



Comparison of biomechanical loading during use of conventional stud welding equipment and an alternate system

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ABSTRACT

We investigated the effect of an alternative welding system designed to reduce exposure to extreme trunk flexion on measures of trunk inclination and muscle activity. Among 10 participants, data were collected while using conventional stud welding equipment and while using the alternate system. Paired *t*-tests were used to compare results between the two welding systems. Mean trunk inclination angle was reduced with the alternate system (34.4° versus 9.7°, $p < 0.01$). Percent time with trunk inclination angles greater than 60° was also reduced (40.0% versus 4.7%, $p < 0.01$). In general, the alternate system resulted in less desirable upper trapezius muscle activity levels. The alternate system appears to be effective in reducing exposure to extreme trunk flexion among stud welders. Continued development of the system should explore features designed to reduce shoulder forces and improve productivity.

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1. Introduction

Musculoskeletal disorders are common among workers in the construction trades (Schneider, 2001). Low back pain, in particular, is a major source of morbidity and disability among workers in several trades, including ironworkers (Elders and Burdorf, 2004; Forde et al., 2005; Goldsheyder et al., 2002, 2004; Latza et al., 2000; Merlino et al., 2003). Physical risk factors in the working environment, including repetitive motion, awkward postures, forceful exertions, and whole-body vibration have been associated repeatedly with low back pain (Bernard, 1997; Burdorf and Sorock, 1997; National Research Council – Institute of Medicine, 2001). Evidence of these associations from ecologic, case-control, and cross-sectional studies is supported by the results of more recent prospective cohort studies (Hoogendoorn et al., 2000; Van Nieuwenhuysse et al., 2006).

Previous studies of physical risk factors associated with ironwork have focused on concrete reinforcement tasks (Albers and Hudock, 2007; Buchholz et al., 2003; Dababneh and Waters, 2000; Forde et al., 2005; Vi, 2006). Exposures to physical risk factors among ironworkers specializing in welding activities have not been reported.

Ironworkers weld shear stud connectors (Fig. 1) to structural steel to strengthen steel and concrete composite materials. On road

bridges, for example, shear stud connectors are used to 1) anchor the concrete slab to the structural steel, 2) increase longitudinal shear load bearing capacity, and 3) reduce the amount of steel needed in the structural members, minimizing overall steel cost. A typical shear stud connector consists of a steel rod between approximately 8.0 cm and 26.0 cm length and up to 1.9 cm in diameter, with a flange at one end. A ceramic ferrule is used to keep heat and molten material within the appropriate zone when welding a stud to the steel beam (American Society of Civil Engineers, 2002).

Ironworkers who install shear stud connectors are exposed to prolonged, extreme forward flexion of the trunk during the welding activity and related subtasks (Fig. 2). Therefore, the primary exposure may be considered a stooped work posture, which Holmström et al. (1992) found to be associated with an elevated risk of low back pain when the duration of exposure exceeded 4 h per day.

Stud welding is a four-step arc welding operation (American Welding Society, 2004). First, a stud is loaded into a semi-automatic arc welding gun (stud gun) which is then positioned through a ferrule and in direct contact with the steel. Second, the operator triggers the stud gun, sending current through stud. The stud gun will then slightly elevate the stud, creating an arc of electricity between the stud and steel, forming a path for the weld current. Third, after the weld current has melted both the stud tip and base steel, the stud gun will plunge the stud downward into the molten material. The lift and plunge operations are performed automatically by the stud gun, but the operator must exert downward pressure to maintain the vertical position of the welding gun relative to the steel. Finally, once the completed weld has cooled,

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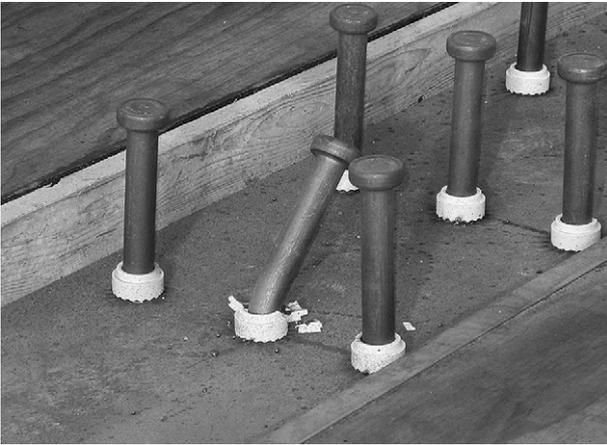


Fig. 1. Welded shear stud connectors with ceramic ferrules during bridge construction.

the ceramic ferrule is discarded. In the case of bridge construction, each weld location is prepared with an angle grinder (Fig. 2b).

Typically, stud welding is a two-person job. The overall job using conventional equipment consists of several subtasks, including setting up the welding equipment (generator, cabling, welding controller, and stud gun), grinding, laying out the ceramic ferrules and studs, welding studs, and occasionally repositioning the cabling and welding controller. A standard welding cable may weigh in excess of one pound per linear foot, depending on the amperage rating; therefore, high shoulder forces may be required to move cable. The ironworker designated as the stud welder will be solely responsible for setting up the welding equipment and welding studs. The support worker will lay out the majority of the ferrules and studs for the stud welder, assist with repositioning of the cabling and welding controller as necessary, and perform the majority of the grinding.

An alternate system with the potential to reduce exposure to extreme trunk flexion during stud welding is shown in Fig. 3. The system includes a wheeled cart with an articulating arm to which standard stud gun components are attached. The articulating arm allows the operator to maintain a more upright working posture, potentially reducing the mechanical load on the low back. The cart weighs 175 lbs. The system uses standard shear stud connectors, ferrules, welding cables, and welding controllers, and functions essentially as a pass-through for the weld current. The support worker is responsible for moving the cart, feeding studs into the cart, and will share in the responsibility of laying out ferrules using a semi-automatic dispenser (Fig. 3b). On a bridge site,

the cart rests atop wheels, allowing the support worker to move it easily. A footbrake mechanism is used to lock the cart in place during active welding, which prevents the support worker from exerting forces to maintain the position of the cart. A brief multi-person lift is required to move the cart across the girders. During our preliminary observations, such lifts took less than 5 s, did not require the full weight of the cart to be lifted at one time (i.e., the workers could “shuffle” the cart across the beams), and occurred infrequently (<5 per day).

