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Electromyographic and discomfort analysis of confined-space shipyard welding processes

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Abstract

This study examined muscle fatigue and discomfort in a confined-space welding operation at a shipyard. Surface electromyography (SEMG) was recorded from seven upper extremity and torso muscles of welders welding in a mock-up of the work environment. Following spectral transform of the SEMG data the percentage of the total signal power in the 10–30 Hz frequency band was compared over time during welding. For the conventional stick electrode welding process (SMAW) several muscles exhibited an increase in the percent of the total signal power in the low-frequency band. Fewer muscles exhibited this fatigue-related spectral density shift with a wire welding process (FCAW) the shipyard has considered adopting. This finding suggests that localized muscle fatigue may be reduced by a change to the wire welding process. Subjectively reported discomfort was generally low for both processes, but confirmed the finding that discomfort in the low back and shoulder regions is experienced in this welding operation. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Muscle fatigue; Confined space; Welding; Electromyography

1. Introduction

Welders suffer from musculoskeletal symptoms of the neck, shoulders, and low back (Torner et al., 1991). In a comprehensive musculoskeletal evaluation study of 58 welders and 33 office clerks Torner et al. (1991) reported that 76% of the welders reported subjective shoulder and/or neck symptoms in the past year, more than double the percentage of office clerks reporting such symptoms. Herberts et al. (1981) found that the prevalence ratio of shoulder pain (supraspinatus tendinitis) in shipyard welders was 18%, which was significantly higher than the ratio for clerks within the same yard. Given these relatively high rates of symptom prevalence, welders as an occupational group have been studied inadequately in terms of the ergonomic factors that affect health and performance. Relatively few studies examining the ergonomic aspects of welding, let alone welding in confined spaces during the construction of ships, have been reported. The few studies that have been conducted indicate that welders have a high prevalence of musculoskeletal symptoms and clinical signs due primarily to static loading of the shoulders (Jarvholm et al., 1991; Torner et al., 1991), neck (Torner et al., 1991), and low back (Torner et al., 1991).

Electromyography (EMG) has been used to evaluate localized muscle fatigue in the shoulder muscles in overhead and shoulder-level welding (Kadefors et al., 1976). In a later study of a similar shoulder-level welding simulation with arm supports others from Kadefors' group (Jarvholm et al., 1991) focused on intramuscular recordings from the supraspinatus. Using surface EMG Beauchamp et al. (1997) examined "percent muscle use" from "five muscles in the upper limbs most called upon during the welding activity", which included the anterior deltoid and the anterior cubital. They evaluated five welding guns and three welding positions ("horizontal", "vertical", and "ceiling") reporting an increase in the activity of the anterior deltoid in overhead welding as the angle between the wire tip and the weld gun handle decreases. The anterior cubital was reported to be most active in the horizontal welding position in which the moment was highest. The activity of other muscles was not reported. Thus, there have been studies reporting significant shoulder muscle activity in overhead welding,

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and evaluations of different welding units in well-controlled welding positions. However, to our knowledge, no study has evaluated musculoskeletal demands in confined space welding — a job observed in many shipbuilding operations.

Several ergonomic studies of work in restricted space (most associated with mining) have focused on the physiological demand and spinal loading associated with manual handling and lifting. Gallagher et al. (1988) reported increases in metabolic demand and decreases in psychophysical lifting capacity in kneeling postures (relative to stooped postures) necessary in low seam mines with restricted vertical space. Gallagher et al. (1994) examined spinal compressive forces in symmetric and asymmetric lifting while lifting in kneeling and stooped postures representative of postures in low-seam mines. Studies using intra-abdominal pressure have not been conclusive in showing increased spinal loading associated with vertically restricted headroom (Sims and Graveling, 1988).

With the exception of Mozrall et al. (2000) most studies evaluating physiological and/or biomechanical demands of restricted space work have investigated only vertical restriction. Mozrall et al. have examined the isolated and combined effects of vertical, sagittal, and lateral restrictions on a variety of behavioral, physiological, psychophysical, and performance measures in a simulated cognitive inspection task. The degree of restriction they presented to their subjects was defined by the subject's anthropometry so that the clearances within the restricted space were equivalent across subjects. Their vertical restriction was set to 75% of the subject's stature, which is consistent with most studies of vertical restriction examining ceiling heights of well over 1 m, and even heights that afford upright kneeling and stooping.

The space restriction in the confined-space environment examined in the present study precluded upright kneeling or stooping postures due to a fixed "ceiling" height of only 0.61 m. In this study welders were observed kneeling with a near-maximally flexed trunk, supporting the welding unit in front of them (see Fig. 1). In some portions of the task the welders rested completely on their side in a prone posture. This type of confined space welding, that stresses the low back and shoulders due to static awkward postures and confinement of the welder, are often observed in shipbuilding operations.

This study examined a confined space welding operation specific to a vessel construction operation found at a medium-sized shipyard. Anecdotal complaints of low back pain motivated the attempt to electromyographically quantify low back, as well as shoulder and digit flexor/extensor fatigue. The objectives of the study were to: (1) examine surface electromyographic (SEMG) activity from seven muscle groups for evidence of fatigue during sustained welding in this confined space, and compare two different welding processes for differences in EMG-measured fatigue, and, (2) obtain subjective reports of regional discomfort in welding using these two processes for comparison with the electromyographic fatigue measures.

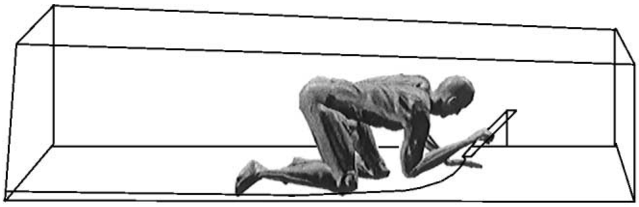

Fig. 1. Schematic illustration of a welder in the honeycomb mock-up in a typical welding posture.

The specific hypothesis of this investigation was that a conversion from a stick-electrode to a continuous-feed wire welding process would result in a reduction in muscle fatigue as measured electrophysiologically, by surface EMG, and subjectively, by discomfort questionnaire. The two welding processes compared in the study were a stick-electrode welding process — Shielded Metal Arc Welding (SMAW) currently used at the shipyard, and a continuous feed wire welding process — Flux-Cored Arc Welding (FCAW) the shipyard management has considered implementing (see Fig. 2).

In stick electrode welding (SMAW) the weight of the welding assembly (holder, electrode, and cable) depends on the size of the stick electrode. In shipyard construction, the stick electrode can be up to 45 cm long and the total assembly can weigh up to 2.32 kg with an unconsumed electrode. (In this investigation the electrode/holder assembly consisted of a Twecotong A-38-HD holder. The 7024-type electrodes were used.) Thus, the static load supported by the welders is generally low, however, it must be maintained with precision for the duration of the stick's consumption. In addition, gradual consumption of the stick electrode results in a gradual reduction in the weight and length of the total assembly as a function of welding time. This affects the moment created by the assembly's mass and distance from the torso. When a stick electrode is fully consumed, it must be replaced with a new electrode of the original length. The electrode change-out time provides a forced mini-break (typically on the order of 10–20 s).

