

Muscle Fatigue Analysis During Welding Tasks Using sEMG and Recurrence Quantification Analysis

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ABSTRACT

The main goal of this study was to detect muscle fatigue and to identify muscles vulnerable to musculoskeletal disorders by evaluating muscle activation of subjects during welding tasks. In this study, six subjects performed two different welding tasks for a total of three hours. Surface electromyography (sEMG) was used to record the muscle activation of 16 different muscles. Recurrence quantification analysis (RQA) was then used to analyze the EMG data. In addition, a subjective fatigue assessment was conducted to draw comparisons with the RQA results. According to the RQA results, 12 of the tested muscles experienced fatigue by showing significant difference in RQA values (p -value < 0.05) between the first and last 10 minutes of the experiment. Moreover, time-to-fatigue results obtained from RQA and subjective analysis were closely correlated for seven muscle groups. This study showed that RQA can be used in ergonomic studies for evaluating muscle activation during construction tasks.

KEYWORDS

Construction Welding, Muscle Fatigue Analysis, Recurrence Quantification Analysis, Subjective Fatigue Assessment

INTRODUCTION

Work-related musculoskeletal disorders (WMSDs) are common health problems which have tremendous impact on manual workers (Stattin & Järvholm, 2005). In the United States, 37% of all injuries in construction are caused by WMSDs (Schneider, 2001). WMSDs are believed to be caused by prolonged and repetitive work, localized muscle fatigue, tedious and short tasks (Amell & Kumar, 2001; Buckle & Devereux, 2002), as well as repeated awkward postures and handling tasks (Valero et al., 2017). Such musculoskeletal disorders can affect the lower back, shoulder, elbow, forearm, wrist, and hand (Gazzoni, 2010). One construction task which has most of the above mentioned characteristics is welding. Welding is a highly precise and mostly static type of task which requires strength and capability to carry out proficient movements (Kadefors et al., 1976). Research shows that musculoskeletal disorders are common among welders, especially in the shoulder (Jarvholm et al., 1991; Torner et al., 1991), neck, and low back (Torner et al., 1991). Welders also have a prevalence of supraspinatus tendinitis development, even new welders with relatively limited time on the job (Herberts et al., 1981). Torner et al. (1991) found that welders experienced significantly

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more supraspinatus tendinitis than office clerks. They also found that 35 out of 131 surveyed welders experienced shoulder pain during work, and 34 out of 58 surveyed welders experienced dysfunction in the right shoulder, while 15 of them experienced dysfunction in the left shoulder. Moreover, 44 out of 58 surveyed welders faced subjective shoulder and/or neck symptoms during the previous year. In addition, 16 of them encountered symptoms of an earlier hand injury. Investigation of the task and muscle activity related to welding tasks is warranted to identify ways to prevent musculoskeletal disorders related to welding. Therefore, a quantitative measure for evaluating muscle activity and detecting risk factors can be of great importance in preventing WMSDs. Moreover, development of real-time quantitative health and safety-related feedback about worker's activities in construction sites is an emerging area of investigation in construction research (Clasby et al., 2003; Harvey & Peper, 1997; Oldham et al., 2000).

SURFACE ELECTROMYOGRAPHY (SEMG):

The use of sEMG (Surface Electromyography) has been shown to be one of the most effective and quantitative methods to evaluate muscle activity and risk factors (Dennerlein et al., 2003; Farina, 2006; Lowe et al., 2001; Panahi & Cho, 2016; Sporrang et al., 1999). Moreover, sEMG offers a great advantage to be used as a real-time measurement method. There are two major physiological elements of the muscle that affect the EMG signal: reduction in conduction velocity in the muscle fibers and enhanced motor unit synchronization, the state in which motor units fire at the same time. These phenomena cause the frequency of the EMG signal to decrease and the amplitude to increase. These two phenomena, reduction in conduction velocity and increase in motor unit synchronization, are believed to be the myoelectric manifestations of muscle fatigue (Farina et al., 2002; Jensen et al., 2000; Li et al., 2004). Muscle fatigue analysis using sEMG has shown promising results in quantifying muscle activation for ergonomic purposes (Peppoloni et al., 2016).