The objective of this study was to compare estimates of trunk inclination, muscle activity, and spinal compression during use of conventional equipment and during use of the alternate system.

2. Methods

2.1. Description of study design

This study was a repeated-measures, field-based assessment of trunk inclination angle and erector spinae and upper trapezius muscle group activation levels among ironworkers using a conventional and an alternate stud welding system. Data were collected from each participant for one complete work shift. Conventional stud welding methods were used during half of the shift and the alternate system was used during the other half shift. The order of welding method used was randomized. All participants were experienced in the use of both the conventional and alternate stud welding systems prior to enrollment in the study. The effect of stud welding method on muscle activation, trunk inclination, and estimated spinal compression was examined.

2.2. Participants

Study participants were a convenience sample of ten healthy stud welders. Participants provided written informed consent when enrolled and were provided \$100 compensation.

2.3. Measurement overview

Eight hours of data collection was the target for each study day. However, variations in equipment set-up time, weather, and job site often reduced measurement time.

2.4. Surface EMG methods

2.4.1. EMG equipment

Myoelectric activity of the upper trapezius and thoracic erector spinae (T9 level) muscles were recorded bilaterally. Surface EMG

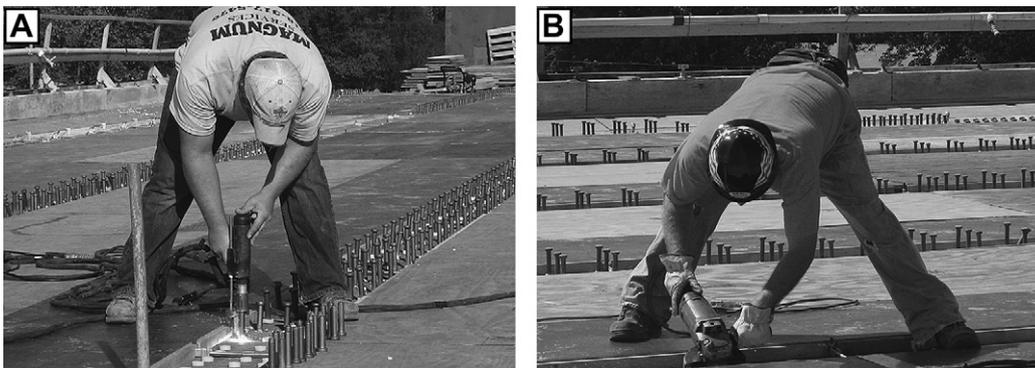


Fig. 2. A – stud welding using conventional equipment; B – preparing weld locations with an angle grinder. Bridge construction.



Fig. 3. A – stud welding using alternate system; B – placing ferrules with automatic dispenser. Bridge construction.

electrodes were secured with tape over each muscle using standard placement guidelines (Zipp, 1982). The skin was cleaned with alcohol and hair removed with a shaver. The electrodes had dual, bipolar, 10×1 mm silver bars, an inter-electrode distance of 10 mm, differential amplification with a gain of 1000, and a 20–450 Hz bandwidth (model DE2.3, Delsys Inc., Boston, MA). A reference electrode was placed over the non-dominant clavicle.

The electrodes were connected to a data logger (Myomonitor IV[®], Delsys Inc., Boston, MA) and the EMG signals digitized at 1000 Hz and recorded on a compact flash memory card. The data logger fit into a small pack worn on the waist. The logger had a liquid crystal display to allow viewing of the EMG signals for quality monitoring.

2.4.2. EMG pre-analysis processing

EMG recordings were processed with custom software (Fethke et al., 2004). The unprocessed EMG recordings were first visually scanned for obvious transient artifacts which were removed and replaced with the mean voltage of the entire recording period. This method ensured that 1) equal numbers of samples remained for each channel of EMG data and 2) removing the transients did not alter the mean value of the entire EMG voltage record.

Occasionally, an electrocardiogram artifact was observed on the erector spinae recordings. In these cases, additional high pass filtering was performed using standard methods (Drake and Callaghan, 2006; Redfern et al., 1993).

After transient inspection and electrocardiogram filtering, the mean voltage value of the unprocessed EMG files was subtracted to remove DC offset. Then, the power spectral density (PSD) of each EMG recording was examined to identify frequencies of noise contamination. Based on the PSD characteristics, digital IIR filters could then be designed to attenuate specific noise frequencies, if observed, prior to further processing.

The final step in preparing the EMG data for analysis involved converting the unprocessed recordings to instantaneous root-mean-square (RMS) amplitude. RMS conversion was done using a 100-sample moving window with a 50-sample overlap. The resulting RMS-processed EMG files thus had an effective rate of 20 Hz.

2.4.3. EMG normalization procedures

For each muscle group, myoelectric activity was expressed as a percentage of the electrical activation obtained during submaximal reference contractions (%RVE). For the upper trapezius, reference contractions were obtained while the participant held a 2 kg weight in each hand with arms abducted to 90° in 20° horizontal adduction, elbows fully extended and forearms pronated (Mathiassen et al.,

1995). For the erector spinae, participants flexed forward to a trunk inclination angle of 30° from vertical and held loads with both hands and arms hanging vertically. Two reference loads were used (62.3 N and 113.4 N); the heavier load was used as the reference to estimate %RVE values while both were used to estimate spinal compression (Section 2.6). Subjects were standing for all reference contractions.

Three repetitions of each submaximal reference contraction were performed, with a rest period of at least 1 min between repetitions. Participants maintained each submaximal reference contraction for 15 s, and the mean RMS amplitude of the middle 10 s of each contraction was calculated. The average of the mean RMS EMG amplitudes from the three reference contractions was used as the RVE activation level for each muscle.

