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# Reduction of Biomechanical and Welding Fume Exposures in Stud Welding

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## ABSTRACT

The welding of shear stud connectors to structural steel in construction requires a prolonged stooped posture that exposes ironworkers to biomechanical and welding fume hazards. In this study, biomechanical and welding fume exposures during stud welding using conventional methods were compared to exposures associated with use of a prototype system that allowed participants to weld from an upright position. The effect of base material (i.e. bare structural beam versus galvanized decking) on welding fume concentration (particle number and mass), particle size distribution, and particle composition was also explored. Thirty participants completed a series of stud welding simulations in a local apprenticeship training facility. Use of the upright system was associated with substantial reductions in trunk inclination and the activity levels of several muscle groups. Inhalable mass concentrations of welding fume (averaged over ~18 min) when using conventional methods were high (18.2 mg $m^{-3}$ for bare beam; 65.7 mg $m^{-3}$ for through deck), with estimated mass concentrations of iron (7.8 mg $m^{-3}$ for bare beam; 15.8 mg $m^{-3}$ for through deck), zinc (0.2 mg $m^{-3}$ for bare beam; 15.8 mg $m^{-3}$ for through deck), and manganese (0.9 mg $m^{-3}$ for bare beam; 1.5 mg $m^{-3}$ for through deck) often exceeding the American Conference of Governmental Industrial Hygienists Threshold Limit Values (TLVs). Number and mass concentrations were substantially reduced when using the upright system, although the total inhalable mass concentration remained above the TLV when welding through decking. The average diameters of the welding fume particles for both bare beam (31 ± 17 nm) through deck conditions (34 ± 34 nm) and the chemical composition of the particles indicated the presence of metallic nanoparticles. Stud welding exposes ironworkers to potentially high levels of biomechanical loading (primarily to the low back) and welding fume. The upright system used in this study improved exposure levels during stud welding simulations, but further development is needed before field deployment is possible.

**KEYWORDS:** construction; ergonomics; welding

## INTRODUCTION

Welding shear stud connectors (stud welding) to structural steel is essential to most major construction projects, requiring structural ironworkers to weld thousands of shear stud connectors (studs) in a single shift (Means, 2004). Stud welding is a type of electric arc welding in which a stud (a headed steel rod) is welded to a base material using a semiautomatic arc welding gun (stud gun) (Chambers, 2001). Current is delivered from the stud gun through the stud to the base material. In building construction, studs are welded to structural steel through galvanized steel decking, which serves as the subfloor to subsequently poured concrete. Studs are directly welded to bare structural steel in bridge construction.

When performed, stud welding is generally an all-day job for a team consisting of one structural ironworker and at least one laborer. The ironworker sets up the welding equipment (i.e. generator, welding controller unit, cabling, and stud gun) and performs the welding. The laborer assists by laying out studs and ceramic ferrules used as arc shields, helping to move equipment, and grinding to prepare weld locations for bare steel. During a typical workday, an average of about 1000 studs may be installed per stud welding team (Means, 2004). Based on observations in a previous study (Fethke *et al.*, 2011), the stud welding activity typically occurs in continuous bouts of 20–30 min in duration before the welding equipment must be moved, with a cycle time ranging from 3 to 8 s per weld. Both the required welding current and the welding arc duty cycle increase as the stud diameter increases. Studs commonly used in building and bridge construction range in diameter from 12.7 to 25.4 mm, requiring welding currents of 800–1900 A (DC) and welding arc duty cycles of ~0.5–1.4 s (Chambers, 2001).

Stud welding with conventional equipment exposes workers to musculoskeletal and fume hazards (Fig. 1). Stud welding requires frequent bouts of prolonged stooping (Fethke *et al.*, 2011), a posture that can lead to an elevated risk of low back pain (Punnett *et al.*, 1991; Seidler *et al.*, 2001; Jansen *et al.*, 2004).This posture also frequently places the breathing zone in the buoyant plume of the welding fume (Fig. 1). Exposure to welding fume is associated with a wide range of adverse health outcomes, including lung cancer, metal fume fever, an increased incidence of bronchitis and pneumonia, manganism, and may be a risk factor for Parkinsonism (Hansen *et al.*, 1996; Lauritsen and Hansen, 1996; Korczynski, 2000; Racette *et al.*, 2001; Antonini *et al.*, 2003; Flynn and Susi, 2009).

Fethke *et al.* (2011) evaluated the ergonomic benefits of an alternative stud welding system that promoted a more upright working posture. Use of the alternate system was associated with a substantial reduction in the proportion of work time with trunk inclination angles >60°. In contrast, the alternate system did not reduce muscular loading in comparison to the conventional approach, suggesting that features of the system's design could be improved. Importantly, Fethke *et al.* (2011) did not examine exposure to welding fume. Although different types of arc welding are known to produce hazardous fume exposures (Flynn and Susi, 2010), we are aware of no peer-reviewed literature reporting the characteristics of welding fume generated during stud welding.

The objectives of this study were to estimate the effects of stud welding system configuration (conventional and a prototype upright system) and base material (bare beam and through galvanized decking) on (i) biomechanical loading and (ii) the concentration and composition of welding fume in the breathing zone. Biomechanical loading was estimated with the use of surface electromyography (EMG) and accelerometer-based measurement of trunk posture. Welding fume number concentrations were measured with a portable direct-read instrument, and inhalable mass concentrations were measured with filter-based, inhalable samplers. Welding fume composition and morphology were evaluated by elemental analysis of the filter-based samples and transmission electron microscopy.

## METHODS

### Stud welding equipment and simulation mock-ups

The conventional stud welding equipment consisted of a stud welding controller unit (ARC 3000, Pro-Weld International, LaGrange, OH, USA) that supplied power to a conventional hand-held stud gun (AG-900, Pro-Weld International). A diesel, electric generator (XQ350, Caterpillar Inc., Peoria, IL, USA) was used to supply power to the process. As shown in Fig. 2a, the use of conventional equipment required manual holding of the stud gun (weight = 41.2 N).