Alternatively, in FCAW, continuous-feed wire welding, the weight and moment of the assembly is constant. (In this investigation, the wire feed gun was a Lincoln Magnum.) The wire feed weld gun is lighter (approximately 1.65 kg) and can be supported close to the torso for the entire welding time, unlike the stick/holder assembly. The consumable wire metal is in a long coil fed through a hose to the gun, so that no change-out is required as with the stick electrode process. Because of its lighter weight, relative to a new, unconsumed stick electrode, and a shorter length (moment arm) the wire

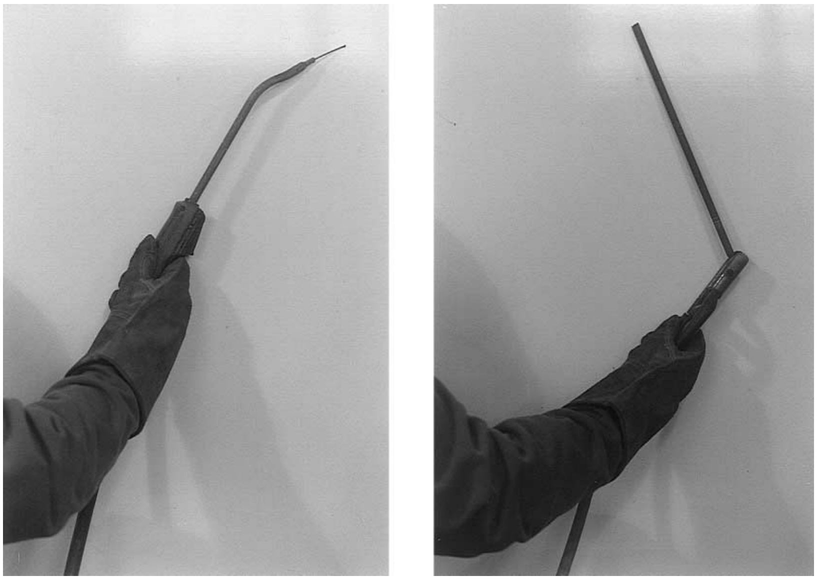

Fig. 2. Welding processes. (Left) Flux-core arc welding (wire fed). (Right) Shielded metal arc welding (stick electrode).

welding process was hypothesized to result in less localized muscle fatigue than the stick welding process. Since the weight and moment arm of the stick electrode assembly gradually change as the electrode is consumed (see *Discussion*), this hypothesis was tested by examining the processes (and their associated EMG activity from experienced welders) during continuous welding.

Subjective discomfort reports of welding with these processes were considered to be important. However, since the stick welding process has traditionally been used at this particular shipyard, biases in subjective ratings of discomfort between the two processes were of concern. Electrophysiological fatigue patterns (as measured by EMG) are not sensitive to preference biases and were thus utilized as an objective measure of localized muscle fatigue. Subjective fatigue evaluation, by discomfort assessment survey, was conducted realizing that biases might exist in welders' opinions about the conventional stick electrode versus the less familiar wire welding process.

2. Methods

2.1. Subjects

Eight welders were recruited from the shipyard where this particular job is performed. These individuals had achieved certification for at least second class welding (American Welding Society, 1984) with the stick electrode (SMAW) process. Each subject had experience, but not necessarily certification, with the wire (FCAW) welding process. The subjects were all right-handed males between the ages of 19 and 36 years. Table 1 lists selected characteristics of the study participants. Informed consent was provided by these welders who were working on company time at their regular working wage. No incentives were given for participation in the study. The study protocol received Human Subjects Review Board approval at the National Institute for Occupational Safety and Health.

Table 1
Selected anthropometric and other characteristics of the study participants

	Mean	S.D.	Range
Age (yrs)	29	5	19–36
Weight (kg)	89	17	63.3–106.3
Height (m)	1.77	0.03	1.73–1.83
Functional reach (m)	0.81	0.03	0.75–0.84
Bideltoid breadth (m)	0.55	0.04	0.50–0.61
Buttock-knee length (m)	0.60	0.03	0.57–0.65
Chest circumference (m)	1.09	0.11	0.93–1.22
Resting heart rate (beats min^{-1})	72	11	52–88
Months on the job (months)	28.6	17.7	2.5–56
Hours per week worked (hrs)	40.6	1.8	40–45
Lost work days last year (days)	1.4	2.7	0–7
Light duty days last year (days)	0.25	0.71	0–2
Welding class certification	41 st Class, 42 nd Class		
Musculoskeletal pain within last year?	4 of 8 responded "yes"		

2.2. Study design

A 2 × 2 factorial design with repeated measures on each subject was adopted in this study. In this design each subject had two replicates at each treatment. A total of four weld conditions (2 *ventilation methods* × 2 *weld processes*), described in the table below, were tested. Thus, there were four treatments in each replicate. The order of treatments presented to each subject was determined either by Latin Square design (Cochran and Cox, 1957) — four 4 × 4 squares with two subjects per square — or, for two of the subjects, by randomization in each of the replicates. The Latin square design was used in this case to minimize the potential for a presentation order effect on fatigue. Although the design, as described above, would have required ten subjects, data were not collected for two of the subjects in two different Latin Squares. Thus, there were only eight subjects.

	Weld process	
Ventilation device	Stick (SMAW)	Wire (FCAW)
Air-horn (normal ventilation device)	(NS)	(NW)
Vent tube (prototype ventilation device	(VS)	(VW)

The "stick" condition of the weld process variable refers to the static-loading condition resulting from using the stick-welding process (Shielded Metal Arc Welding) for the welding trial (see Fig. 2). This condition did include the mini break that was afforded by normal task requirements including: changing the weld sticks, body-positioning, striking the arc, and de-slagging (chipping away excess slag from the weld with a small hammer). The "wire" condition of the weld process variable refers to the static-loading condition resulting from using the wire-welding process (Flux Core Arc Welding or FCAW). This condition also included the mini break that was afforded by normal task requirements including: adjusting "stick-out," body-positioning, triggering the arc, and de-slagging (chipping away excess slag from the weld with a small hammer).

The "air horn" ventilation device refers to the conditions in the confined space using the ventilation method currently employed at the participant shipyard. This device consisted of a blower-type air horn that directed a combination of compressed and outside fresh air into the confined space. The "ventilation tube" ventilation device refers to the conditions in the confined space using a redesigned prototype ventilation tube/vortex designed by NIOSH researchers. These ventilation devices are presented only for the purposes of experimental design completeness — they were part of a separate study of air quality and exhaust removal (Wurzelbacher et al., 2000) and were not expected to affect postural confinement or muscle fatigue.

2.3. Confined-space mock-up and welding procedure

A functional mock-up of the confined-space welding environment was constructed to replicate the 0.61 m × 0.61 m (opening) × 4.88 m (length) spaces which are found on the double-hull sections of the vessels built at this shipyard. Each of these spaces is referred to as a "honeycomb" (see Fig. 1). The honeycomb mockup ceiling and upper walls were made of transparent plexiglass, allowing view of the welder inside the honeycomb when weld fume levels were low. The floor, lower walls, and lower seams were steel with removable angular junctions between the walls and floor (angle irons). The angle irons served as disposable right angle seams which could be removed for assessment of weld quality and replacement with a fresh seam.

The study participants welded beads approximately one meter in length in the corners of these removable angle irons. The task required the welder to crawl to the back of the honeycomb, weld a continuous 1-m bead along the bottom right corner, move to the back left side of the honeycomb and weld a continuous 1-m bead along the bottom left corner. This process took approximately 2–3 min per side, 4–6 min for both left and right sides. A total of eight trials were performed by each subject; two welding processes were combined factorially with two ventilation/exhaust removal devices and two replicates. The welders were given approximately 15 min rest between trials, during which the experimenters replaced the angle irons and prepared for the next trial. Including preparation and rest breaks between trials, a session with one welder took approximately four hours. Two subjects were tested each day during a one-week period in April, 1999.

