig. 8) and ulnar deviation (Fig. 9) on the top surface when the work piece was in the raised position, a result consistent with
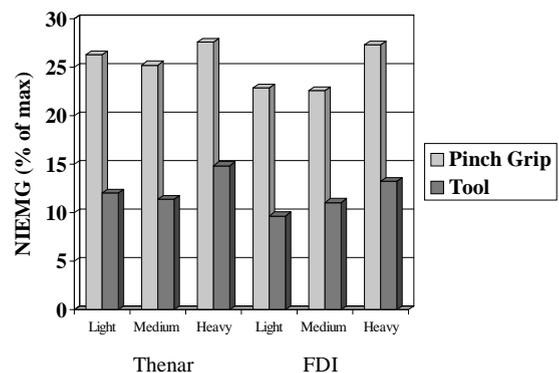

Fig. 7. Effect of upholstery handtool on the muscle activity of the intrinsic muscles of the hand.

the design of the tool. Finally, the results of the evaluation of the random orbital sander interface showed a 30% reduction in the muscle activity of the extensor muscle group but little impact on the
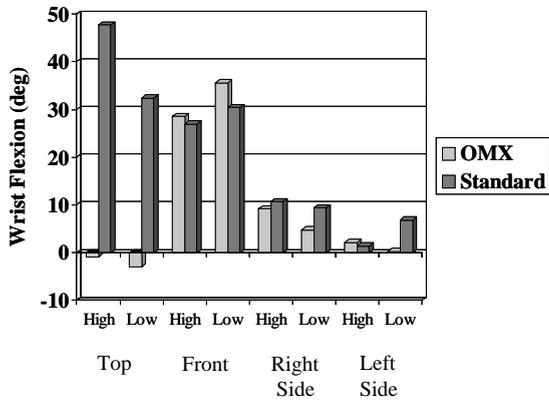
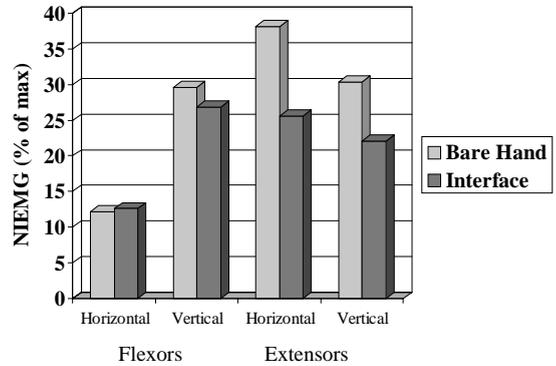Fig. 8. Effect of the OMX spray gun on the peak wrist flexion of the dominant wrist.

Fig. 9. Effect of the OMX spray gun on the peak ulnar deviation of the dominant wrist.

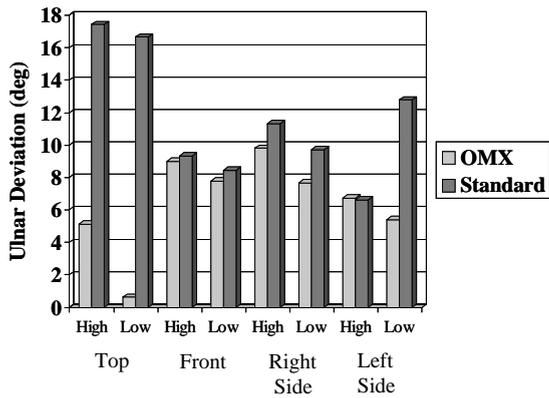Fig. 10. Effect of the random orbital sander interface on the activity of the extrinsic muscles of the dominant hand.

activity of the flexor group with the use of the sander interface (Fig. 10).

4. Discussion

A review of the significant results found in this experiment finds a strong correlation between the location of furniture workers' subjective discomfort and the positive changes that resulted from the interventions. Specifically, the upholsterers often complain of discomfort (burning, pain, fatigue) in the non-dominant hand when working with heavy fabrics or leather, a symptom of overuse of the intrinsic, pinch grip muscles. The data in this

research suggest that the upholstery hand tool developed and evaluated in this study removes the burden from these intrinsic hand muscles as they perform this repetitive fabric-pulling task. Users of the random orbital sanders complain of discomfort in the back of the forearm with long duration use of the sanders. The data in this study would suggest that the interface intervention specifically reduces the static load burden that those extensor muscles are asked to carry. Finally, the wrist flexion and ulnar deviations of the wrist of the dominant hand in sprayers are risk factors that have led to reports of wrist discomfort and a higher-than-average incidence of various hand/wrist disorders in this worker population. The modified-design spray gun tested in this study did, in fact, have a positive impact on these extreme postures particularly during work on the large horizontal surfaces such as the surface of a desk or conference table. While the size of the product "sprayed" in the current study was quite a bit larger than that of the Lee et al. (1997) study, the results of the current study support the earlier findings. These data collectively represent the first step in the development of useful tools for reduction of the incidence of work-related musculoskeletal disorders of the upper extremity in the furniture manufacturing industry. The next step in our process of intervention development and evaluation is to assess the effectiveness and efficacy of these ideas in industrial environments. The data collected in the laboratory will form the founda-