The prototype upright welding system used the same conventional equipment but allowed welding from an upright position. The upright system consisted of a mobile stand (Mini Stand, Equipois Inc., Manchester, NH, USA), an articulating arm with an integrated tool balancer (ZeroG®, Equipois Inc.), and an aluminum tube mounted to the articulating arm. The stud gun was attached to one end of the aluminum

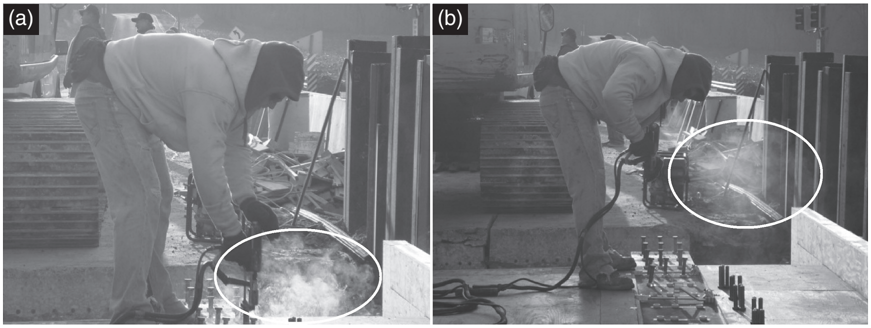


Figure 1 Movement of welding fume plume from generation at the base material (a) to near the breathing zone upon completion of the weld (b).

Figure 2 Stud welding simulations. Clockwise from upper left: (a) welding to bare beam using conventional equipment, (b) welding to bare beam using prototype upright system, (c) welding through deck using prototype upright system, and (d) welding through deck using conventional equipment.

tube, and a handlebar (with a thumb trigger to initiate the weld) was attached to the other end. No physical contact was possible between electrically conductive components of the stud gun and the aluminum tube of the prototype system.

Mock-ups were constructed in a local ironworkers apprenticeship training center under supervision of the apprenticeship training coordinator to simulate welding of studs to bare structural steel beams ('bare beam', as during bridge construction; Fig. 2a) and to structural steel beams through galvanized steel decking ('through deck', as during commercial building construction; Fig. 2c). In this study, we used 20 gauge galvanized steel decking and studs of 11.1 cm in length and 1.9 cm in diameter based on suggestions from union representatives, contractors, and material suppliers as typical to the industry. The mock-ups each encompassed 45 m$^2$ and were located in a large workshop (460 m$^2$) with a high ceiling (6.1 m) at the training center.

### Study design

A convenience sample of 30 ironworkers (18 journeymen and 12 apprentices) were recruited from the membership of Ironworkers Local 89 in Cedar Rapids, IA. All participants were experienced with stud welding or trained by the apprenticeship training coordinator prior to participation. The mean age of participants was 36 years (range: 21–62 years), mean height was 1.8 m (range: 1.7–1.9 m), and mean body mass was 89 kg (range: 64–120 kg). All but three participants were right-hand dominant. Study procedures were approved by the University of Iowa Institutional Review Board, and all participants provided written informed consent.

Each participant welded 25 studs in each of four experimental conditions (Fig. 2): (i) to bare beam using conventional equipment, (ii) through deck using conventional equipment, (iii) to bare beam using the upright system, and (iv) through deck using the upright system. The order of the experimental conditions was randomized. The apprenticeship training coordinator configured the settings of the stud welding controller unit to ensure the proper welding current (~1700 A) and welding arc duty cycle (~0.95 s per weld). The output voltage of the stud welding controller was rated as 44 V (DC) and was not adjustable. The lift and plunge of the stud gun were also adjusted to ensure satisfactory weld quality. Participants completed all 25 welds in one condition at a self-selected pace before starting another condition. Across participants and experimental conditions, the time needed to complete 25 welds averaged just below 6 min. A short rest break (up to 5 min) was provided between conditions. Consistent with stud welding on an active construction site, participants inserted the studs manually into the chuck of the stud gun for the conventional equipment. When using the upright system, however, a research assistant or the apprenticeship training coordinator inserted studs into the chuck of the stud gun for the participants. This assistance was needed due to limited vertical travel of the articulating arm, which did not allow participants to easily reach the chuck from a standing position.

### Trunk inclination measurements

A triaxial accelerometer (ADXL335, Analog Devices, Norwood, MA, USA) was used to estimate inclination of the trunk (i.e. flexion/extension). The accelerometer was attached to the chest just below the sternal notch, with the $x$-axis oriented in the lateral direction, the $y$-axis in the vertical direction, and the $z$-axis in the fore-aft direction. The accelerometer was connected to an instrumentation amplifier (Myomonitor IV®, Delsys Inc., Boston, MA, USA) placed in a small pack worn about the waist. The amplifier was connected wirelessly to a computer, which sampled the raw accelerometer voltage signals at 1000 Hz.

The accelerometer signals were processed using custom LabVIEW programs (version 2013, National Instruments, Inc., Austin, TX, USA). The raw accelerometer voltages were low pass filtered (zero phase, second order Butterworth, 5 Hz corner frequency) and converted to units of gravity (g). Inclination angle was then computed as the arctangent of the ratio of the $z$-axis acceleration to the square root of sum of the squared accelerations on the $x$- and $y$-axes. For each participant, an inclination offset was calculated as the mean accelerometer inclination angle observed during 30 s of upright standing. The inclination offset angle was subtracted from the inclination angles observed during experimental testing. For each experimental condition, the arithmetic mean of the inclination angle recording (in degrees) was extracted for statistical analysis.

### Surface electromyography measurements

Surface EMG recordings were obtained bilaterally from the flexor digitorum superficialis (forearm flexors), extensor digitorum communis (forearm extensors), upper trapezius, and thoracic erector spinae (T9 level) muscle groups. The surface EMG electrodes (model DE2.3, Delsys Inc.) had a 20–450 Hz bandwidth and onsite differential amplification (gain of 1000). A reference electrode was secured to skin over the nondominant clavicle. The electrode cables were attached to the instrumentation amplifier, and the raw EMG voltage signals were wirelessly sampled at 1000 Hz.