The resting RMS EMG amplitude level was also measured. While participants sat in a relaxed posture with the upper back and arms supported, EMG was recorded for 60 s. The resting level was defined as the lowest RMS amplitude during the 60 s recording period and was quadratically subtracted from all subsequent RMS EMG amplitude values (Thorn et al., 2007). Following subtraction of the resting level, RMS voltage values collected during welding activities were divided by the reference RMS voltage levels, providing EMG amplitude as a percentage of the submaximal reference RMS voltage (i.e., %RVE).

2.4.4. EMG summary measures

The arithmetic mean of the normalized RMS EMG amplitude (in %RVE) was calculated for each muscle during the use of the two welding methods. In addition, the peak, median, and static EMG levels for each muscle were obtained by calculating amplitude probability distribution functions (APDF) from the normalized RMS EMG waveforms (Jonsson, 1982). The peak EMG level was defined as the normalized RMS EMG value associated with the 90th percentile of the APDF, the median EMG level was defined as the normalized RMS EMG value associated with the 50th percentile of the APDF, and the static EMG level was defined as the normalized RMS EMG value associated with the 10th percentile of the APDF.

Periods of minimal EMG activation were evaluated using EMG gap analysis. EMG gap analysis provides two summary measures; *gap frequency* is the average number of gaps per minute over the total analysis time and *percent rest* is the summed duration of all identified gaps divided by the total analysis time (Veiersted et al., 1990). In this study, an EMG gap was defined for the upper trapezius muscles as a period of normalized RMS amplitude below 5 %RVE for at least 0.25 s. For the erector spinae muscles, the threshold amplitude used to define an EMG gap was the %RVE observed during upright standing hands resting naturally at the sides and holding no load.

2.5. Inclinometry methods

2.5.1. Inclinometry equipment

The angles of postural inclination in the flexion/extension and lateral bending planes relative to vertical were estimated with a triaxial accelerometer (model ADXL330, Analog Devices, Norwood, MA). The accelerometer was encased in a 40 × 20 × 5 mm polycarbonate block and secured with tape to the skin just below the sternal notch. For the purposes of this study, inclination angle in the flexion/extension plane was defined as *trunk inclination angle*, and inclination in the lateral bending plane was defined as *lateral inclination angle*. The accelerometer was connected to a data logger system (Myomonitor IV®, Delsys Inc., Boston, MA). The unprocessed acceleration signals were digitized at 1000 Hz and recorded on a compact flash memory card.

2.5.2. Inclinometer pre-analysis processing

The unprocessed acceleration recordings were first low pass filtered using a 4th order Butterworth digital IIR filter with a 5 Hz corner frequency to remove high frequency components unrelated to postural excursions. The filtered recordings were then additionally smoothed using a 100-sample moving average window with a 50-sample overlap. The resulting acceleration files thus had an effective rate of 20 Hz. Along with the smoothing, the moving average process also maintained a sample-to-sample temporal relationship between the inclination and RMS-processed EMG signals.

2.5.3. Inclinometer calibration

Once the accelerometer was secured to the skin, trunk and lateral inclination offset voltages were obtained by having each participant stand upright in a comfortable posture for 15 s. The upright standing posture offset voltage was subsequently subtracted from the accelerometer voltage measured during work activities prior to conversion to inclination angles. Postural inclination angles were computed as an arcsin of the ratio of the offset-adjusted sensor acceleration to gravitational acceleration.

2.5.4. Inclinometry summary measures

The arithmetic means of the trunk inclination, lateral inclination, and the absolute value of the lateral inclination angles were calculated for each stud welding method and APDFs were calculated from the from the trunk inclination, lateral inclination, and absolute value of the lateral inclination waveforms. Peak, median, and static inclination angles levels were then defined in a manner analogous to the peak, median, and static EMG values, above.

Exposure variation analysis (EVA) was used to simultaneously depict the level and duration of sustained trunk inclination and lateral inclination angles. While originally developed for EMG measurement (Mathiassen and Winkel, 1991), EVA has been used with inclinometer and electrogoniometer data in previous studies (Hägg et al., 1997; Jansen et al., 2001). Three trunk inclination angle categories were created: 1) $\leq 30^\circ$ of trunk inclination, 2) $> 30\text{--}60^\circ$ of trunk inclination, and 3) $> 60^\circ$ of trunk inclination. Similarly, three lateral inclination angle categories (absolute value) were created: 1) $\leq 15^\circ$ of lateral inclination, 2) $> 15\text{--}30^\circ$ of lateral inclination, and 3) $> 30^\circ$ of lateral inclination. For both inclination planes, five categories of the duration of sustained inclination angles were created: 1) ≤ 1 s, 2) $> 1\text{--}2$ s, 3) $> 2\text{--}5$ s, 4) $> 5\text{--}10$ s, and 5) > 10 s. The resultant EVA matrices provided the proportion of total observation time spent in each combination of the inclination angle and duration categories. For statistical analyses, the EVA matrices were collapsed across duration categories, providing the total proportion of observation time spent in each inclination angle category. In addition, the EVA profiles from each participant were used to compute an average EVA

matrix for each stud welding method and for each inclination plane in order to make qualitative comparisons between the methods.

2.6. Compression normalized EMG (CNEMG) methods

A procedure described by Mientjes et al. (1999) was modified and used to transform the RMS-processed EMG waveforms from the erector spinae muscles into estimated spinal compression. First, the height and weight of each participant was entered into computerized biomechanical model (3DSSPP, University of Michigan, Ann Arbor, MI). The posture of the model's digital mannequin was then adjusted to match the posture from the erector spinae EMG normalization procedure. The weight applied at the mannequin's hands was set to either 63.2 N or 113.4 N, depending on the normalization trial, and the estimated compression at the L4/L5 disc was noted from the model output. Similarly, the L4/L5 compression with the mannequin standing in an upright posture with no load at the hands was also estimated from the model. An EMG-to-compression calibration was then developed by assuming a linear relationship between the total erector spinae RMS amplitude and spinal compression (Village et al., 2005).