Antwi-Afari and et al. (2017) used sEMG to evaluate the risk factors for work-related musculoskeletal disorders during repetitive lifting task in construction workers. They studied the effects of lifting weights and postures on muscle activity and muscle fatigue. They were able to show that increased lifting weights significantly increased muscle fatigue of the biceps brachii, brachioradialis, lumbar erector spinae, and medial gastrocnemius. Kadefors and et al. (1976) applied quantitative electromyography analysis to the muscles of the shoulder (deltoideus, biceps brachii, rhomboideus major, upper and middle trapezius, and supraspinatus) to find localized muscle fatigue in both experienced and inexperienced welders while performing standard welding tasks, for a total of 10 minutes for each subject. According to their study, inexperienced welders showed signs of muscle fatigue in the deltoid, supraspinatus and upper trapezius muscles, while experienced welders showed signs of muscle fatigue in the supraspinatus muscle only. They concluded that training and enhanced skills may lower the muscle fatigue in welders, but this would not eliminate the load on the supraspinatus muscle.

Lowe and et al. (2001) utilized EMG and discomfort analysis to study muscle fatigue of several muscle groups (upper trapezius, middle deltoid, anterior deltoid, latissimus dorsi, erector spinae, extensor digitorum communis, and flexor digitorum superficialis). The subjects were welders working in a confined space. Their study showed that during SMAW (Shielded Metal Arc Welding), several muscles showed signs of fatigue; however, fewer muscles showed such a symptom during FCAW (Flux-cored Arc Welding), suggesting that this welding method may cause less muscle fatigue in welders.

Ergonomic studies on welding tasks such as these are mainly conducted in laboratories with isometric loads or for relatively short periods of time. It is more applicable to study such tasks during real-world tasks that involve dynamic muscle activity. It is also more pertinent to extend the length of simulated studies to represent the real world situation as close as possible. There is, however, a major challenge when it comes to evaluating dynamic activities from the perspective of data analysis. The mechanism involved with such activities is more intricate and less understood than static activities with

isometric contractions (Dennerlein et al., 2003). Variations of the distance between the muscle and the sEMG sensor, the muscle fiber length, as well as the output force are the cause of such complexity (Farina, 2006) and as a result, in the case of dynamic activities, the sEMG data are not stationary. Therefore, in order to evaluate sEMG signals recorded from dynamic activities, a proper data analysis technique must be selected. Most of the traditional techniques, however, require stationary data.

Recurrence Quantification Analysis (RQA)

Recurrence Quantification Analysis (RQA) is a novel data analysis method that does not require stationary data and has shown promising results in detecting muscle fatigue during dynamic activities (Bauer et al., 2017; Clasby et al., 2003). Synchronization of motor units is believed to create deterministic patterns in EMG signal during the fatiguing stage (Li et al., 2004). Motor unit synchronization takes place to prevent task failure during the fatiguing stage (Jensen et al., 2000). This phenomenon has been identified during conventional occupational tasks utilizing one of the RQA measures called Determinism (DET) (Farina et al., 2002), which is discussed in section 2.4. Consequently, DET can be used to detect muscle fatigue in dynamic activities (Clasby et al., 2003).

This article is structured as follows. Firstly, the method of the research is provided which includes the research design, description of the welding tasks used in this study, sEMG data collection, description of the data analysis method (recurrence quantification analysis) implemented in this study, subjective assessment of muscle fatigue, and statistical analysis. Then, the results are presented and discussed utilizing different subsections which also includes future studies. Lastly, a conclusion is drawn.