2.4. Discomfort assessment survey (DAS) procedure

Corlett and Bishop's method for surveying body part discomfort has been widely applied to measure regional discomfort resulting from physical work activities with postural and other musculoskeletal demands (Corlett and Bishop, 1976; Corlett and Manenica, 1980). A discomfort assessment survey (DAS) was given to each participant following each welding trial using a Corlett and Bishop questionnaire. From this questionnaire, discomfort measures were derived in the manner of Corlett and Bishop (1976) and will be referred to as: DAS-General, DAS-Number, and DAS-Specific.

DAS-General represented the subject's 'overall discomfort level' as determined by his 7-point visual analog scale rating immediately following each weld trial . The DAS-General scale ranged from a score of "0" for "extremely comfortable" to "6" for "extremely uncomfortable". DAS-Number represented the sum of body areas (out of a potential 15 that were depicted) that the subject indicated as experiencing discomfort immediately following each weld trial [Σ (body areas listed as uncomfortable)]. DAS-Specific represented the body areas listed as uncomfortable multiplied by a discomfort severity factor from 0–3 and then summed [Σ (severity ratings)]. Thus, the highest potential DAS-Specific score was 45 (15 body regions multiplied by a maximum severity of 3).

To determine DAS-Number and DAS-Specific, the subject was first asked to specify those areas of his body that were most uncomfortable using the diagram on the questionnaire. These areas were colored red and were later coded with a severity rating of "3". The participant was then asked to indicate those areas of his body which were the next most uncomfortable. These areas were colored yellow and were later coded with a severity rating of "2". Finally, the participant was asked to indicate any other areas that were uncomfortable. These areas were colored green and were later coded with a severity rating of "1". During the DAS administration, the participant was not required to list discomfort and was permitted to stop at any level. If the participant did not wish to list discomfort for any body regions (because he did not perceive discomfort) , the survey was terminated and unlisted body areas were given a severity rating of "0". Non-parametric Friedman χ^2 tests were performed to determine significant differences in DAS measures between experimental conditions.

2.5. *EMG data acquisition*

Surface EMG was recorded from seven torso and upper extremity muscles on the welders' dominant hand (right) side. These muscles were the upper trapezius, middle deltoid, anterior deltoid, latissimus dorsi, erector spinae, extensor digitorum communis, and flexor digitorum superficialis. Disc electrodes were oriented in parallel with the fibers of these muscle groups as per the electrode placement recommendations of Zipp (1982) and Perotto (1996). The electrode configurations were bipolar, with preamplification at the recording site. The EMG signal was sampled at 992 Hz, notch filtered at 60 Hz, and stored digitally on a computer. In post processing the data was filtered digitally with a sixth order Butterworth bandpass filter (10–350 Hz cutoffs).

In each welding trial, a 120-s window of data was extracted from the raw, filtered EMG signal from the welding on each side of the honeycomb. This 120-s window was slightly shorter than most subjects' welding times for a single side (which were typically about 120–180 s). This 120-s data set was partitioned into five, 24-s windows for which the following procedure was performed. The percent of the total signal power spectrum falling in the 10–30 Hz frequency band was calculated by fast Fourier transform (FFT) and generation of a power spectral density function for each 1-s interval of data (spectogram) using custom software written in Labview$^{\text{TM}}$ (National Instruments, Austin, Texas). The area under each 1-s spectogram function integrated between 10 and 30 Hz was divided by the total area under the function integrated over 10–350 Hz. These 24 percentage values (1 per second, for 24 s) were averaged over each of the five, 24-s periods. Statistical analyses were performed on the series of five average percentages of the total spectral power in the 10–30 Hz frequency band (henceforth abbreviated as PP_{10-30}). This procedure is illustrated graphically in Fig. 3.

The interior of the honeycomb mock-up reached temperatures in excess of 29°C, with the welders wearing protective long sleeve shirt(s), half-mask respirator, hard hat, and welding visor. Not surprisingly, heavy sweating occurred, resulting in some instances of electrode detachment from the welder. This was believed to be unavoidable in this environment. As a precaution for data integrity the electrode attachments were inspected visually before and after each trial and detachments were noted. Electrode detachments were usually obvious from visual monitoring of the signal in real-time. In trials where an electrode detached, data for that particular muscle in that trial were discarded.

There were initial concerns about the possibility of interference in the myoelectric potentials from the AC current source of the stick electrode welding process (SMAW). Potential interference was tested by conducting a realistic postural simulation of a welding trial without actual welding taking place (no current). The myoelectric power spectrum in the signal recorded during this "test" trial was compared to that in the regular "live" trial in which actual welding took place. The power spectra from the two live trials showed no consistent patterns of spectral interference from that of the test trial. This was interpreted as evidence for no interference between the AC welding current and the surface electromyogram.

2.6. *EMG data treatment and analysis*

Temporal shifts in the percent of the total EMG spectral power in the 10–30 Hz frequency band (PP_{10-30}) were measured by the slope of the linear function regressing PP_{10-30} against time segment. An estimate of the linear parameter (i.e. the slope) relating PP_{10-30} to the segment number (1–5) was obtained by regressing PP_{10-30} on the time segment number. Trials that had only four completed time segments (e.g. 96 s of data) were retained in the analyses. Trials with fewer than four completed segments, due to an electrode detachment, early completion of the weld, or the rare cases of technical difficulties, were excluded from the analyses. A reliable slope estimate would not have been facilitated by fewer than four completed time segments.

Since the objective of the study was to examine the welding processes for evidence of an increase in the fatigue measure over time, the estimate of a positive linear trend was believed to be adequate. Other groups (Roy et al., 1989; Seroussi et al., 1989; Moffroid et al., 1994) have demonstrated linear shifts in power spectral density compression associated with localized muscle