2.6.1. Specific CNEMG summary measures

The arithmetic mean of the CNEMG waveform (in kN) was calculated separately for each of the stud welding methods and an APDF was calculated from the CNEMG waveforms. Peak, median, and static CNEMG levels were then defined in a manner analogous to the peak, median, and static EMG values, above.

Exposure variation analyses were performed on the CNEMG waveforms to the compute the percentage of work time spent below 3400 N of L4/L5 of compression, between 3400 N and 6800 N of compression, and above 6800 N of compression. These compression categories represent NIOSH action and upper limits for spinal compression (Waters et al., 1993).

Due to differences in the time each participant spent using each welding system, direct comparisons of cumulative compression could not be performed. Instead, the compression rate, in kN per minute, was calculated for each system by dividing the cumulative compression by the total work time.

2.7. Statistical analyses

All statistical analyses were conducted with SAS, version 9.2 (SAS Institute, Cary, NC). Each summary measure was described with descriptive statistics (e.g., mean, sd) by stud welding method. Paired *t*-tests (two-tailed) were used to compare the summary measure means between the stud welding methods.

3. Results

3.1. Participant characteristics

Demographic characteristics of the ten study participants are presented in Table 1. All participants were male, right-handed, journeyman ironworkers, and had been employed with his current employer for a minimum of three years at enrollment.

3.2. Sampling duration

Exposure data were recorded for an average of 5.3 h (sd = 1.4 h) per participant (total for both welding methods, combined). The mean sampling duration was longer for conventional equipment (3.7 ± 1.6 h) than for the alternate system (2.2 ± 1.3 h).

Table 1
Participant demographics ($N = 10$).

Demographic variable	Median (range)
Age (yrs)	32 (24–44)
Height (m)	1.80 (1.68–1.85)
Body mass (kg)	91.8 (63.5–99.3)
Body mass index (kg/m^2)	27.8 (22.6–34.3)
Years with current employer	9.5 (3.0–16.0)

3.3. EMG data quality

3.3.1. Transient artifacts

The EMG recordings were generally unaffected by transient artifacts. On average, 5.34 s of unprocessed EMG were replaced with the mean voltage value per muscle (range: 0–36.4 s). Transients represented, on average, 0.03% of the original EMG information. No differences in the number or total duration of transients were observed between the stud welding methods.

3.3.2. Noise contamination

Frequency analysis of the unprocessed upper trapezius and erector spinae EMG recordings revealed no evidence of noise contamination at specific frequencies. Therefore, additional filtering was not required prior to RMS processing and computation of summary measures.

3.3.3. Exclusion of erector spinae EMG

The left and right erector spinae EMG recordings were excluded for two of the 10 participants. For these two participants, attachment tape failure resulting in losses in the integrity of the skin-to-electrode interfaces occurred after approximately 2 h of sampling.

3.4. Trunk inclination angles

Descriptive statistics of trunk inclination angle by welding method are presented in Table 2. In general, the alternate system resulted in substantial reductions in trunk inclination angle in

Table 2
Mean (sd) of trunk inclination and lateral inclinations summary measures by stud welding method, and paired t -test results.

Exposure variable	Conventional	Alternate	p -Value ^a
Trunk inclination angle^b			
Mean ($^{\circ}$)	34.4 (10.4)	9.7 (7.0)	<0.01
APDF 10th ($^{\circ}$)	-9.0 (4.7)	-10.1 (2.8)	0.26
APDF 50th ($^{\circ}$)	30.6 (28.6)	4.9 (7.0)	0.02
APDF 90th ($^{\circ}$)	81.7 (6.4)	34.6 (18.6)	<0.01
$\leq 30^{\circ}$ (% time)	52.6 (12.9)	85.8 (11.3)	<0.01
>30 – 60° (% time)	7.4 (5.9)	9.6 (10.1)	0.60
$>60^{\circ}$ (% time)	40.0 (10.1)	4.7 (5.7)	<0.01
Lateral inclination angle^c			
Mean ($^{\circ}$)	1.3 (3.8)	-3.0 (3.7)	0.03
APDF 10th ($^{\circ}$)	-13.2 (4.6)	-15.0 (5.2)	0.42
APDF 50th ($^{\circ}$)	0.7 (4.0)	-4.4 (4.3)	0.03
APDF 90th ($^{\circ}$)	18.8 (7.0)	10.5 (3.5)	0.02
Absolute value of lateral inclination angle			
Mean ($^{\circ}$)	10.6 (2.4)	9.4 (2.6)	0.31
APDF 10th ($^{\circ}$)	1.5 (0.4)	1.5 (0.7)	0.89
APDF 50th ($^{\circ}$)	8.1 (2.0)	8.0 (3.4)	0.93
APDF 90th ($^{\circ}$)	22.9 (5.4)	18.3 (3.9)	0.06
$\leq 15^{\circ}$ (% time)	76.2 (10.1)	79.9 (13.8)	0.50
>15 – 30° (% time)	18.7 (6.8)	17.7 (13.5)	0.84
$>30^{\circ}$ (% time)	5.1 (3.5)	2.4 (0.9)	0.04

^a p -Values obtained from paired t -tests for $N = 10$ participants.

^b Negative values = rearward inclination; positive values = forward inclination.

^c Negative values = left lateral inclination; positive values = right lateral inclination.

comparison to the conventional equipment. For example, mean trunk inclination angle was reduced from 34.4° ($sd = 10.4^{\circ}$) during use of the conventional equipment to 9.7° ($sd = 7.0^{\circ}$) during use of the alternate system ($p < 0.01$). Peak trunk inclination angle was reduced from a mean of 81.7° ($sd = 6.4^{\circ}$) during use of the conventional equipment to a mean of 34.6° ($sd = 18.6^{\circ}$) during use of the alternate system ($p < 0.01$). In addition, the percentage of work time spent in trunk inclination angles of greater than 60° was reduced from a mean of 40.0% ($sd = 10.1\%$) during use of the conventional equipment to a mean of 4.7% ($sd = 5.7\%$) during use of the alternate system ($p < 0.01$).