METHODS

RESEARCH DESIGN

Increasing importance of avoiding WMSDs among construction workers, especially welders, motivated this study to apply a novel non-stationary data analysis method for analyzing muscle activation of subjects during welding tasks. The authors hypothesized that muscle fatigue which is one of the causes of WMSDs can be investigated using RQA and significant difference can be detected between the beginning and end of the experiment. Firstly, EMG sensors were utilized in this study to capture muscle activation of sixteen muscle groups of six right-hand-dominant participants who performed two different welding tasks for total of three hours. Secondly, RQA was used to analyze the EMG data to detect any deterministic pattern. DET, one of the RQA measures, was used for this purpose and it was applied to every minute of the experiment. Average DET% values were calculated among all the participants to find out the determinism values of the first and last 10 minutes of the experiment for each muscle. Thirdly, the muscles which showed significant difference between the first and last 10 minutes were further investigated to find their time-to-fatigue using both RQA and subjective analysis. In order to determine the time-to-fatigue moment for each muscle, the authors first used exponential smoothing and then by calculating the slope of the graph for each minute of the experiment the authors determined the time at which the average slope became positive. This time was considered time-to-fatigue. For subjective results, time-to-fatigue was considered the average of the times at which the fatigue score became non-zero. Finally, statistical analysis was implemented to determine the correlation between subjective and RQA results.

Welding Tasks

A total of six right-hand-dominant subjects participated in this study. The subjects' demographic information can be seen in Table 1. All the subjects were engineering students who volunteered to

Table 1. Participants' demographic information

Subject	Sex	Age (year)	Height (cm)	Weight (kg)
1	M	34	178	72
2	M	25	172	81
3	M	31	182	70
4	M	23	177	85
5	M	24	165	64
6	M	28	180	98

participate in this study. To exclude unhealthy subjects from the study, they were asked if they had any history of health issues such as chronic back or shoulder pain, cardiovascular disease or any considerable trauma to the target muscle groups. All the participants were healthy and did not have any experience of health problems. None of the subjects had any previous experience with welding tasks. A day before the experiment, all participants received an hour's training on the welding tasks using welding simulator and became familiar with the study procedure. A virtual reality welding trainer (VRTEX 360, LINCOLN, Figure 1) was used in this study to perform Shielded Metal Arc Welding (SMAW) on two different types of coupons. Each subject performed 15 minutes welding on each coupon, first using a T-Joint coupon and then a 6" Diameter Schedule 40 Pipe coupon. Subjects repeated this sequence for a total of three hours.

sEMG Data Collection

Bicep, tricep, deltoid, upper trapezius, brachioradialis, lower erector spinae, medial gastrocnemius, and wrist extensor were the target muscle groups for this study, as they were studied by other researchers from different ergonomic fields (Antwi-Afaria et al., 2017; Bauer et al., 2017; Clasby et al., 2003; Halim, Omar, Saman, & Othman, 2012; Milerad et al., 1991; Peppoloni et al., 2016; Rogers & MacIsaac, 2011; Uhrich et al., 2002). A 16-channel sEMG system noninvasive Surface Electromyography (sEMG) device (Trigno Wireless sEMG System, DELSYS INC.) was used to record EMG data from the above-mentioned muscle groups. The surface of the skin was wiped with rubbing alcohol, and after letting it dry, the sensors were placed in the center of the muscle belly and parallel to the muscle fibers using Delsys Adhesive Sensor Interface. There was not any need to shave the sensor locations in any of the subjects. The sensors were placed firmly on the skin and there was a good contact between the skin and sensors. Trigno EMG Sensors use silver bar contacts for detecting the EMG signal at the skin surface. It is very important to make the orientation of these bars perpendicular to the muscle fibers for maximum signal detection. There is an arrow on the top of the sensor to determine this orientation. This arrow was placed parallel to the muscle fibers in the center of the muscle belly away from tendons and the edge of the muscle. Once the general locations were determined, muscle contraction was performed for each muscle to test the quality of the signals. Delsys Surface EMG Sensor does not require skin preparation and attachment for basic function. This allowed us to find the optimal position by adjusting the location of the sensors until the detected signal was maximized as the muscle was contracted. The EMGworks Signal Acquisition (DELSYS INC.) was utilized to capture and filter data with a sampling rate of 1926 Hz.

Recurrence Quantification Analysis (RQA)

Recurrence Quantification Analysis (RQA) is a novel nonlinear data analysis method which is based on recurrence plots (RP) displaying the recurrence of a dynamical system. In fact, RP is a visualization

Figure 1. VRTEX 360, LINCOLN welding simulator



of all the times at which a phase space trajectory of a dynamical system passes approximately through the same area.