The surface EMG recordings were processed using custom LabVIEW programs. Signal quality was verified through inspection of the time and frequency domain representations of each surface EMG recording. Following removal of DC offset, the signals were then converted to instantaneous root-mean-square (RMS) amplitude using a 100-sample window with a 50-sample overlap.

Normalization of the RMS-processed EMG recordings occurred in the bioelectric domain, with the muscle activity during the stud welding simulations expressed as a percentage of the activity observed during isometric, submaximal reference contractions (i.e. %RVE). Participants were standing for all reference contractions. For the forearm flexor and forearm extensor muscles, participants held a hand grip dynamometer using a power grip (Commander GripTrack, JTech Medical, Salt Lake City, UT, USA). With the elbow in 90° of flexion and the forearm in a neutral position, participants produced 89 N of hand grip force (Anton *et al.*, 2005). For the upper trapezius, participants held a 1 kg load in each hand with the shoulders abducted to 90°, the elbows fully extended, and the forearms pronated (Mathiassen *et al.*, 1995). For the erector spinae, participants flexed forward to a trunk inclination angle of 30° and held a 16.7 kg load with both hands and the arms hanging vertically (Fethke *et al.*, 2011).

Three repetitions of each reference contraction were performed, with a minimum rest of 1 min between repetitions. Participants maintained each reference contraction for 15 s, and the mean RMS amplitude of the middle 10 s was calculated. For each muscle, the reference activation level was defined as the average mean RMS amplitude of the three repetitions. Baseline noise was defined for each muscle separately as the lowest RMS amplitude recorded during the experimental conditions and was subtracted in a power sense (Thorn *et al.*, 2007). For each experimental condition and muscle group, the arithmetic mean of the normalized surface EMG recording (in %RVE) was extracted for statistical analysis.

### Welding fume measurements

Throughout all testing, particle number concentrations were sampled at 1 Hz with a miniature diffusion size classifier (DiSCmini, Matter Aerosol, Wholen, Switzerland) placed in the small pack worn about the waist. The DiSCmini measures particle number concentrations within 16% of those measured with reference condensation particle counters (Mills *et al.*, 2013). An electrically conductive tube affixed to the participant transported aerosol from the breathing zone to a dilution filter (6702–7500, Whatman Inc., Florham Park, NJ, USA) with a hole (diameter = 0.040 cm) drilled into its end cap. The dilution filter was needed to maintain the number concentration when measured below the upper measuring limit of the DiSCmini. The dilution factor (DF) was estimated by dividing the arithmetic mean of the three number concentration measurements made without by that made with the dilution filter present. Actual number concentrations were estimated as the number concentration measured with the DiSCmini times DF.

DiSCmini data were analyzed using a custom LabVIEW program. For each participant and experimental condition, the arithmetic mean and the 5th and 95th percentiles of the welding fume number concentration (particles $\mathrm{cm}^{-3}$) were extracted for descriptive and statistical analyses. The geometric mean and geometric standard deviation of the welding fume number concentration across participants were also calculated. Because testing occurred indoors, mean background aerosol concentration was also evaluated (Supplementary Data).

Integrated over three participants, two inhalable samplers (button samplers, 225–360, SKC Inc., Eighty Four, PA, USA) were used to collect fume at 4 Lpm onto mixed cellulose ester filters (225–1912, 1.2 µm MCE filters) for each experimental condition. Samples were integrated over three subjects in anticipation of low collection of mass and metals content because each sample represented a short duration of ~18 min (~6 min per condition × 3 subjects). The samplers were affixed to the aluminum tube that held the stud gun in the upright system, and positioned so that they were in the breathing zone when welding with the conventional and upright system (Supplementary Fig. S1). In total, four integrated samples were collected (one for each experimental condition). The filters were first analyzed gravimetrically to estimate mass concentration (mg $\mathrm{m}^{-3}$) and then by inductively coupled plasma atomic emission spectrometry (ICP-MS, NIOSH 7300) for nine metals [cadmium (Ca), chromium (Cr), cobalt (Co), copper (Cu), iron (Fe), lead (Pb), manganese (Mn), nickel (Ni), and zinc (Zn)].

For each welding condition, additional samples of particles were collected onto transmission electron microscope (TEM) grids (Cu, 01810G-F, Ted Pella, Redding, CA, USA) using an electrostatic precipitator

(Model 100, ESP nano, Spokane, WA, USA). The inlet of the electrostatic precipitator was held in the plume ~0.3 m above the stud welding process. Samples were collected for 1 and 20 s to accommodate for potential overload of the sample. The 20-s samples were overloaded so only data from 1-s samples are reported. Particle size and morphology were obtained by imaging using a TEM (JEM 1230, JEOL USA, Inc., Peabody, MA, USA). The size distribution of the primary particles was determined through image analysis using ImageJ software. Composition of individual particles was analyzed by scanning electron microscopy (SEM, Hitachi S4800, Hitachi High Technologies America, Inc. USA) equipped with an energy dispersive X-ray analysis detector (EDX). SEM images were collected with an accelerating voltage of 20 kV and 8.5–9.0 mm working distance. EDX point spectra were analyzed using Iridium Ultra microanalysis software (IXRF Systems Inc., Austin, TX, USA). Additionally, elemental mapping of particles was conducted using a high-resolution TEM with an accelerating voltage of 20 kV (JEM 2100, JEOL USA, Inc.).