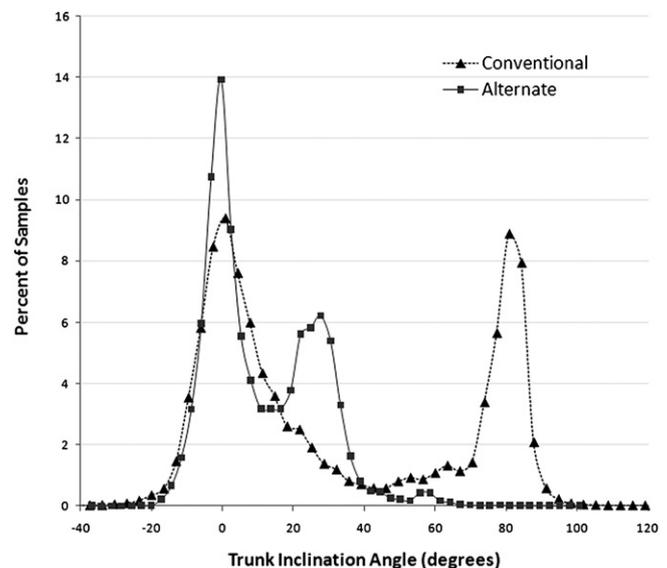
Histograms of trunk inclination angles for the conventional equipment and the alternate system are provided for one typical participant in Fig. 4. During use of the conventional equipment, the histogram of trunk inclination angle is bimodal, with one peak of inclination angles centered near 0° and a second peak centered near 80° . Thus, stud welders are either standing upright or assume a fully stooped posture while working, with little variation. During use of the alternate system, the inclination angle peak near 80° is shifted to near 30° . This indicates that while the alternate system minimizes exposure to stooped postures, some forward inclination is still required for operation.

The EVA of trunk inclination angles reflected the results of the APDF analyses. However, the EVA also revealed information about the duration over which trunk inclination angles were sustained during use of the two welding systems. The percentage of working time with trunk inclination angles greater than 60° for at least 10 continuous seconds was reduced from a mean of 29.2% ($sd = 12.9\%$) during use of the conventional equipment to a mean of 2.6% ($sd = 4.7\%$) during use of the alternate system ($p < 0.01$).

3.5. Lateral inclination angles

Descriptive statistics of lateral inclination angle by welding method are presented in Table 2. Examination of the lateral inclination angles indicates that the alternate system resulted in a shift of lateral inclination toward the left side compared to the conventional equipment.

The 90th percentile of the APDF of the absolute value of lateral inclination angle was nearly statistically significantly reduced from

**Fig. 4.** Trunk inclination angle histograms from one participant over 1 h of data collection with each stud welding method.

22.9° (sd = 5.4°) during use of the conventional equipment to 18.3° (sd = 3.4°) during use of the alternate system ($p = 0.06$). The percentage of work time spent with an absolute value of lateral inclination angle exceeding 30° was reduced from 5.1% (sd = 3.5%) during use of the conventional equipment to 2.4% (sd = 0.9%) during use of the alternate system ($p = 0.04$).

3.6. Upper trapezius EMG

Descriptive statistics and probabilities for the upper trapezius EMG summary measures are provided in Table 3. The alternate system resulted in greater upper trapezius muscle activity and reduced EMG gaps and rest time, bilaterally, compared to the conventional equipment.

For the left upper trapezius, the mean RMS activity increased from 16.0 %RVE (sd = 6.5 %RVE) during use of conventional equipment to 22.0 %RVE (sd = 10.7 %RVE) during use of the alternate system ($p = 0.01$), the static EMG level increased from 1.2 %RVE (sd = 0.6 %RVE) to 1.9 %RVE (sd = 1.2 %RVE) ($p = 0.04$), the median

EMG level increased from 6.8 %RVE (sd = 5.4 %RVE) to 13.6 %RVE (sd = 10.4 %RVE) ($p = 0.02$), and the percentage of work time with the muscle at rest decreased from 46.2% (sd = 15.6%) to 23.6% (sd = 15.4%) ($p < 0.01$). In addition, the peak EMG level increased and the number of EMG gaps per minute decreased during use of the alternate system, although these differences were not statistically significant. For the right upper trapezius, trends similar to the left upper trapezius were observed.

3.7. Erector spinae EMG

Descriptive statistics for erector spinae EMG measures are provided in Table 3. Few statistically significant differences were observed. For the right erector spinae, the number of EMG gaps per minute decreased from 18.8 (sd = 7.1) during use of conventional equipment to 12.1 (sd = 2.0) during use of the alternate system ($p = 0.03$), and the percentage of work time with muscle activity below the levels observed during upright standing decreased from 22.2% (sd = 10.9) to 14.2% (sd = 5.1%) ($p = 0.02$).

3.8. Compression normalized EMG

Descriptive statistics and the results of the paired t -tests related to CNEMG summary measures are provided in Table 3. No statistically significant differences were observed between the conventional equipment and the alternate system in terms of estimated spinal compression.

Table 3

Mean (sd) of EMG and CNEMG summary measures by stud welding method, and paired t -test results.