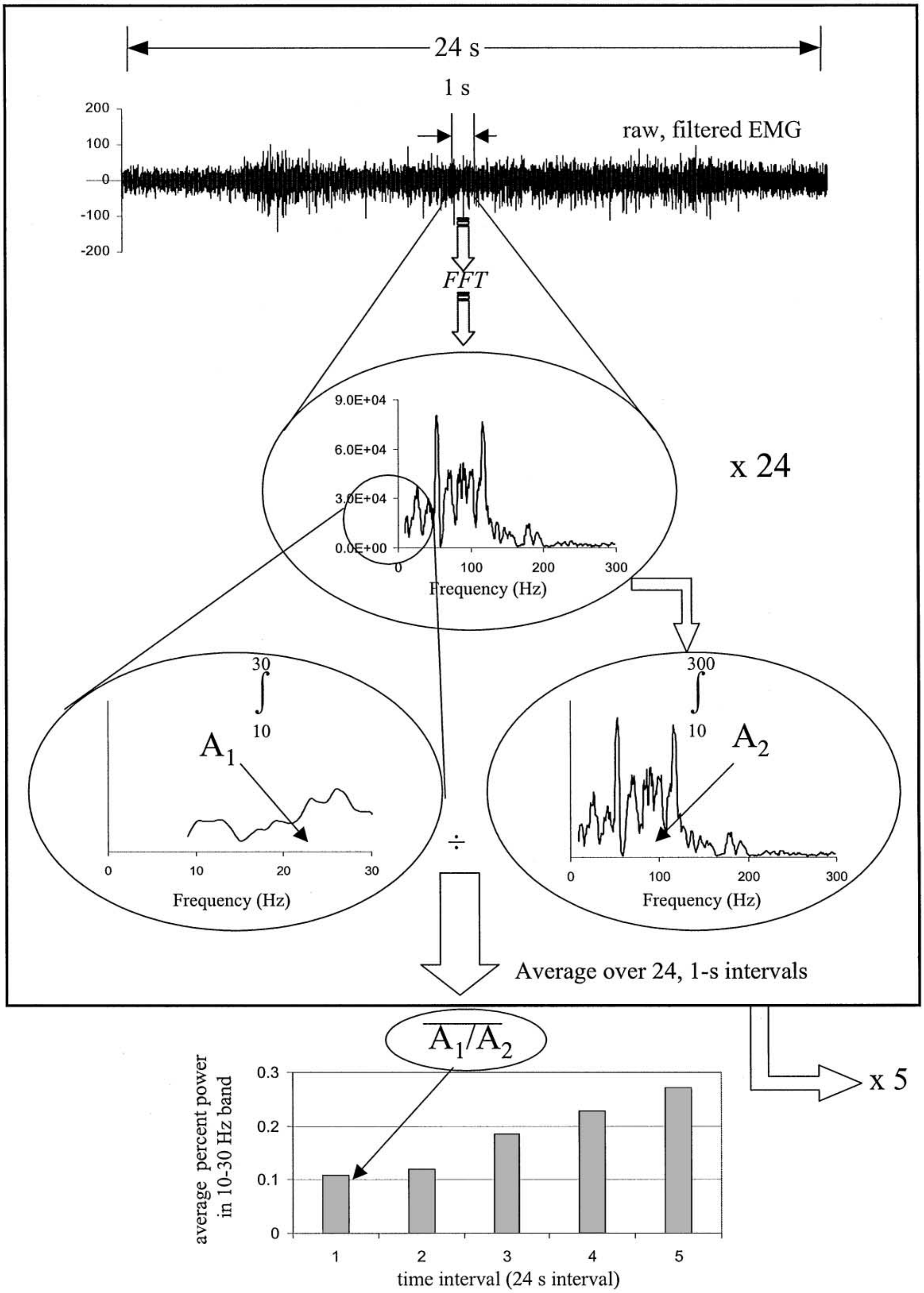

Fig. 3. Procedure for deriving the average percent of the total EMG signal power in the 10–30 Hz frequency band (PP_{10-30}).

fatigue. The slope estimates presented in Table 2 are in units of fraction increase in $PP_{10\text{-}30}$ per time unit, where the time unit is the length of time between the midpoints of the time segments, or 24 s. A positive slope in this relationship indicates power spectral density compression, and, the presence of localized muscle fatigue.

Statistical models (*Proc Mixed*; SAS Institute, Cary, NC, 1997) were generated to evaluate the differences in

Table 2
Statistical tests on slopes in PP_{10-30}[a]

	Trapezius	Middle deltoid	Anterior deltoid	Latissimus dorsi	Erector spinae	FDS	EDC
Stick (left)	0.015, 2.42, **0.03**[b]	0.022, 2.66, **0.02**[b]	0.006, 1.07, 0.30	−0.013, −1.58, 0.14	0.022, 2.81, **0.01**[c]	0.012, 2.39, **0.02**[b]	0.018, 2.14, 0.05[d]
Stick (right)	0.007, 1.34, 0.20	0.006, 0.88, 0.39	0.011, 2.15, **0.05**[b]	0.008, 1.35, 0.20	0.009, 1.72, 0.11	0.011, 3.52, **0.003**[c]	0.003, 0.78, 0.45
Wire (left)	0.014, 1.86, 0.09	0.008, 1.00, 0.33	−0.002, −0.35, 0.73	0.004, 0.60, 0.55	0.017, 2.07, **0.05**[b]	0, 0.06, 0.95	0.002, 0.34, 0.734
Wire (right)	0.012, 1.62, 0.13	0.017, 1.23, 0.23	0.019, 2.11, 0.05[d]	0.003, 0.40, 0.69	−0.002, −0.20, 0.85	0.003, 0.62, 0.55	0.008, 1.09, 0.29
Stick-wire (left)	0.001, 0.14, 0.89	0.013, 1.02, 0.32	0.008, 0.89, 0.38	−0.018, −1.48, 0.15	0.005, 0.38, 0.71	0.011, 1.46, 0.15	0.016, 1.58, 0.128
Stick-wire (right)	−0.005, −0.48, 0.63	−0.011, −0.65, 0.52	−0.007, −0.67, 0.50	0.005, 0.49, 0.63	0.012, 0.85, 0.40	0.008, 1.2, 0.24	−0.005, −0.56, 0.58
Normal (left)	0.013, 1.92, 0.07	0.009, 1.18, 0.25	−0.001, −0.12, 0.90	−0.008, −0.99, 0.33	0.028, 3.48, **0.001**[c]	0.009, 1.85, 0.07	0.015, 2.26, **0.04**[b]
Normal (right)	0.004, 0.71, 0.49	0.011, 1.11, 0.28	0.01, 1.56, 0.13	0.005, 0.8, 0.43	0, 0.01, 0.99	0.007, 1.82, 0.08	0.007, 1.28, 0.22
Vent tube (left)	0.016, 2.60, **0.02**[b]	0.021, 2.85, **0.01**[c]	0.005, 0.87, 0.39	−0.002, −0.29, 0.78	0.011, 1.64, 0.11	0.003, 0.68, 0.50	0.004, 0.72, 0.48
vent tube (right)	0.015, 2.89, **0.01**[c]	0.013, 1.32, 0.20	0.02, 3.02, **0.01**[c]	0.006, 1.12, 0.27	0.007, 0.83, 0.42	0.007, 1.76, 0.09	0.004, 0.76, 0.46
Normal-vent (left)	−0.003, −0.30, 0.77	−0.012, −10.04, 00.31	−0.005, −0.66, 0.51	−0.006, −0.54, 0.59	0.017, 1.55, 0.13	0.006, 0.92, 0.36	0.011, 1.17, 0.26
Normal-vent (right)	−0.011, −1.66, 0.11	−0.002, −0.15, 0.88	−0.009, −1.05, 0.31	−0.002, −0.2, 0.84	−0.007, −0.62, 0.54	0.001, 0.11, 0.92	0.003, 0.39, 0.70

[a] Tests results are for the hypothesis either that the slope (of stick or wire) is not 0 or that the difference in slopes (stick-wire) is not 0. In each cell the digit at the top left is the slope estimate, the digit to the top right is the t-statistic, and the digit underneath is the Type-I error probability level (p-value). P-values in bold indicate approximate statistical significance at 5%, when each test is considered individually.

[b] $p < 0.05$.

[c] $p < 0.01$.

[d] These p-values are not considered to be statistically significant because they are rounded to 0.05 from below.

the slope in PP_{10-30} between levels of the *ventilation device* and *weld process* variables, with separate models for the data from the right and left side. Models were fitted to the slope values averaged over muscles, except that for the left side muscle average the latissimus dorsi was excluded, since separate analyses indicated that the latissimus dorsi slope estimates were different than those of the six other muscles. Subsequently, the same form of model was used to obtain estimates for each muscle individually.

Because of values missing from the Latin Squares and because some data were collected as randomized blocks, the data were analyzed via mixed models. For the average muscle data on each side, a model was fitted allowing for different means for ventilation device, weld process, and their interactions. Since the data on each subject were collected in two replicates, a term (one degree of freedom) allowing for differences between the first and second replicate (averaged over subjects) was included in the model. Also, a term (three degrees of freedom) allowing for order within replicate (averaged over subjects and replicates) was included, as well as a term (three degree of freedom) for replicate by order interaction. Finally, the model also included interaction terms between replicate number (first or second) and the study variables (ventilation device, weld process, and their interaction), in order to allow for the possible dependence of the study variable differences on the replicate. All of the above fixed effect terms were included in the final model.