### Statistical analyses

The distributions of all welding fume number concentration, trunk inclination, and surface EMG summary measures were examined for violations of normality (e.g. Shapiro–Wilk and Q–Q plots; no violations of normality were observed) and then described using means and standard deviations (with the exception of the geometric mean and geometric standard deviation of welding fume number concentration). For each summary measure extracted for statistical analysis, the fixed effects of the welding system configuration (conventional versus upright) and the base material (through deck versus bare beam) were examined using a two-way repeated measures analysis of variance. The Tukey procedure was used to perform *post hoc* pairwise comparisons of summary measure distributions between experimental conditions. All statistical procedures were performed using SAS (version 9.4, SAS Institute Inc., Cary, NC, USA).

## RESULTS

### Trunk inclination

As expected, forward inclination of the trunk was substantially lower with the upright system than with the conventional equipment (Table 1; main effect of system configuration $P < 0.01$). Across base materials, mean trunk inclination with the upright system (9.6° ± 6.6°) was 12% of that with the conventional equipment (79° ± 15.6°). Neither the main effect of base material nor the interaction between welding system configuration and base material on mean trunk inclination was statistically significant.

### Surface electromyography

Muscle activity, except for the upper trapezius, was lower with the upright system than with the conventional equipment (Table 1; main effect of system configuration $P < 0.01$ for each muscle). As a percentage of the muscle activity observed during use of the conventional welding system, the reductions ranged from about 19% for the left erector spinae to >70% for the left forearm extensor (Table 2). In contrast, upper trapezius muscle activity increased with the upright system, although the levels remained well below those observed during the reference contractions. Neither the main effect of base material nor the interaction between welding system configuration and base material on mean normalized muscle activity was statistically significant for any muscle.

### Welding fume number and mass concentrations

Particle number concentrations were substantially lower with the upright system than with the conventional equipment for either base material (Fig. 3, Table 1; main effect of system configuration and base material significant on arithmetic mean and 95th percentile, $P < 0.01$). Across base materials, the 95th percentile number concentration was substantially reduced with the upright system ($5.3 \times 10^6 \pm 4.8 \times 10^6$ particles $cm^{-3}$) than when using the conventional equipment ($26.2 \times 10^6 \pm 17.8 \times 10^6$ particles $cm^{-3}$). Across the system configurations, the 95th percentile number concentration when welding though decking ($23.1 \times 10^6 \pm 19.5 \times 10^6$ particles $cm^{-3}$) was substantially higher than when welding to bare beam ($8.3 \times 10^6 \pm 8.6 \times 10^6$ particles $cm^{-3}$). The difference between base materials was visually apparent, with greater formation of weld splatter when welding through decking (Supplementary material includes a video illustrating the difference). The interaction between welding system configuration and base material on both the mean and 95th percentile welding fume number concentrations was also statistically significant. In each case, the

**Table 1. Trunk inclination, surface EMG, and welding fume summary measures by base material (bare beam versus through decking) and welding system configuration (conventional versus upright)**

| Summary measure[a] | Bare beam | | Through decking | | Tests of fixed effects (*P*) | | |
|---|---|---|---|---|---|---|---|
| | Conventional | Upright | Conventional | Upright | *Sys.* | *Base* | *Int.* |
| **Trunk inclination (°)**[b] | 80.4 (16.6) | 8.9 (6.6) | 77.7 (14.8) | 10.3 (6.8) | <0.01 | 0.76 | 0.22 |
| **Surface EMG (% RVE)** | | | | | | | |
| Right forearm flexor | 215.6 (105.5) | 141.8 (107.4) | 238.1 (111.7) | 144.4 (100.6) | <0.01 | 0.17 | 0.27 |
| Left forearm flexor | 202.9 (111.2) | 107.1 (51.4) | 226.3 (136.5) | 104.7 (53.5) | <0.01 | 0.33 | 0.24 |
| Right forearm extensor | 154.5 (125.3) | 72.4 (89.2) | 186.1 (228.7) | 68.9 (89.2) | <0.01 | 0.47 | 0.36 |
| Left forearm extensor | 139.5 (69.0) | 38.7 (21.3) | 154.8 (104.6) | 41.1 (23.8) | <0.01 | 0.30 | 0.44 |
| Right upper trapezius | 12.5 (7.7) | 32.3 (16.3) | 11.9 (6.3) | 32.1 (17.2) | <0.01 | 0.78 | 0.89 |
| Left upper trapezius | 8.6 (5.1) | 29.2 (14.9) | 9.4 (5.8) | 27.7 (13.8) | <0.01 | 0.81 | 0.42 |
| Right erector spinae | 96.5 (114.9) | 70.4 (50.6) | 90.5 (88.7) | 69.6 (59.8) | <0.01 | 0.62 | 0.70 |
| Left erector spinae | 78.2 (33.0) | 64.2 (32.6) | 79.1 (34.0) | 63.9 (32.0) | <0.01 | 0.92 | 0.85 |
| **Fume number concentration**[c] | | | | | | | |
| Arithmetic mean | 2.8 (1.9) | 0.8 (0.5) | 6.9 (2.8) | 1.5 (0.9) | <0.01 | <0.01 | <0.01 |
| Geometric mean (GSD)[d] | 2.4 (0.2) | 0.6 (0.2) | 6.4 (0.2) | 1.2 (0.2) | | | |
| 5th percentile | 0.2 (0.1) | 0.1 (0.03) | 0.2 (0.2) | 0.1 (0.1) | | | |
| 95th percentile | 13.3 (9.5) | 3.3 (2.8) | 39.2 (14.4) | 7.2 (5.6) | <0.01 | <0.01 | <0.01 |

[a] All summary measures distributions expressed as mean (SD) except geometric mean and geometric standard deviation.
[b] Positive values indicate forward trunk inclination (i.e. flexion).
[c] All fume concentrations expressed as the number of particles per $cm^3$ ($\times 10^6$).
[d] Geometric standard deviations are unit less quantities.