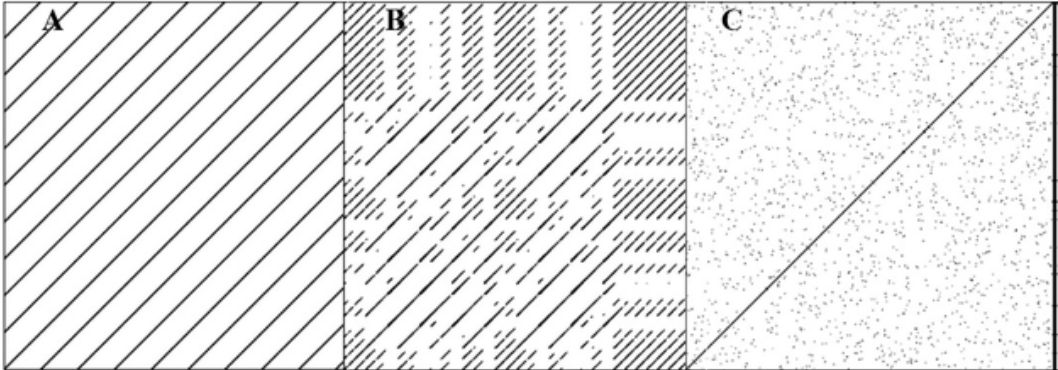
Let's assume that $\{\vec{x}_i\}_{i=1}^N$ is a trajectory of a system in its phase space (Eckmann et al., 1987). The RP will be according to the following recurrence matrix:

$$R_{i,j} = \begin{cases} 1: \vec{x}_i \approx \vec{x}_j, \\ 0: \vec{x}_i \not\approx \vec{x}_j, \end{cases} \quad i, j = 1, \dots, N, \quad (1)$$

Where $\vec{x}_i \approx \vec{x}_j$ is equality within a certain distance ε in which the system recurs. N is the number of examined states. In fact, the states of a system at times i and j are compared by the matrix. If the states are similar $R_{i,j}$ will be equal to 1 and if they are not similar, then $R_{i,j}$ will be considered 0. Figure 2 shows examples of three different recurrence plots for different systems (Marwan et al., 2007). In this study, since the authors are evaluating EMG data, x_i and x_j are voltage values in time series. The authors converted a single dimension time series into 2-dimensional matrix form for recurrence plot analysis. Figure 2.A displays the RP of a periodic motion on a circle by long and continuous diagonals with vertical distance between them representing the period of the oscillation.

Figure 2.B displays the RP of a chaotic Rössler system by shorter diagonal lines. Lastly, Figure 2.C displays the RP of uniformly distributed noise by many single black dots with inconsistent distribution. It can be concluded from these three recurrence plots that the longer the diagonal lines, the more predictable the system (Marwan et al., 2007).

Figure 2. RP of (A) a periodic motion with one frequency, (B) the chaotic Rössler system and (C) of uniformly distributed noise (Santy & Dawal, 2010)



Marwan et al. (2007) defined the tool to measure recurrences of a trajectory $\vec{x}_i \in \mathbb{R}^d$ in phase space. According to their study, the RP can be shown as follows (Marwan et al., 2007):

$$R_{i,j}(\varepsilon) = \Theta(\varepsilon - \|\vec{x}_i - \vec{x}_j\|), \quad i, j = 1, \dots, N, \quad (2)$$

Where N is the number of measured points \vec{x}_i , ε is a threshold distance, $\Theta(\cdot)$ the Heaviside function and $\|\cdot\|$ is a norm. They introduced the following for states which are within ε threshold distance (Marwan et al., 2007):

$$\vec{x}_i \approx \vec{x}_j \Leftrightarrow R_{i,j} \equiv 1 \quad (3)$$

The recurrence matrix obtained from Eq. 2 is then used to create an RP using different colors for binary entries. For instance, a black dot is assigned to the coordinates (i, j) , if $R_{i,j} \equiv 1$, and a white dot is used if $R_{i,j} \equiv 0$. Both axes of the RP are time (Fig. 2). Recurrence plots will always have a black main diagonal line called line of identity (LOI) since $R_{i,i} \equiv 1 \Big|_{i=1}^N$. It is also symmetric with reference to the LOI, since $R_{i,j} \equiv R_{j,i}$.