The random effect terms included in the final models were as follows. For both sides the interaction between subject and ventilation factor was included, allowing for different variance estimates by weld process. The right-side model included an extra term for replicate within subject, also allowing for different variance estimates by process. These random terms were selected from a larger set of terms involving subject, replicate in subject, and order in subject, which were removed after tests of statistical significance yielded non-significant results. It seemed sensible to simplify the random components of the model, since the random terms in the model affect the degrees of freedom of the estimates. Since the models include several variance components and more than one error component in each model, Satterthwaite-type approximations were used to obtained estimated degrees of freedom for comparisons (Littell et al., 1996).

2.7. Welding Performance

Welding performance was assessed by quantifying the relationship between welding and non-welding ("break") time. A "break" was operationally defined to be any continuous time period (greater than 1 s in duration) in which the electric weld arc was not present. Conversely, "arc time" was operationally defined to be any continuous time period (greater than 1 s in duration) in which the electric weld arc was present. Hence, the trial arc time plus the trial break time equals the trial total welding time. The non-welding activities observed in the break periods included postural adjustments for the welder to reposition himself further along the seam, electrode change-out for the stick process, occasional adjustment of "stick-out" for the wire process, and deslagging.

Weld quality measures were attempted in the form of visual assessment and ratings of weld quality by a welding instructor. However, these ratings were not believed to be reliable indicators of true weld quality for two reasons. Wire welds are inherently less visually aesthetic than stick welds, and visual ratings of weld quality are not necessarily indicative of the strength of the weld. Weld strength is best measured by destructive or X-ray testing which was not logistically possible in this study. Hence, weld quality measures are not reported.

3. Results

3.1. EMG analysis of muscle fatigue

Slope estimates for the $PP_{10\text{-}30}$ vs. welding time relationship are presented for each of the seven muscles, separately by side (left or right seam), by process (stick welding, wire welding), and by ventilation device (conventional "normal" ventilation device, ventilation tube ventilation device) averaged across subjects in Table 2. Separate models were generated for the left and right-side because different static postures were adopted by the welders for the two sides. The rates of power spectral density compression are not comparable between different working postures.

The "average models", which test for the overall effect of weld process and ventilation device, resulted in a slope in $PP_{10\text{-}30}$ for the stick process of 0.015 ($t_{12.8} = 3.5; p = 0.004$) and a slope for the wire process of 0.007 ($t_{29.7} = 1.95; p = 0.06$) for the left side and 0.008 ($t_{13.2} = 2.76; p = 0.016$) for the stick process and 0.007 ($t_{17.0} = 1.25; p = 0.23$) for the wire process for the right-side. None of the differences in slopes between the stick and wire welding processes reached statistical significance at the 0.05 level. However, with an alpha-error criterion of 0.05 only the slopes for the stick process are statistically significant (i.e. positively different from zero), suggesting that, on average, only the stick process was associated with measurable EMG power spectral density compression.

The ventilation devices were not hypothesized to have any affect on muscle fatigue. The conventional and prototype (ventilation tube) ventilation devices had air return hoses of slightly different diameters which were believed to have negligible effects on the degree of postural confinement experienced by the welders. However, the average model, which tested for differences in the $PP_{10\text{-}30}$ slopes attributable to the type of ventilation device, revealed that the average slope for the normal (conventional) ventilation device when welding the left side was 0.013 ($t_{25.4} = 3.27; p = 0.003$) and was 0.01 ($t_{22.2} = 2.75; p = 0.01$) for the vent tube ventilation device. For right-side welding the slopes were 0.006 ($t_{25.3} = 1.42; p = 0.17$) for the normal ventilation device and 0.009 ($t_{22.6} = 2.49; p = 0.02$) for the vent tube device. None of the differences in the slopes between the normal and ventilation tube ventilation devices were statistically significant. Since all but one (right-side welding with the normal ventilation device) combination of ventilation device with side resulted in positive slopes in $PP_{10\text{-}30}$, the relationship between the ventilation device and muscle fatigue is less clear.

With respect to specific muscles, for left-side welding, the stick electrode process resulted in positive fatigue in trapezius, middle deltoid, erector spinae, and flexor digitorum superficialis (FDS). This is evidenced by the slopes of the $PP_{10\text{-}30}$ vs. time segment relationship that were significantly different from zero ($p < 0.05$) for these muscles. The wire process resulted in positive fatigue for only the erector spinae ($p < 0.05$). Table 2 shows each muscle's $PP_{10\text{-}30}$ slope estimate, its associated t-statistic and its significance level for each condition of weld process and ventilation device. No differences between the stick and the wire slopes in $PP_{10\text{-}30}$ reached an 0.05 level of significance. (See rows showing "stick - wire" slope estimates.)

Similar modeling was carried out for the right-side data. Table 2 shows the right-side slope estimates for each muscle and indicates which muscles exhibited slopes in $PP_{10\text{-}30}$ that were significantly greater than zero. For the right-side welding trials the stick process results in a positive slope in $PP_{10\text{-}30}$ for the anterior deltoid and FDS ($p < 0.05$). The wire welding process did not result in a positive slope in $PP_{10\text{-}30}$ for any of the muscles in right-side welding. Again, no muscles exhibited a significant difference between the stick and wire welding process in the slope in $PP_{10\text{-}30}$.

Anthropometric characteristics (namely height, weight, bideltoid breadth, and chest circumference) of the welders were hypothesized to have an effect on fatigue. Since larger welders are more confined in the honeycomb space it was hypothesized that they would suffer greater localized muscle fatigue. However, no significant correlations between the anthropometric variables and slopes in the PP_{10-30} vs. time segment relationship were observed.

3.2. Discomfort assessment survey results

Discomfort assessment survey (DAS) scores are shown in Fig. 4. There was little correlation between DAS score and the rate of change in EMG PP_{10-30}. The DAS-general results indicate that stick welding was associated with a mean general discomfort score (DAS-general) of 2.66 whereas wire welding was associated with a mean general discomfort score of 3.03. Both of these scores corresponded to a subjective response in which subjects largely rated their "general state of comfort right now" as "average" to "comfortable". Based on a Friedman χ^2 test, which considers non-parametrically the differences among average ranks of the four treatment DAS-general results over subjects, the weld process and ventilation method factors were determined to be statistically non-significant ($p = 0.205$). DAS-number was shown to be unaffected by both weld process and ventilation method ($p = 0.843$). These results are shown in Fig. 4(a). The effect of weld process and ventilation method on DAS-specific (results provided in Fig. 5b) was also statistically non-significant ($p = 0.825$).

The nature of the musculoskeletal demand can be further revealed through the results of the number of reported discomfort scores (DAS-number) given in Fig. 4(a). These indicate that the lower back was the body area most frequently reported as experiencing discomfort, followed by the knees, shoulders, and lower legs. However, when the reports are weighted for the severity of the discomfort experienced (i.e. DAS-specific), the knees score the highest followed by the lower back, shoulders, lower and upper arms (see Fig. 4b). The reported knee discomfort is probably a result of contact stress on the knee joint from kneeling and not a muscle *fatigue*-related discomfort. DAS-number and DAS-specific were found to be positively correlated with the subjects' *welding class certification* ($r = 0.75$ and $r = 0.83$, respectively). This probably reflects a healthy worker effect as welders who are more skilled (class 1 vs. class 2) have more months welding experience and also report less discomfort in terms of the number and the severity of the regions in which they experience discomfort.