Exposure variable	Conventional	Alternate	p -Value ^a
<i>Left upper trapezius EMG (N = 10)</i>			
Mean RMS (%RVE)	16.0 (6.5)	22.0 (10.7)	0.01
APDF 10th (%RVE)	1.2 (0.6)	1.9 (1.2)	0.04
APDF 50th (%RVE)	6.8 (5.4)	13.6 (10.4)	0.02
APDF 90th (%RVE)	43.1 (15.2)	49.5 (27.0)	0.26
Gaps ^b (#/min)	17.8 (7.9)	13.6 (5.1)	0.18
Rest ^c (%time)	46.2 (15.6)	23.6 (15.4)	<0.01
<i>Right upper trapezius EMG (N = 10)</i>			
Mean RMS (%RVE)	19.7 (8.1)	25.4 (10.3)	0.02
APDF 10th (%RVE)	1.3 (0.7)	1.5 (0.9)	0.45
APDF 50th (%RVE)	9.3 (8.1)	15.0 (11.1)	0.09
APDF 90th (%RVE)	54.1 (23.3)	59.9 (20.5)	0.39
Gaps ^b (#/min)	17.1 (4.6)	13.6 (3.7)	0.03
Rest ^c (%time)	39.5 (14.8)	29.0 (11.3)	<0.01
<i>Left erector spinae EMG (N = 8)</i>			
Mean RMS (%RVE)	64.3 (18.9)	68.7 (22.0)	0.47
APDF 10th (%RVE)	15.2 (3.6)	14.1 (3.6)	0.18
APDF 50th (%RVE)	41.9 (11.9)	46.6 (11.0)	0.31
APDF 90th (%RVE)	136.8 (49.0)	150.5 (69.3)	0.45
Gaps ^d (#/min)	21.2 (8.3)	18.9 (6.3)	0.49
Rest ^c (%time)	23.5 (16.1)	23.0 (8.9)	0.88
<i>Right erector spinae EMG (N = 8)</i>			
Mean RMS (%RVE)	75.1 (41.8)	71.1 (27.9)	0.57
APDF 10th (%RVE)	13.1 (5.3)	14.5 (4.4)	0.15
APDF 50th (%RVE)	46.7 (24.9)	50.5 (18.2)	0.43
APDF 90th (%RVE)	165.7 (99.8)	147.9 (70.3)	0.32
Gaps ^d (#/min)	18.8 (7.1)	12.1 (2.0)	0.03
Rest ^c (%time)	22.2 (10.9)	14.2 (5.1)	0.02
<i>Estimated L4/L5 compression (N = 8)</i>			
Mean (kN)	1.55 (0.48)	1.59 (0.43)	0.71
APDF 10th (kN)	0.50 (0.25)	0.52 (0.24)	0.30
APDF 50th (kN)	1.15 (0.39)	1.25 (0.31)	0.33
APDF 90th (kN)	3.02 (1.11)	3.02 (1.16)	0.99
≤3.4 kN (% time)	91.1 (6.9)	91.5 (7.2)	0.80
>3.4–6.8 kN (% time)	7.5 (5.7)	7.3 (5.9)	0.88
>6.8 kN (% time)	1.3 (1.7)	1.2 (1.7)	0.29
Compression rate ^e (kN/min)	93.3 (29.0)	95.3 (26.1)	0.71

^a p -Values obtained from paired t -tests.

^b EMG gap (upper trapezius) = period of muscle activity below 5 %RVE for at least 0.25 s.

^c EMG rest defined as the summed duration of all identified EMG gaps divided by signal time.

^d EMG gap (erector spinae) = period of muscle activity 1) below the %RVE during upright standing 2) for at least 0.25 s.

^e Compression rate defined as the cumulative compression divided by time.

4. Discussion

4.1. Trunk inclination angle

Epidemiologic evidence suggests that long-term exposure to the trunk inclination exposure pattern observed in this study among stud welders using conventional equipment can lead to an elevated risk of LBP. In a case-control study, Punnett et al. (1991) observed a positive association between the percentage of work time spent in trunk flexion angles exceeding 20° and LBP. When considering trunk flexion angles greater than 45°, the risk of LBP was further elevated. Similarly, Jansen et al. (2004) reported an increased risk of disabling LBP among nursing home workers when trunk flexion exceeded 45° for more than 90 min per week. Seidler et al. (2001) examined the associations between physical risk factors and several low back musculoskeletal outcomes. The cumulative number of hours spent in trunk flexion greater than 90° was associated with LBP-related diagnoses among patients from a variety of occupations.

In this study, we observed significant improvements in the magnitude and duration of exposure to forward trunk inclination during use of the alternate system. The alternate system reduced the mean and peak angles of trunk inclination, the overall percentage of work time with trunk inclination angles of greater than 60°, and the percentage of work time with sustained trunk inclination angles of greater than 60°.

4.2. Muscle activation levels

4.2.1. Upper trapezius

While the alternate system clearly improved trunk inclination angles, it resulted in less desirable upper trapezius EMG profiles. Generally, the left and right upper trapezius muscles had 1) modestly higher amplitudes of activation and 2) moderately decreased duration of rest while using the alternate system. Two interacting factors likely contributed to the observed results. First, the operator's upper body weight was fully supported on the conventional welding gun while in the welding position. This

action secured the welding gun over the weld location without the application of large forces from the shoulder musculature. Resultant low levels of upper trapezius activation (<5 %RVE) were observed throughout the welding activity, as illustrated in Fig. 5.

Second, during use of the alternate system, the operator must repeatedly manipulate the articulating arm and apply downward pressure to load and maintain the position of the stud over the weld. The forces needed to manipulate the articulating arm and apply downward pressure are acting at various horizontal distances from the shoulder joint, resulting in external shoulder joint moments and increased upper trapezius contraction levels for shoulder joint stabilization (Fig. 6).

Numerous studies have evaluated upper trapezius EMG activity in occupational settings (Mathiassen et al., 1995). Decreases in the frequency of EMG gaps or in the proportion of work time with muscle rest, or increases in measures of EMG amplitude among workers with pain versus workers without pain have been reported (Aarås, 1994; Holte and Westgaard, 2002; Jensen et al., 1993; Østensvik et al., 2009; Sandsjö et al., 2000; Vasseljen and Westgaard, 1995; Veiersted et al., 1990; Veiersted, 1994). An important question is whether the potential benefits that result from reduced trunk inclination angles outweigh the potential risks resulting from less desirable upper trapezius EMG. Ultimately, this is an empirical question and must be evaluated by study of musculoskeletal outcomes among workers using both systems for an extended period.