Selecting the distance threshold ε is very crucial to plot an RP. A few percent of the maximum phase space diameter is suggested to a proper value for ε (Mindlin & Gilmore, 1992). It is also suggested that it should not be larger than 10% of the mean or maximum phase space diameter (Zbilut & Webber, 1992).

The amount of predictability of a system can be quantified using one of the RQA measures called Determinism (DET). In order to calculate the percentage of determinism (DET%), the following formula is used (Marwan et al., 2007):

$$DET\% = \frac{\sum_{l=l_{min}}^N lP(l)}{\sum_{l=1}^N lP(l)} \times 100(\%) \quad (4)$$

Where N is the length of a data series, l_{min} is the predefined minimal length of a diagonal line, and $P(l)$ is a histogram or frequency distribution of diagonal line lengths. l_{min} is set to 2 in this study (Li et al., 2004). A cross-recurrence plot (CRP) toolbox was used for RQA analysis (Marwan et al., 2007). To derive DET%, RQA was applied to each minute of the EMG data recorded from each muscle. In addition, the exponential smoothing method was utilized to identify the time-to-fatigue for each muscle group based on the following formula:

$$S_t = \alpha y_{t-1} + (1 - \alpha) S_{t-1} \quad (5)$$

Where S_t is forecast value at time t , y_{t-1} is the actual value at time t , α is the smoothing constant which is set to 0.5, and t is the time period. In order to determine the time-to-fatigue moment for each muscle, the authors first used exponential smoothing and then by calculating the slope of the graph for each minute of the experiment the authors determined the time at which the average slope became positive.

Subjective Assessment of Fatigue

The CR-10 Borg scale (Borg, 1982) was used in this study to rate the level of muscle fatigue in the muscle groups. Each subject was asked to rate their level of muscle fatigue every 10 minutes throughout the experiment. The authors used scores from 0 to 10 (with 0 meaning “nothing,” 5 meaning “intense,” and 10 meaning “very intense”). This was explained to the participants both verbally and in writing. In this study, the average of the times at which the scores of the subjects became non-zero was considered as time-to-fatigue for each muscle.

Statistical Analysis

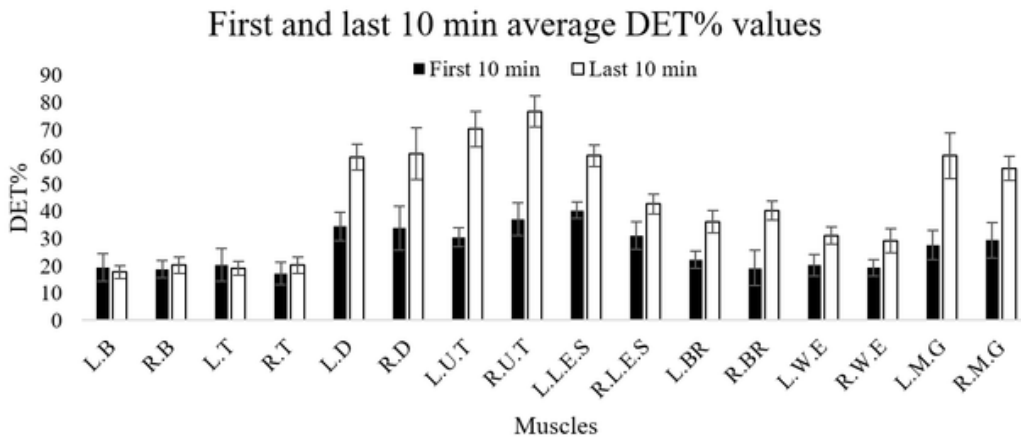
To compare the average DET% values obtained from the first and last 10 minutes of the experiment, paired t-test was used. This test was conducted for each muscle group to find out any significant difference in DET% values between the beginning and end of the experiment. This statistical analysis was performed using SPSS software (IBM Corp., Armonk, NY, USA). The statistical significance level was set at $\alpha=0.05$. Any muscle group which showed significant difference was further analyzed with the same statistical analysis to compare its DET% values to its subjective fatigue results.