tion of our discussions with industry personnel with the goal being a long-term industry-based assessment of these tools. Several studies have shown the importance of participation of the end users in the ultimate acceptance of any modification to the work activity (Laitenen et al., 1997, 1998; Pohjonen et al., 1998; St. Vincent et al., 1997, 1998; Bohr et al., 1997; Moore and Garg, 1998; Halpern and Dawson, 1997; Lanoie and Tavenas, 1996). It is our intention to use these laboratory data to show (to both management and shop floor workers) the direct relationship between the discomfort that the workers are feeling and the nature of the work activities involved. Further, we will then be able to show that we have targeted the specific symptoms and communicate our assessment that these interventions may, in the long run, create a safer and more productive workplace.

Human beings are creatures of habit and inertia, particularly when it comes to their livelihood. Many jobs in the furniture manufacturing industry are compensated on a piece rate system. Due to this, workers who are currently satisfied with their level of compensation will be averse to any type of suggested change. Unfortunately, it may take a serious musculoskeletal disorder to make these workers realize that the short-term financial benefits that come from this compensation system often come at a long-term price. Generally, management is not over-enthusiastic about change unless they are confronted with very high levels of worker-compensation costs. Therefore, the goal of our intervention work is to illustrate, to both the worker and management, that in the long run, this change will not only reap safety benefits but productivity benefits as well. This can only come through education and part of that education needs to be the presentation of solid scientific data showing these benefits.

5. Conclusions

While the ultimate objective of ergonomic intervention research is the development of tools, work methods, etc. that result in the reduction of work-related illnesses and injuries, intermediate steps are often required to illustrate the effectiveness and efficacy of these interventions. Often, the first step in this process is to perform laboratory evaluations of the intervention to demonstrate that it is effective in reducing the level of the specific risk factor determined in the ergonomic task analysis. The quantitative results from the current study indicate a significant reduction in the biomechanical stresses identified in the ergonomic task analyses of the chosen tasks. The dependent measures chosen to quantify these effects are well-correlated, biomechanically, with the subjective discomfort experienced by these workers giving motivation for more in-depth field evaluations. Follow-up field assessments are currently underway to further evaluate the effectiveness of these interventions and to begin our assessment of the potential efficacy of the intervention, i.e. documenting impediments (negative effects on productivity, worker resistance to change, intervention cost, etc.) that might reduce the likelihood of implementation of the interventions.

Acknowledgements

Appendix A. Derivation of test statistics

Experiment 1: upholstery handtool
  A—pull force (3 levels) (random effect)
  B—tool type (2 levels) (fixed effect)
  S—subject (11 levels) (random effect)

  To test the effect of pull force
    $F\text{-ratio} = (SS_A/df_A)/(SS_{AS}/df_{AS})$
  To test the effect of tool type
    $F\text{-ratio} = (SS_B/df_B)/[(SS_{SB}/df_{SB}) + (SS_{AB}/df_{AB}) - (SS_{ABS}/df_{ABS})]$

To test the effect of pull force × tool type
$$F\text{-ratio} = (SS_{AB}/df_{AB})/(SS_{SAB}/df_{SAB})$$

Experiment 2: spray gun
A—gun type (2 levels) (fixed effect)
B—surface location (4 levels) (random effect)
C—height (2 levels) (random effect)
S—subject (11 levels) (random effect)

To test the effect of gun type
$$F\text{-ratio} = (SS_A/df_A)/(MS_{POOLED\ ERR})$$
To test the effect of surface location
$$F\text{-ratio} = (SS_B/df_B)/(MS_{POOLED\ ERR})$$
To test the effect of height
$$F\text{-ratio} = (SS_C/df_C)/(MS_{POOLED\ ERR})$$
To test the effect of gun type × surface location
$$F\text{-ratio} = (SS_{AB}/df_{AB})/(MS_{POOLED\ ERR})$$
To test the effect of gun type × height
$$F\text{-ratio} = (SS_{AC}/df_{AC})/(MS_{POOLED\ ERR})$$
To test the effect of surface location × height
$$F\text{-ratio} = (SS_{BC}/df_{BC})/(SS_{SBC}/df_{SBC})$$
To test the effect of gun type × surface location × height
$$F\text{-ratio} = (SS_{ABC}/df_{ABC})/(SS_{SABC}/df_{SABC})$$

Experiment 3: sander interface
A—interface type (2 levels) (fixed effect)
B—surface orientation (2 levels) (random effect)
S—subject (11 levels) (random effect)

To test the effect of interface type
$$F\text{-ratio} = (SS_A/df_A)/[(SS_{SA}/df_{SA}) + (SS_{AB}/df_{AB}) - (SS_{ABS}/df_{ABS})]$$
To test the effect of surface orientation
$$F\text{-ratio} = (SS_B/df_B)/(SS_{SB}/df_{SB})$$
To test the effect of interface type × surface orientation
$$F\text{-ratio} = (SS_{AB}/df_{AB})/(SS_{SAB}/df_{SAB})$$

References

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