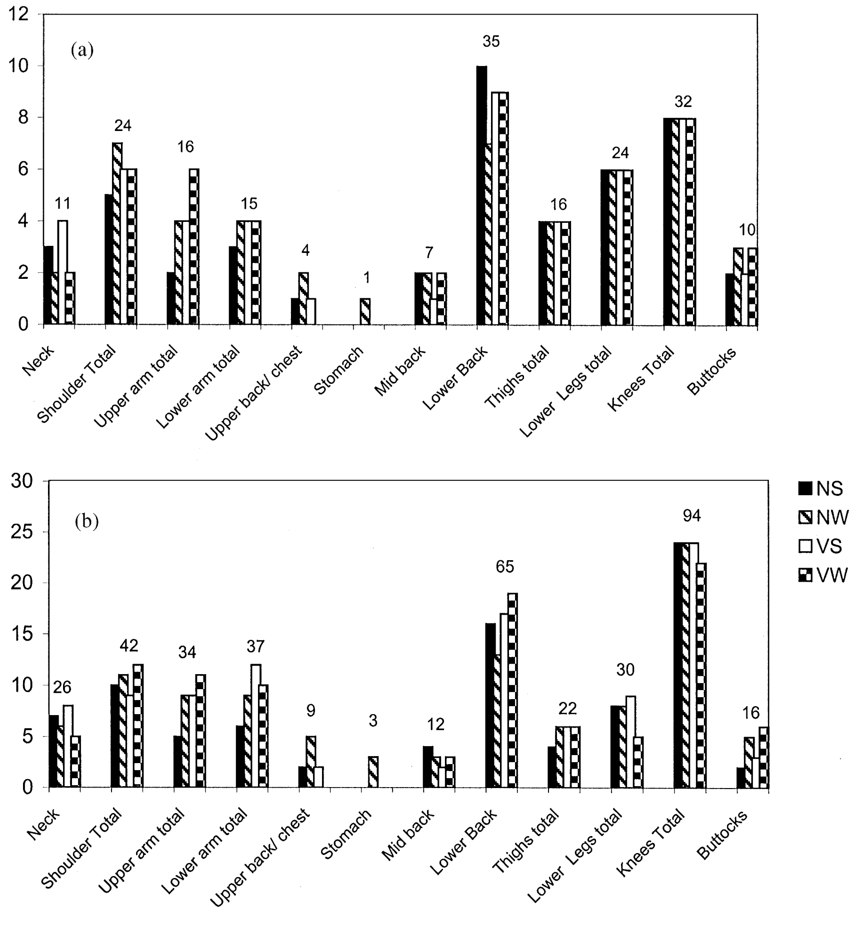

Fig. 4. Discomfort assessment survey results compiled across All Subjects (a) DAS-number scores shown by body region and condition, (b) DAS — specific scores (number of reports × severity) shown by body region, welding process (W — wire, S — stick), and ventilation device (N — normal, V — vent tube prototype) conditions.

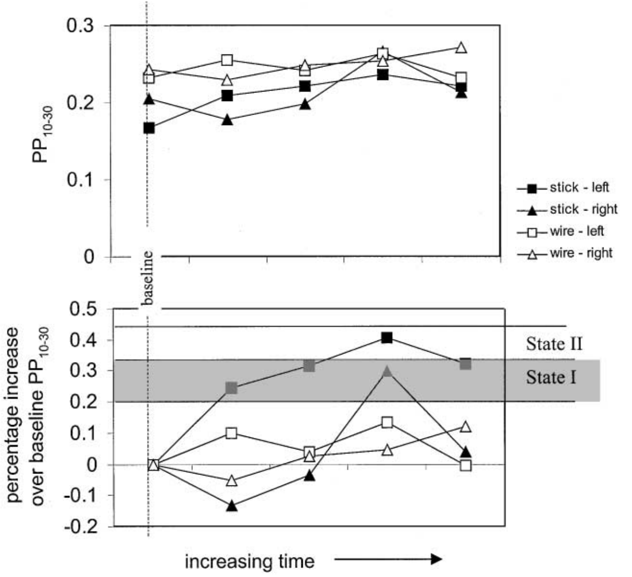

Fig. 5. (Top) Average percentages of the total EMG spectral power in the 10–30 Hz frequency band (PP_{10-30}) for stick and wire welding processes as a function of time segment. (Bottom) Increases in the PP_{10-30} measure relative to its baseline value (time segment 1). The fatigue States I and II correspond to the shifts in power spectral density described by Chaffin (1973). The stick welding process PP_{10-30} values shifted upward by a percentage large enough to be described by Chaffin's fatigue states as State I and lower State II fatigue levels. The wire welding process PP_{10-30} values did not increase (relative to baseline) enough to reach State I levels.

The correlations between the EMG measure of fatigue (slope in $PP_{10\text{-}30}$) and subjectively reported regional discomfort (DAS-specific) were generally low. Table 3 lists the correlation coefficients between the slope in EMG $PP_{10\text{-}30}$ and DAS-specific for comparisons between specific muscles (EMG-measured fatigue) and body regions (ratings of discomfort) that may be anatomically relevant. For instance, the cell which intersects the "lower back" DAS-specific score with the slope in $PP_{10\text{-}30}$ from the extensor digitorum communis (EDC) is shaded because these are not anatomically related and a comparison between them would be nonsensical. The DAS-specific rating from the "shoulders" did exhibit some correlation with the $PP_{10\text{-}30}$ slopes in the middle deltoid ($r = 0.79$) and in the anterior deltoid ($r = 0.56$). For the most part, however, the correlations are low and not statistically significant.

3.3. Welding performance

Table 4 shows the number and duration of the observed non-welding "breaks". The breaks are reported for the sequence of right followed by left-side welding, though the EMG results are broken out by left and right-side. Wire welding was associated with 6.2 ± 1.8 breaks, stick welding with 4.4 ± 0.6 breaks. However, the duration of the these non-welding periods were greater for the stick process (25.9 ± 8.6 s) than for the wire process (14.9 ± 7.0 s). Both of these differences were statistically significant ($p < 0.05$).

4. Discussion

Two phenomena have been associated with fatiguing skeletal muscle that are detectable in the muscle's electrical activity. These are an increase in the amplitude of the myopotentials at equivalent contractile tension and a compression in the power spectral density of the EMG signal towards lower frequencies. DeLuca (1979) claimed that the increases in EMG amplitude are a result of compression in power spectral density of the EMG signal combined with the low-pass filtering properties of muscle tissue which allow more signal power to pass at lower frequencies. Others have claimed that the amplitude increases are a result of an increase in the number of motor units recruited at equivalent tension levels as the muscle fatigues (Moritani et al., 1982). Although the physiologic mechanisms may still be debated, the signal characteristics of increasing amplitude and a downward shift in power spectral density appear to be widely accepted.

Comparing surface EMG amplitudes at multiple points over the course of a work period offers information about changes in the EMG signal that are believed to be fatigue-related. As an example, Habes (1984) examined integrated EMG amplitudes in a standardized static lean exertion before and after four breaks in the workers' work day. His study showed an increase in integrated EMG in the erector spinae in the leaning exertions as they were successively performed over the course of the workday. This increase was believed to be fatigue-related. Habes' approach relied on standardized exertions performed at regular intervals throughout the work period to examine temporal changes in the EMG in identical standardized exertions.