**Table 2. Effect of welding system configuration on mean normalized muscle activity (% RVE), across base materials**

| Muscle | Conventional | | Upright | | |
|---|---|---|---|---|---|
| | Mean (SD) | CV (%)[a] | Mean (SD) | CV (%) | Effect (%)[b] |
| Right forearm flexor | 226.8 (108.3) | 47.8 | 143.1 (103.1) | 72.0 | −36.9 |
| Left forearm flexor | 214.6 (124.0) | 57.8 | 105.9 (52.1) | 49.2 | −50.7 |
| Right forearm extensor | 170.3 (183.5) | 107.8 | 70.6 (88.5) | 125.4 | −58.5 |
| Left forearm extensor | 147.1 (88.2) | 60.0 | 39.9 (22.4) | 56.1 | −72.9 |
| Right upper trapezius | 12.2 (7.0) | 57.4 | 32.2 (16.6) | 51.6 | 163.9 |
| Left upper trapezius | 9.0 (5.4) | 60.0 | 28.4 (14.2) | 50.0 | 215.6 |
| Right erector spinae | 93.5 (101.8) | 108.9 | 70.0 (54.9) | 78.4 | −25.1 |
| Left erector spinae | 78.6 (33.2) | 42.2 | 64.0 (32.0) | 50.0 | −18.6 |

[a] CV, coefficient of variation (i.e. SD/mean × 100%).

[b] Difference between prototype upright and conventional systems, expressed as a percentage of the conventional system.

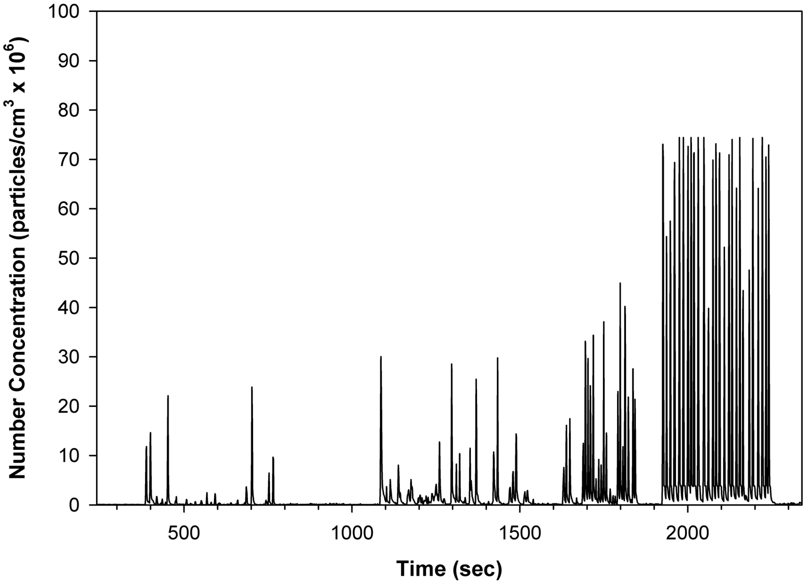


Figure 3 Typical time series of logged particle number concentration across the four experimental conditions (data from one participant).

difference in number concentration between the bare beam and through deck conditions was lower when using the conventional equipment than when using the upright system. Background number concentrations in the training center were negligible compared to those when welding (Supplementary Fig. S2).

Consistent with observed number concentrations, inhalable mass concentrations with the upright system were substantially lower (60% for bare beam; 64% for through decking) than those with the conventional equipment (Table 3). The highest concentrations were observed with the conventional equipment through

**Table 3. Inhalable mass concentration means and metals content of welding fume**

| Summary measure | Bare beam |  | Through decking |  | 8-h TLV (size fraction)[a] |
|---|---|---|---|---|---|
|  | Conventional | Upright | Conventional | Upright |  |
| **Inhalable mass concentration [mg/m$^3$]** | 18.2 | 7.2 | 65.7 | 23.4 | 10 (inhalable)<br>3 (respirable) |
| **Sum of metals [mg/m$^3$ (% of inhalable)]** | 9.0 (49.3) | 3.4 (46.6) | 33.4 (50.8) | 12.2 (52.1) |  |
| **Metals [mg/m$^3$ (% of inhalable metals)][b]** |  |  |  |  |  |
| Copper | 0.07 (0.8) | 0.03 (0.9) | 0.18 (0.5) | 0.07 (0.6) | 0.2 (total) |
| Iron | 7.78 (86.7) | 2.83 (84.4) | 15.80 (47.4) | 5.91 (48.5) | 5 (respirable) |
| Manganese | 0.88 (9.8) | 0.34 (10.1) | 1.54 (4.6) | 0.60 (4.9) | 0.02 (respirable)<br>0.1 (inhalable) |
| Zinc | 0.21 (2.4) | 0.14 (4.3) | 15.80 (47.4) | 5.59 (45.9) | 2 (respirable) |

[a] Threshold limit values established by American Conference of Governmental Industrial Hygienists.

[b] Percentages do not sum to 100% due to rounding and/or small amounts of metals not reported.

the galvanized decking (65.7 mg m$^{-3}$) and lowest with the upright system on bare beam (7.2 mg m$^{-3}$). The concentrations of metals not shown in Table 3 that were analyzed as part of the nine metal scan (Ca, Cr, Co, Pb, Ni, and Zn) were below limits of detection of the analytical method.