4.2.2. Erector spinae

As forward trunk flexion reaches about 70°, erector spinae activity in the lumbar region ceases as passive tissues (e.g., ligaments) assume a greater role in balancing the external torque (Solomonow et al., 2003). This response is commonly referred to as flexion–relaxation. Although trunk inclination angles during use of the conventional equipment were sufficient to elicit the

flexion–relaxation response in the lumbar erector spinae, the thoracic erector spinae remained active, as shown in Fig. 5. During use of the conventional equipment, a cessation of erector spinae activity was evident during the welding action as the upper body weight was fully supported on the welding gun (e.g., Fig. 5, region B → C), followed by a period of activity as the welding gun was loaded and repositioned over the next weld location (e.g., Fig. 5, region C → D). Similar to the upper trapezius response, the erector spinae activity observed during use of the alternate system (Fig. 6) was caused by the increased external bending moments during manipulation of the articulating arm.

The observed reduction in the percentage of work time with muscle activity below the levels needed to maintain an upright standing posture for the right erector spinae during use of the alternate system was a function of posture. Participants tended to lean slightly to the left in order view the work surface when manipulating the articulating arm into the welding position. Inspection of the results shows that left lateral inclination was more common than right lateral inclination during use of the alternate system. Subsequently, the right erector spinae, although not contracting with increased amplitude, was contracting more steadily to maintain posture during use of the alternate system.

4.3. Estimated spinal compression

The CNEMG results agree well with previous research among construction workers. Trask et al. (2010) reported, among a group of 25 construction workers using full-shift data, mean CNEMG levels of 1.77 kN, static and peak CNEMG levels of 0.73 kN and 3.07 kN, respectively, and about 5% of observation time above 3.4 kN. However, we did not observe meaningful differences in estimated L4/L5 compression between the stud welding systems. This is somewhat surprising since, with all other factors constant (e.g., anthropometry, load at the hands, etc.), spinal compression force increases with greater trunk flexion. There are several plausible

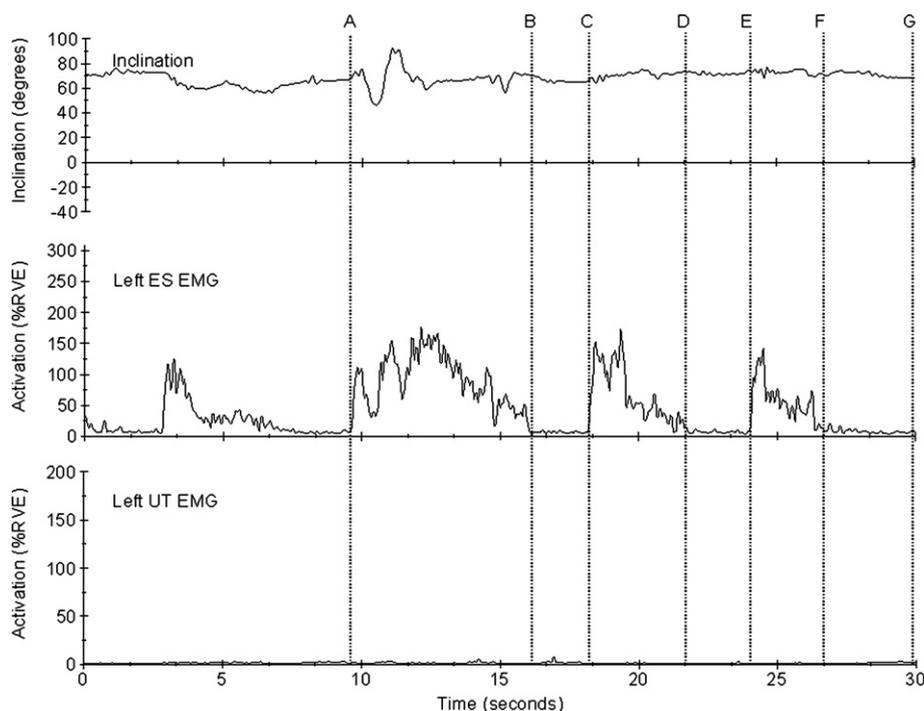


Fig. 5. Trunk inclination angle, left erector spinae (ES) EMG, and left upper trapezius (UT) EMG collected during use of the conventional equipment. A → B: moving to next row and loading first stud; B → C: welding first stud; C → D: loading second stud; D → E: welding second stud; E → F: loading third stud; F → G: welding third stud.