The welding postures adopted by the welders in the confined space honeycomb in this study were difficult to replicate in standardized reference exertions while measuring force. Standardized exertions would have been nearly impossible to conduct for seven different muscle groups in a restricted space with an opening of 0.61 m × 0.61 m as required by the present study. The variability in postures adopted by the welders of varied sized also rendered the standardization of posture difficult. Smaller welders were able to kneel with more vertical and horizontal clearance; larger welders adopted a kneeling posture in which they were more confined and tended to rest some of their body weight on their forearms. These are purely anecdotal observations — no quantitative measures of welding posture were made, and no attempts were made to control the working postures of the welders. It was believed that controlling working posture would be unrealistic of true working conditions

Table 3
Correlation coefficients between slopes in left-side EMG PP_{10-30} data (see text) and DAS-specific scores for relevant anatomic regions and muscles. The unshaded regions indicate meaningful comparisons between anatomic regions and specific muscles that may be related. These relevant regions list correlation coefficients for the welding process (w – wire, s – stick) and ventilation device (n – normal, v – vent tube prototype) conditions. Results for the two replicates for each subject at each (process, ventilation) combination were averaged before calculating the correlation coefficients, so that each estimated correlation coefficient is based on at most eight subjects' data

			Muscle						
		Exper. Condition	Trapezius	Middle Deltoid	Anterior Deltoid	Latissimus Dorsi	Erector Spinae	Extensor Digitorum	Flexor Digitorum
DAS specific Region	Neck	ns	−0.34	0.14	0.42				
		nw	−0.25	−0.51	−0.52				
		vs	0.01	0.37	0.06				
		vw	−0.23	−0.50	−0.45				
	Shoulders	ns	−0.44	−0.05	0.38	−0.51			
		nw	0.29	0.79[a]	0.56	−0.06			
		vs	0.13	0.37	0.09	−0.51			
		vw	0.24	−0.11	−0.57	0.16			
	Upper Arm	ns	0.29	0.16	0.39	−0.06			
		nw	0.37	0.32	0.19	−0.13			
		vs	−0.15	−0.07	−0.65	−0.18			
		vw	0.42	−0.12	−0.61	−0.10			
	Lower Arms	ns						−0.11	0.06
		nw						0.27	0.32
		vs						0.28	0.19
		vw						0.01	−0.01
	Upper Back	ns	—	—	—	—			
		nw	0.26	0.16	0.65	0.85[a]			
		vs	−0.23	—	—	0.06			
		vw	—	—	—	—			
	Mid-back	ns	—	—	—	—	—		
		nw	—	—	—	—	—		
		vs	−0.23	—	—	0.06	−0.30		
		vw	0.68	0.07	−0.31	0.14	−0.19		
	Lower Back	ns				−0.39	0.29		
		nw				−0.44	0.02		
		vs				−0.12	0.36		
		vw				−0.79[a]	−0.01		

[a] $p < 0.05$ — indicates there were no non-zero DAS scores.

and would have adversely affected welding performance. Hence the decision to exclude methods which would require standardized reference exertions such as that employed by Habes (1984) or methods of normalization to MVC (maximum voluntary contraction) or RVC (reference voluntary contraction).

The welding task was believed to be appropriate for EMG spectral analysis because of the static nature of the operation. Some groups have reported success in identifying localized muscle fatigue patterns using spectral analyses in association with well-controlled isometric exertions, particularly for the lumbar paraspinal muscles (Kondraske et al., 1987; Moffroid et al., 1994; Roy et al., 1989; Stulen and DeLuca, 1982; DeLuca, 1993). The welding operation investigated in this study involved static exertions that appeared to be appropriate for the assumptions of constant muscle length–tension and force–velocity relationships necessary for applying spectral analysis techniques validly.

Since all workers were right-handed, the differences between the results for the left and right sides are not surprising. Welding the left side of the honeycomb required the right-handed welders to reach forward and across the body, with the upper arm suspended, creating a greater moment about the dominant side shoulder and the lower back. In addition to the biomechanical disadvantages of right-handers welding on the left side, the left side weld was always made after the right-side weld, in immediate succession, introducing the potential for fatigue carry-over to influence the fatigue results for the left side. However, the potential for fatigue carry-over was equivalent across all treatment conditions and separate

Table 4
Mean number of non-welding "breaks" and mean duration of non-welding "breaks" during a sequence of left followed by right-side welding. The number and duration of non-welding "breaks" includes deslagging for the stick process. Each cell denotes the average over two trials unless noted. N – Normal ventilation device, V – Ventilation tube ventilation device, S – Stick, W – wire

Subject	Stick		Wire	
	NS	VS	NW	VW
(a) Mean number of non-welding "breaks"				
1	4.5	4.5	5.0	6.5
2	4.0	4.0	6.5	5.5
3	5.0	5.0	7.0	7.0
4	4.0	4.0	6.0	3.5
5	4.0	4.5	4.5	8.0[b]
6	5.0	4.5	5.0	5.0
7	5.0	4.5	8.0	7.0
8	4.5	4.0	6.5	9.0
Process mean[a]	4.4		6.2	
Process s.d.	0.6		1.8	
(b) Mean duration of non-welding "breaks" (s)				
1	19.8	28.7	15.3	14.0
2	31.5	32.8	13.6	19.8
3	14.5	15.0	9.9	9.0
4	24.3	26.4	10.3	16.8
5	34.8[b]	44.6	23.7[b]	29.0[b]
6	15.5	18.1	7.4	9.6
7	27.6	32.2	18.4	29.2
8	21.0	24.4	11.3	12.2
Process mean[a]	25.9		14.9	
Process s.d.	8.6		7	

[a] $p < 0.05$ for process difference.

[b] Only one trial included, one trial non-weld time exceeded $\mu + 3\sigma$.

models were generated for the left and right sides. The consistent sequence of right-side followed by left side welding adopted in the study favored the preservation of actual work sequence rather than a rigorous counterbalanced experimental design.

Chaffin (1973) defined four states of muscle fatigue for which he related perceived muscle symptoms to measurable power spectral density compression. State I fatigue, described subjectively as the "realization of 'tightness' or 'slight cramping'", corresponds to a 19% increase in the percentage of signal power in the 4–30 Hz frequency band over its baseline (pre-task) value. Little myoelectric power was observed below 10 Hz in the present study (certainly not after filtering with a 10 Hz cut-off frequency), so the difference between the 4–30 Hz frequency range reported by Chaffin (1973) and that used in the present study (10–30 Hz) is probably negligible. PP_{10-30} averaged across all muscles in this study averaged 16.8% and 23.3% for the stick and wire processes on the left side, respectively, in the first 24-s sampling window. The values in the fourth sampling window averaged 23.6% and 26.4%, corresponding to a 40% and 13% increase from the initial baseline values for the stick and wire welding processes, respectively.

Fig. 5 shows the percentage increases in PP_{10-30} in successive averaging periods over its baseline value for both welding processes and a comparison of these relative increases with Chaffin's (1973) fatigue states. The figure shows that the stick welding process was associated with average EMG power spectral density shifts that should correspond to perceivable localized sensations associated with State I ("realization of 'tightness' or 'slight cramping'") and even into the low end of State II ("'cramping' continuous with deep 'hot' pain intermittent") fatigue. Conversely, the wire welding process was associated with relative power spectral density shifts consistent with levels below the state in which perceivable fatigue is realized based on the fatigue state framework. However, the application of the fatigue state, power spectral density shift values must be undertaken with caution as they are based on fatigue patterns and spectral compression characteristics of the biceps muscle. Other muscle groups may have dissimilar fatigue patterns owing to different fiber type compositions and their corresponding fatiguabilities (Komi and Tesch, 1979). It is also unclear how sensations of "tightness" or "slight cramping" would be manifested in the discomfort assessment survey scaling applied in this study, even if such symptoms did exist.