Results and Discussion

The subjects performed the welding tasks on a virtual reality welding trainer which enabled us to evaluate welding tasks in a standardized fashion. RQA was used to evaluate sEMG non-stationary data recorded from the welding tasks. The dynamic nature of these type of activities increases the complexity level of the data analysis. Thanks to the capability of the RQA method, the authors were able to overcome this complexity and successfully analyze the EMG data. RQA, specifically DET, allowed us to detect the deterministic pattern in EMG data which is used as the indicator of muscle

fatigue in this study. Figure 3 shows the average DET% values for the first and last 10 minutes of the experiment for all sixteen muscle groups.

Figure 3. First and last 10 min average DET% values for all sixteen muscles



(L.B: Left Bicep, R.B: Right Bicep, L.T: Left Triceps, R.T: Right Triceps, L.D: Left Deltoid, R.D: Right Deltoid, L.U.T: Left Upper Trapezius, R.U.T: Right Upper Trapezius, L.L.E.S: Left Lower Erector Spine, R.L.E.S: Right Lower Erector Spine, L.BR: Left Brachioradialis, R.BR: Right Brachioradialis, L.W.E: Left Wrist Extensor, R.W.E: Right Wrist Extensor, L.M.G: Left Medial Gastrocnemius, R.M.G: Right Medial Gastrocnemius)

Left and right biceps and triceps did not show any significant changes in DET% value between the first and last 10 minutes of the experiment (p -value > 0.05). Unlike these two muscles, other muscle groups (left and right deltoid, upper trapezius, brachioradialis, lower erector spinae, medial gastrocnemius, and wrist extensor) showed significant difference in DET% (p value < 0.05) between the first and last 10 minutes. The increase in DET% values can be because of the fact that motor units are firing more rapidly at regular intervals in a synchronized manner, a phenomenon that occurs during the fatiguing stage (Hussain et al., 2018). As discussed before, DET% measures the predictability of the EMG data. Therefore, the lower the DET%, the higher the randomness, and the less the determinism and stationarity of the EMG data. This can be noticed during the first 10 minutes of the operation for all the muscle groups when they are all fresh and in non-fatigued stage. In the beginning of an activity, motor units of the muscles usually fire at higher rates, which can be the cause of non-stationarity and randomness in EMG data. Yet, as the muscles start becoming fatigued, an increase in motor unit synchronization and reduction of conduction velocity increase the predictability and determinism of the EMG data. Other studies confirm that higher determinism is an indication of fatigue (Felici et al., 2001; Ikegawa et al., 2000).

Table 2 provides the time-to-fatigue for all of the twelve muscles which experienced fatigue (left and right biceps and triceps are therefore omitted from this table). Time-to-fatigue values were obtained from both DET% and subjective results. DET% and subjective results were not significantly different in seven muscles (left deltoid, right deltoid, left upper trapezius, right upper trapezius, left lower erector spine, left medial gastrocnemius, and right medial gastrocnemius). However, there was significant difference between DET% and subjective results for right lower erector spine, left brachioradialis, right brachioradialis, left wrist extensor, and right wrist extensor. Table 2 lists all the twelve muscles and their time-to-fatigue in order from first to last muscle.

Table 2. Time-to-fatigue for twelve muscle groups

Muscles	Average Time-To-Fatigue		P<0.05
	Based on DET%	Based on subjective fatigue score	
right deltoid	41.2 (SD = 8.4)	40 (SD = 14.2)	
right upper trapezius	44.5 (SD = 5.7)	45 (SD = 10.4)	
right lower erector spine	47.1 (SD = 10.3)	53.3 (SD = 6.3)	▼
left upper trapezius	48.6 (SD = 7.8)	46.6 (SD = 10.3)	
left lower erector spine	51.0(SD = 11.4)	48.3 (SD = 14.7)	
left deltoid	54.8 (SD = 9.3)	55 (SD = 10.4)	
right brachioradialis	59.6 (SD = 10.3)	70 (SD = 14.1)	▼
left medial gastrocnemius	60.5 (SD = 10.2)	56.6 (SD = 10.3)	
right medial gastrocnemius	62.1 (SD = 6.6)	60 (SD = 3.2)	
left brachioradialis	63.3 (SD = 8.4)	70 (ST = 10.9)	▼
left wrist extensor	77.3 (SD = 6.7)	86.6 (SD = 10.3)	▼
right wrist extensor	81.2 (SD = 9.4)	90 (SD = 8.9)	▼