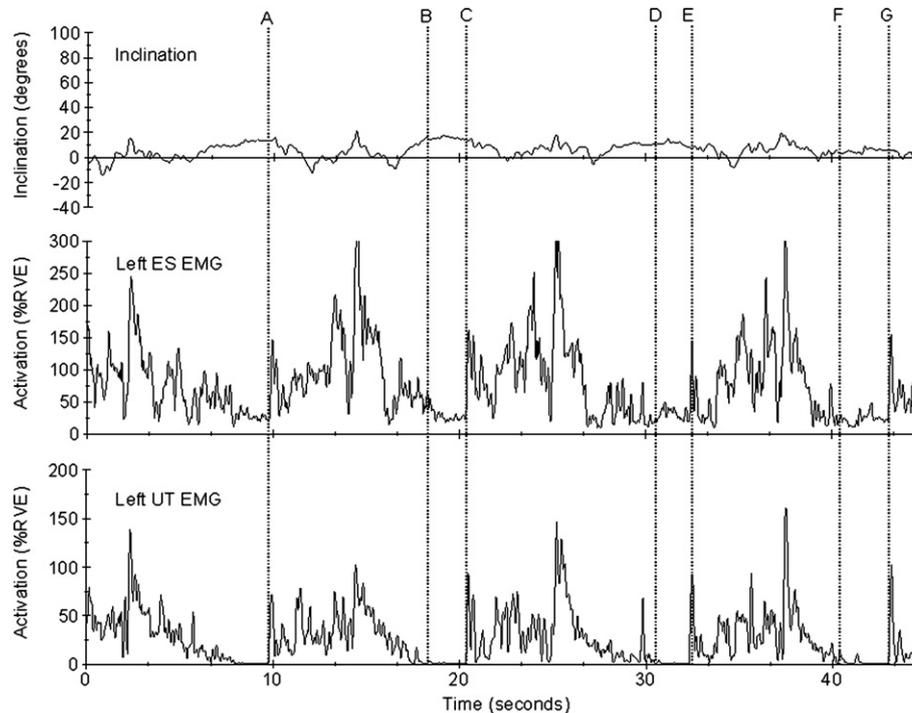


Fig. 6. Trunk inclination angle, left erector spinae (ES) EMG, and left upper trapezius (UT) EMG collected during use of the alternate system. A → B: loading first stud in row; B → C: welding first stud; C → D: loading second stud; D → E: welding second stud; E → F: loading third stud; F → G: welding third stud.

explanations. First, the external moments imposed upon the L4/L5 during use of the alternate system may have resulted in erector spinae activity levels similar to those observed during use of the conventional equipment. The absence of observed significant differences in the mean RMS erector spinae amplitude between the welding methods supports this possibility.

Second, the relationship between erector spinae EMG activation levels and spinal compression may not be linear across the range of trunk postures observed in this study. Nonlinear relationships between EMG activation levels and muscle tension estimates are common, especially when considering a wide range of forces, postures, and dynamic activities (Cram and Kasman, 1998). In addition, the relationship between EMG activation and spinal compression may not be linear, and the linear EMG-to-compression calibration technique used to derive the CNEMG waveforms may have resulted in erroneous estimates of spinal compression. A more robust calibration would use a range of postures, hand loads, and anthropometric measures as model inputs. However, because data were collected on active job sites, increasing the complexity and time requirements of our normalization and calibration procedures were not feasible.

We selected the thoracic region for our erector spinae electrode placement location (versus the lumbar region) to minimize the effect of the flexion–relaxation phenomenon in our recorded EMG signals (Dolan and Adams, 1993; Potvin et al., 1996). However, the correlation between erector spinae activation levels at T9 and activation levels in the lumbar region was not assessed. If the correlation was weak, then our estimates of spinal compression may not accurately reflect the biomechanical loads imposed on lumbar region.

Finally, the summary measures presented in this study, including those related to estimated spinal compression, reflect job-level and not task-specific exposures. Restricting the analysis to periods of active welding time could accentuate the differences between the conventional equipment and the alternate system.

4.4. Productivity

Although not formally evaluated, we did observe productivity during use of the stud welding methods. The cycle time for the conventional equipment ranged between 3 and 8 s per weld, and for the alternate system, the cycle time ranged between 11 and 18 s per weld. Production rates, considering welding and all supporting tasks (e.g., grinding, dispensing ferrules, etc.) and breaks, were also reduced during use of the alternate system (~250 welds per hour) versus the conventional equipment (~350 welds per hour). If a formal comparison of productivity during use of the conventional and alternate stud welding methods confirms our informal observations, contractors may be reluctant to adopt the alternate welding system as standard work practice.

4.5. Limitations

There were several limitations to this study. The trunk inclination and lateral inclination angles reflect the spatial orientation of the accelerometer, adjusted for a neutral reference posture, and were not direct measures of trunk posture in the flexion/extension and lateral bending planes. The unprocessed acceleration signals were low pass filtered and smoothed to minimize errors in the estimation of the trunk and lateral inclination angles resulting from higher frequency acceleration components unrelated to posture. Previous studies have reported minimal error associated with the use of accelerometers in estimating inclination angles in dynamic settings, especially during slower movements (Miller and Fathallah, 2007; Paquet et al., 2001; Wong et al., 2009). Other aspects of trunk motion (e.g., axial rotation) may also contribute to LBP risk but were not assessed in this study (Marras et al., 1995).

Although a sample size of 10 stud welders was sufficient to detect differences in several EMG and inclination summary measures using the repeated-measures design, we were not able to assess modification of the effect of welding system by other variables. The effect of

the alternate system on trunk inclination and muscle activation during stud welding may depend partly on the anthropometric characteristics of the operator. For example, operators with shorter arm lengths might experience higher levels of upper trapezius activity when manipulating the articulating arm of the alternate system than operators with longer arms. In addition, the non-random selection of participants limits our ability to generalize the observed results to the larger population of stud welders.

Finally, the data included in our analyses were collected during bridge construction only. The effect of the alternate system on trunk inclination and muscle activity may be different during other activities. In bridge construction, the welding occurs along each structural member in an essentially linear manner, with each row of three studs spaced approximately eight to ten inches apart along the beams (Figs. 2 and 3). In buildings, the studs are welded in an area pattern, and welders using conventional equipment may have more opportunity to return to an upright posture between welds.

A potential, secondary benefit of the alternate system is a reduction in the concentration of welding fume within the operator's breathing zone when compared to the conventional equipment. Adverse health effects associated with exposure to welding fume include respiratory illnesses such as asthma, bronchitis, and a possible increased risk of lung cancer (NIOSH, 2003). Future research concerning the stud welding alternate system should include an industrial hygiene component to assess these exposures.

4.6. Conclusions

The primary objective of this study was to evaluate the potential of an alternate stud welding system designed to reduce exposure to extreme trunk flexion among ironworkers. The results suggest that the alternate system is effective in reducing both the magnitude of trunk inclination and the percentage of work time spent in trunk inclination angles exceeding 60°. However, the alternate system appears to result in less desirable estimates of upper trapezius muscle activation levels. The observed results should be interpreted with caution in light of the small sample size and non-random selection of study participants.

Further development and study of the alternate system is recommended. Possible design enhancements should focus on 1) minimizing the forces required to operate the articulating arm and 2) increasing the production capability to encourage adoption of the system among workers in the trade.

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