For each body region above the waist other than shoulders and low back, more than 50% of the DAS-specific scores were zero. (For the shoulders there were 42% zero, and for the low back there were 27% zero.) The lack of correlation between the DAS-specific scores and EMG fatigue measures is likely a result of insufficient spread in the discomfort score data, since there was a low percentage of nonzero scores. Despite the high percentage of zero discomfort ratings, both the stick and wire welding processes were associated with an "average" to "comfortable" general discomfort rating (DAS-general) that exceeded 2.6. These ratings reflect a somewhat lower overall level of discomfort than might be expected with this welding task. Higher discomfort levels have been reported for other occupational tasks that appear to have involved less postural and static load demands, such as semi-automated spot welding (Corlett and Bishop, 1976). However, in other studies such as Saldana et al. (1994) and Corlett and Bishop (1976) the overall discomfort levels were measured over the course of an entire work shift to register the accumulation of regional discomfort. The present study was a controlled comparison designed to assess discomfort over a short duration welding period and to *limit* fatigue across trials (by including intervening rest periods). As a result, it is not surprising that the absolute overall discomfort levels were relatively low.

Nonetheless, the specific discomfort assessment survey scores (DAS-specific) reflect the regional musculoskeletal stresses that would be expected with the working postures observed in the task. The principle musculoskeletal discomfort associated with this confined space welding job was reported in the low back and knees in addition to the shoulders. This can be explained by considering the constrained working posture of the welders. Each welder crawled into the 0.61 m × 0.61 m opening and assumed a kneeling posture on the hard metal floor of the honeycomb. This posture involved severe flexion of the low back and some flexion and abduction of the shoulder that supports the welding apparatus. This posture induced a large degree of contact stress in the knee area and static loading of the low back and shoulders. These areas accounted for a large percentage of the DAS-reported discomfort.

The latissimus dorsi and extensor digitorum communis (EDC) showed little fatigue in this welding operation. Latissimus dorsi did not exhibit an increase in spectral density compression for any condition average, and no significant increases in PP_{10-30} were observed in EDC for the stick or wire process averages. Conversely, erector spinae exhibited a significantly positive slope in PP_{10-30} for left-side welding with both wire and stick welding processes, which is most likely attributable to the postural difference between left- and right-side welding. In right-side welding the right-handed subjects tended to lie more on their side, creating less of a forward trunk flexion moment than in left-side welding in which they kneeled and flexed forward. Anecdotal observation of differences in trunk posture explains this difference in erector spinae fatigue that is associated with left- vs. right-side welding.

Flexor digitorum superficialis (FDS) exhibited a significantly positive slope in PP_{10-30} for stick welding, but not for wire welding, which is likely a result of the higher grip force required to support the stick welding assembly. Trapezius, middle deltoid, and anterior deltoid exhibited significantly positive slopes in low frequency spectral compression for the stick, but not the wire process. This is also likely to be a result of increased biomechanical demands on the upper arm and shoulder created by the higher weight and increased moment about the shoulder joints created by the stick assembly. The differences in the physical dimensions (weight and length) between the stick and wire welding assemblies obviously affect the static muscular load they present to the welder. The longer and heavier stick electrode assembly creates a greater moment about each joint in the link system from the hand to the knees in contact with the floor of the honeycomb. However, the comparison is complicated by the fact that the stick electrode is consumable, so that its weight and length decrease throughout its consumption, unlike the wire assembly. The weight of the stick assembly is reduced from approximately 2.32 kg to approximately 2.11 kg and the total length of the assembly (distance from the grip area to the distal end of the electrode) is reduced from approximately 66 cm to approximately half this length. While still heavier in its fully consumed state, the length of the stick assembly is less than that of the wire welding assembly. Thus, the difference in the moment created by the stick assembly relative to that created by the wire decreases significantly as the stick electrode is consumed. When fully consumed the moment created by the stick assembly may even be lower than that created by the wire.

For the average of the six muscles on the left side (excluding latissimus dorsi), the estimated difference between the stick and wire slopes is about 0.009. The *p*-value of this result is about 0.17. For this size difference to have greater than 90% chance of giving a statistically significant result for a test at the 5% significance level (assuming equal variability to that found in the present data), 16 subjects would have been required, compared to the 8 subjects tested in this study. While 16 subjects is reasonable from an experimental design perspective, it would have created too large of a productivity loss to be acceptable to this facility.

This study was a realistic *spatial* replication of the welding job insofar as the mock-up was of identical dimensions to the actual work space. However, the *temporal* characteristics (work/rest) of the job could not be simulated realistically by sampling EMG for an entire productive work day. Thus, it is not clear from this study how the difference in fatigue between the two welding processes observed in shorter welding periods is manifested in fatigue over a day of productive welding. The welding performance results in Table 4 shed little light on this issue. Stick welding was associated with fewer breaks than wire welding but the breaks were of longer duration. Longer duration breaks were expected with the stick welding process, since the non-welding activities include virtually all of the activities that are observed in wire welding with the addition of stick electrode change-out. However, the unexpected finding of a greater number of breaks with the wire welding process indicates that the potential for more continuous welding believed to be afforded by the wire welding process was not exploited by the welders in this study. Since the optimal distribution of work/rest periods is dependent on the duration and frequency of the rest periods (Rohmert, 1973), and neither of the two welding processes showed a clear advantage in this regard, the present data preclude speculation on the welding process which minimizes muscle fatigue over an entire day's welding. The effect of welding process on fatigue in the shorter periods of welding observed in this study appears to be more clear in favoring the wire welding process.

When the static exertion times examined in this study (2–3 min of welding) are related to the classic endurance time curves of Rohmert (1960) an exertion level of approximately 25–35% of maximum voluntary contraction (MVC) is indicated. This means that an exertion level of 25–35% MVC can be maintained for 2–3 min. The static exertions in the welding operation examined in this study were probably lower than 25% MVC . However, measurable changes in a muscle's EMG and in the perception of regional discomfort occur well before the endurance time is reached. While the perceived regional discomfort and fatigue appear to have been relatively low in this study, several electromyographic manifestations were of statistical significance — particularly with the stick welding process. The small proportion of non-zero discomfort reports might suggest that the electrophysiologic measures of EMG spectral shift are of little practical significance. Conversely, these electrophysiologic indicators may be viewed as precursors to localized muscle fatigue that would be perceived in the form of regional musculoskeletal discomfort over longer periods of welding. Anecdotal evidence and informal reports of workers at this shipyard suggest that the latter is the case.

For the shipyard management considering the relative advantages/disadvantages of these two welding processes these data provide some support for the implementation of the wire welding process. While other factors such as work/rest cycle (*Discussion*), cost, productivity, air particulate concentrations, and weld quality affect this decision the electromyographic analysis of upper extremity and trunk muscle fatigue appears to favor the wire welding process.

5. Conclusion

This study examined a confined space welding task at a shipyard and compared localized muscle fatigue in seven trunk and upper extremity muscle groups between two welding processes. The results showed small rates of power spectral density compression (a measure of localized muscle fatigue onset) for a wire welding process (Flux-Core Arc Welding) compared to a stick electrode welding process (Shielded Metal Arc Welding) currently employed at this shipyard. The latter were, in many cases, significantly positive. While the differences in EMG power spectral shift between the two welding processes were not statistically significant, and the subjectively rated discomfort was low for both processes, measurable low frequency shifts in the EMG power spectra were evident in the 2 min welding periods from the trapezius, middle deltoid, anterior deltoid, erector spinae, and flexor digitorum superficialis. This was particularly the case for the stick welding process in which downward shifts in power spectral density were often statistically significant. While it is recognized that other issues must also be considered in the decision, the wire welding process (flux-core arc welding) may reduce localized muscle fatigue and may be a preferred process if the goal of reducing low back and shoulder fatigue is given precedence.

Disclaimer

Mention of company names or products does not constitute endorsement by the National Institute for Occupational Safety and Health.

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