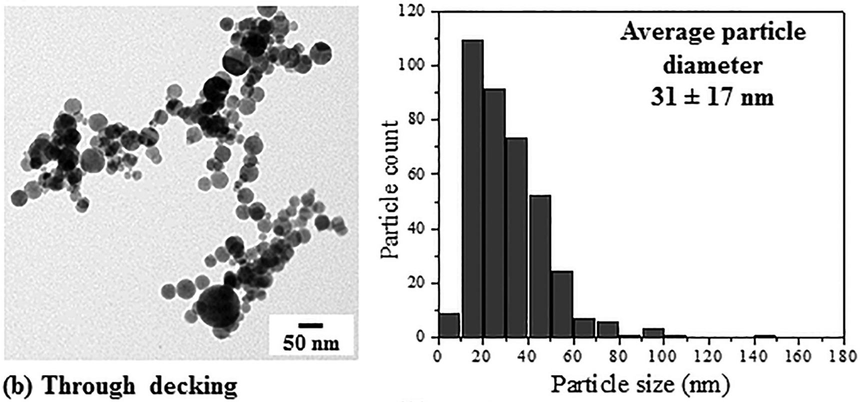
Threshold limit values (TLVs) established by the American Conference of Governmental Industrial Hygienists (ACGIH) are also provided in Table 3 to present some context for interpreting the mass and metal concentrations. The ACGIH does not have a TLV for welding fume but rather publishes TLVs for specific metal constituents. Substances that lack a specific TLV are considered to have 'low toxicity' and TLVs for both respirable and inhalable particles not otherwise specified (PNOS) are 3 and 10 mg m$^{-3}$, respectively. In addition, these TLVs are based on an 8-h, time-weighted-average exposure (sample duration for our experiments was ~18 min and integrated over three subjects). The fact that stud welding is a job typically performed by a single person over a full work shift does provide some validity of comparing our measurements to TLVs.

The aggregate mass concentrations of metals accounted for roughly 50% of the total inhalable mass concentration and were often above applicable TLVs (Table 3). For Mn, observed mass concentrations were substantially above the inhalable TLV for all conditions. Mass concentrations of Zn were above the respirable TLV only when welding through decking, consistent with the zinc used to galvanize the deck to prevent rust. Fe mass concentrations were above the respirable TLV for all conditions, except upright, bare beam. The mass concentrations of Cu were substantially lower than the total TLV in all cases except for when welding through decking using conventional equipment (which was just under the TLV).

### Characterization of welding fume particles

The results from microscopic imaging of particles are shown in Figs 4–6. For bare beam conditions, particles were agglomerates of spheres (Fig. 4a) with a heterogeneous size distribution. Based on the analysis of 377 particles, the average diameter of primary particles was 31 ± 17 nm. These particles were homogeneous in composition (Fig. 5a) consisting of iron. In contrast, for through deck conditions, particles were agglomerates of spheres, rods with crystalline structure and very small nanoparticles (Fig. 4b). Based on the analysis of 250 particles, the average diameter of

(a) Bare beam



(b) Through decking

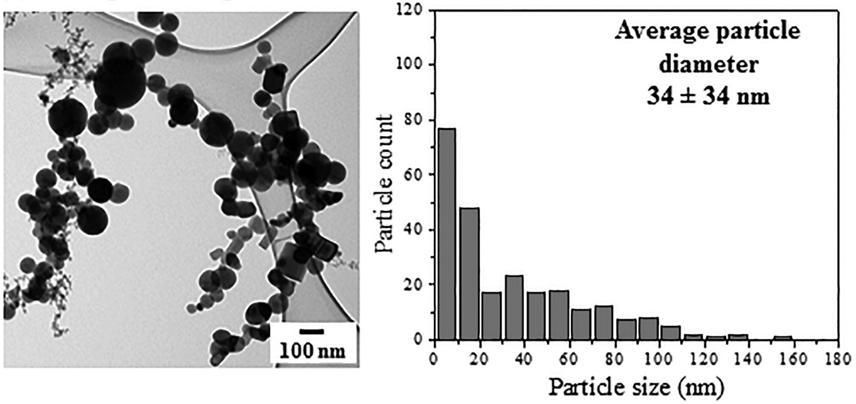


Figure 4 Left panel: TEM images of particles collected when stud welding (a) to bare beam and (b) through decking. Right panel: Corresponding size distributions counting 377 and 250 particles yield for images (a) and (b) respectively.

the primary particles was calculated to be 34 ± 34 nm, indicating a broader size distribution. These primary particles were shown to be highly heterogeneous with some particles found enriched in Zn and Fe while others contained only Zn (Fig. 5b).

These observations are consistent with bulk elemental analysis by ICP-MS (Table 3). The quantitative elemental analysis of samples with ICP-MS also indicated high levels of Fe (~85%) in samples generated from bare beam while samples generated from through decking contained high levels of both Fe (~48%) and Zn (~47%). However, Mn quantified using ICP-MS analysis for both samples was not observed with EDX as a result of low concentration. Although EDX spectra showed strong peaks for Cu, they result from background as TEM grids contain Cu. The ICP-MS data in Table 3 also shows low concentrations of Cu the samples (<1% for all the samples).

Elemental maps of several particles from the through deck condition (Fig. 6) suggest that the smaller particles were composed of mainly Fe while the larger particles were mostly bimetallic (Fe and Zn). In addition, there was little oxygen in these particles indicating that these are metallic nanoparticles not metal oxide nanoparticles. Overall, we observed a clear segregation of elements between different nanoparticle size fractions.

## DISCUSSION

A prototype upright system to weld shear stud connectors reduced biomechanical loading compared to conventional equipment. Substantial improvement in mean trunk inclination angle was observed during use of the upright system, as intended by its design. Although the relationship between trunk flexion (i.e. inclination) and low back pain is complex (Wai *et al.*, 2010), the results of prospective epidemiological

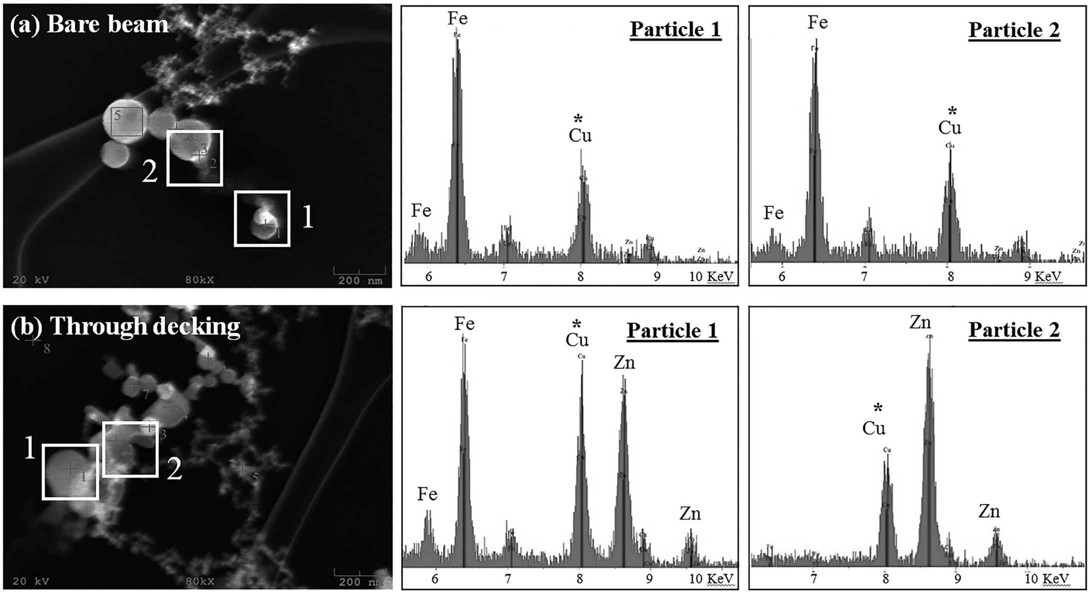


Figure 5 Left panels: Scanning electron microscopy images of particles collected when stud welding (a) to bare beam and (b) through decking. Right panels: Energy dispersive X-ray spectra of individual particles. During bare beam welding, particles were enriched only in Fe [(a): Particles 1 and 2]. When welding through decking, some particles are enriched in Zn and Fe [(b): Particle 1] whereas others are enriched in only Zn [(b): Particle 2].*Cu signal mainly comes from the TEM grid.

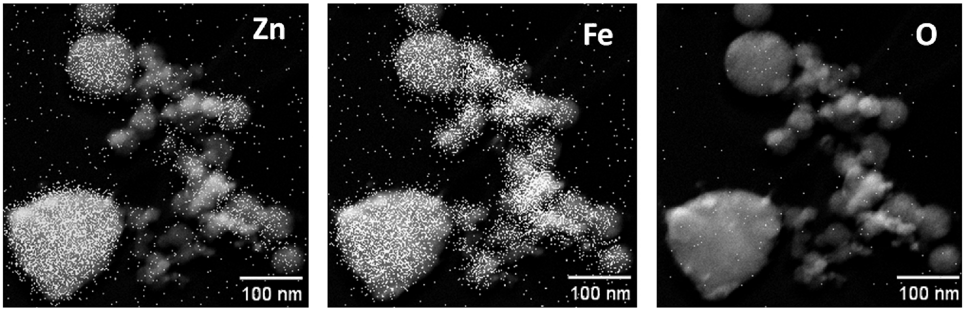


Figure 6 Elemental maps of welding particles collected through decking were obtained using high-resolution TEM. Elemental maps of individual particles show in agreement to the SEM-EDX data in Fig. 5b that particles have different chemical compositions. Smaller particles are nearly pure Fe whereas larger particles contain both Fe and Zn. The oxygen map shows no signal, indicating particles are metals and not metal oxides.

studies suggest that risk increases as the proportion of work time with trunk flexion >45° increases (Hoogendoorn *et al.*, 2000; Jansen *et al.*, 2004). With the exception of the upper trapezius, mean muscle activation levels were also reduced during use of the upright system. Although cumulative exposure to sustained and/or forceful muscular exertions is associated with musculoskeletal health outcomes (Hanvold *et al.*, 2013; Dalboge *et al.*, 2014), the magnitude of risk reduction associated with a given reduction in muscle activation is not well characterized. Therefore, while the observed reductions in biomechanical loading are mostly positive, definitive conclusions about the potential of the upright system to prevent musculoskeletal health outcomes are premature.

The mean normalized RMS EMG amplitudes of the upper trapezius and erector spinae muscles observed in the current study during use of both the conventional equipment and the upright system were similar to the levels observed in a previous field study (Fethke *et al.*, 2011). While the mean trunk inclination angle during use of the upright system (8.9°) was also similar to that observed in the field study (9.7°), the mean trunk inclination during use of conventional equipment was much greater (80.4° in this study versus 34.4° in the field study). In the field study, however, data were collected over prolonged periods during actual work. Field study participants would typically weld for up to 30 min and then perform ancillary tasks, move to a new area of the job site, or take a short rest break. Consequently, differences in comparable biomechanical summary measures between the current study and the field study in part reflect differences between task-level (i.e. welding only) and job-level exposures.

As in the study by Fethke *et al.* (2011), a modest increase in upper trapezius muscle activity was observed during use of the upright system. Regardless of welding system configuration, downward force is needed to maintain a secure contact between the stud and the base material. When using the conventional approach, the upper body weight is supported by the stud gun to supply the downward force (refer to Fig. 2). However, when using the upright system, the horizontal distance between the shoulder joint and the handles creates an external load moment about the shoulder and increases the upper trapezius activation levels. Even so, the mean normalized RMS EMG amplitudes observed during use of the upright system (32.2%RVE for the right upper trapezius; 28.4%RVE for the left upper trapezius) may be considered relatively low.

In addition to reductions in biomechanical loading, welding fume exposures expressed as number and mass concentration were substantially lower using the upright system compared to the conventional equipment. The 95th percentile of number concentrations, an indicator of peak exposures, observed with the upright system were 4 times lower for bare beam and 5.5 times lower for through decking compared to the conventional equipment (Table 1). Time-integrated inhalable mass concentrations were also reduced with the new upright system compared to the conventional equipment: 2.5 times lower for bare beam and 2.8 times lower for through decking (Table 2). Similar reductions were observed for metals. We attribute these reduced fume exposures to the increased distance of the breathing zone from the weld fume source with the upright system (~1.4 m) compared to that with the conventional equipment (~0.5 m). A longer distance from the source increases the probability that a horizontal air current will move the buoyant hot plume of welding fume away from the breathing zone. Further reduction is anticipated on actual worksites because air currents are likely to promote movement of the plume away from the breathing zone.

The number and mass concentrations of fume observed during stud welding, a form of resistance welding, were unexpectedly high. With conventional equipment, the arithmetic mean fume concentrations were $2.8 \times 10^6$ particles cm$^{-3}$ for bare beam and $6.9 \times 10^6$ particles cm$^{-3}$ for through decking. Although there are no regulatory or health-based exposure limits for particle number concentrations in the USA, particle exposures have increasingly been estimated using this metric due to potentially greater toxicity of nanoparticles (<100 nm) compared to larger particles. The number concentrations observed in this work are substantially higher than those reported by others for arc welding ($<0.5 \times 10^6$ particles cm$^{-3}$) (Brand *et al.*, 2013; Debia *et al.*, 2014) and for resistance welding in automotive assembly ($<10^5$ particles cm$^{-3}$) (Buonanno *et al.*, 2011).

Inhalable mass concentrations were often above TLVs established by the ACGIH (Table 2). With conventional equipment, inhalable mass concentrations were well above the TLV for PNOS (10 mg m$^{-3}$): 18.2 mg m$^{-3}$ for bare beam and 65.7 mg m$^{-3}$ for through decking. Resistance welding mass concentrations reported in literature are typically much lower, such as 0.4 mg m$^{-3}$ reported for worst-case conditions in automotive spot welding (Buonanno *et al.*, 2011). For Mn, observed mass concentrations were substantially above the inhalable TLV for all experimental conditions. The size distribution of this fume was dominated by respirable-sized particles, lending legitimacy of comparing our inhalable measurements to respirable and total TLVs. Mass concentrations of Zn were above the respirable TLV only for through deck experiments, consistent with the Zn used to galvanize the deck for rust prevention. Iron mass concentrations were above the respirable TLV for all conditions, except when using the upright system to weld to bare beam. The mass concentration of Cu was lower than the total TLV for all conditions. These observations of high number and mass concentrations during stud welding compared to other forms of resistance welding are attributed to the energy input to the process, as fume generation rates increase with increased energy delivery (Yoon *et al.*, 2003). Based on operating parameters, ~71 kJ of energy was delivered for each weld in this study (44 V × 1700 A × 0.95 s arc duration per weld). For comparison, a modern resistance spot welder capable of joining two pieces of 16 gauge galvanized metal (LMSW-52T, Miller Electric Manufacturing Co., Appleton, WI, USA) can deliver about 2.4 kJ of energy over a 0.95 s arc duration (2.5 kVA output × 0.95 s, and assuming a power factor of 1.0). Higher observed concentrations may also be due in part to our use of the DiSCmini with a diluter, which allowed us to measure in the breathing zone, whereas other researchers have measured concentrations with large instruments further away from the source.

Several important limitations may impact the ability to generalize the results of this study to field environments. First, the biomechanical summary measures extracted for statistical comparison (e.g. mean trunk inclination angle and mean normalized RMS EMG) do not fully capture the overall biomechanical demands of the stud welding activity. Summary measures such as the static and peak muscular loads (Jonsson, 1988) or periods of rest and recovery derived from the posture data (Kazmierczak *et al.*, 2005) may have been used to describe biomechanical loading with greater detail. However, such summary measures may be more important to include under field conditions during which greater variability is expected in muscular effort and working postures. Second, the stud welding simulations occurred in an indoor environment with only limited horizontal airflow. Consequently, welding fume exposures (particle number and time-integrated mass concentrations) measured in this study may overestimate exposures measured in some field settings where the welding activity is more intermittent and air movement may be greater. Third, only a small number of samples ($n = 4$) were collected for estimation of time-integrated mass concentrations, particle size distributions, and metals content of the fume. Finally, the simulations were conducted using a single size (length and diameter) shear stud connecter and through a single thickness of the galvanized decking (20 gauge) typical of the industry. Larger studs and thicker decking material increase the required power to produce high-quality welds, which may impact the amount of fume generated. Recognizing these limitations, it is noteworthy that the inhalable exposure concentrations for each experimental condition exceeded the respirable TLV (3 mg m$^{-3}$) and all but one (upright, bare beam) exceeded the inhalable TLV (10 mg m$^{-3}$) for PNOS.

Limitations were also apparent in the design of the prototype upright welding system that must be resolved before its use in the field is possible. Aside from general durability concerns expressed by participants, the relatively small wheels hindered maneuverability of the system, especially when welding through decking. Most importantly, however, the vertical travel of the articulating arm needs to be increased to allow the structural ironworker to load a new stud into the chuck of the stud gun from an upright position. These issues increased the time needed to complete the 25 welds using the upright system by ~2.5 min in comparison to the conventional approach (data not shown). Without assistance from a laborer to load studs, the increased time needed to complete the 25 welds using the prototype system would have been substantially greater and, ultimately, adoption of an upright welding system will depend on its cost and production capabilities as much as (if not more than) its potential benefits to worker safety and health. Moreover, the transfer of biomechanical loads from the ironworker to the laborer (who needed to stoop to load studs) is an undesirable consequence of the current prototype that will need to be corrected. In addition, reducing the downward force needed to maintain contact between the stud and the base material and/or reconfiguring the prototype to reduce the horizontal distance between the handles and the operator is desirable to minimize biomechanical loads to the shoulder.

In conclusion, biomechanical loading and fume exposures were substantially reduced with the use of a novel upright stud welding system compared to conventional equipment. We found that particle number and mass concentrations measured in the breathing zone were high during stud welding with conventional equipment, often exceeding health-based occupational exposure limits. The upright system reduced exposures but concentrations of metals, especially with stud welding through galvanized decking, may warrant further integration of fume control (e.g. a fume extraction system) into the upright system. Future work is needed to optimize usability of the system and to characterize personal exposures on worksites.

## SUPPLEMENTARY DATA

Supplementary data can be found at http://annhyg.oxfordjournals.org/.

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