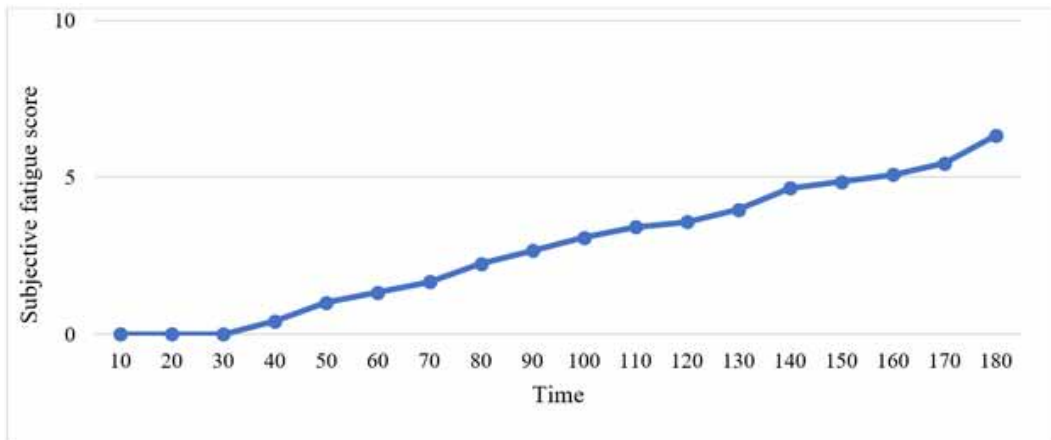
The difference between the time-to-fatigue obtained from DET% and subjective analysis might be due to the evaluation time interval for subjective analysis which was every 10 minutes. As can be seen, right deltoid was the first muscle to experience fatigue after 41.2 minutes of experiment, and right wrist extensor was the last muscle to experience fatigue after 81.2 minutes of experiment.

It is worthwhile to mention that the subjective fatigue scores which were used to obtain time-to-fatigues are considered low intense. This means that if the authors used, for instance, intense fatigue scores (for example: 5) as a criterion to obtain time-to-fatigue values, most likely there will not be any close correlation between time-to-fatigues obtained from DET% and time-to-fatigues obtained from subjective fatigue scores. Figure 4 shows the subjective fatigue scores obtained from right deltoid of one of the subjects. For this particular subject, the time-to-fatigue is at 40 minutes, but if the authors change the criteria and use intense fatigue (for example 5) the time-to-fatigue is going to increase to around 150 minutes. Comparison between the quantitative and subjective time-to-fatigues reveals the sensitivity level of the RQA analysis to the changes in EMG.

Fatigue in Upper-Limb Muscles

It is interesting to note that right upper-limb muscles (deltoid, upper trapezius, and brachioradialis) experienced muscle fatigue before their left ones. According to DET%, right deltoid fatigued 13.6 minutes before left deltoid, right upper trapezius fatigued 4.1 minutes before left upper trapezius, and right brachioradialis fatigued 3.7 minutes before left brachioradialis. Even though all the subjects were right-hand-dominant, the authors believe the difference between time-to-fatigue of right and left upper-limb muscles was mainly due to the fact that the subjects were required to hold the VR SMAW device with their right hand with proper travel speed and work angle for a long duration of time. In addition, the right hand was responsible for holding a constant contact tip to work distance. Therefore, the task required precise movements which may impose awkward postures on the subjects, especially on their right side muscles. The difference between the time-to-fatigue of right and left deltoid, which was 13.6 minutes, shows that right deltoid was affected by these awkward postures more than other right hand muscles. Other studies that investigated the muscle activation of subjects found similar impact on upper-limb muscles during different occupational and prolonged tasks. For

Figure 4. Subjective fatigue score obtained from right deltoid of one of the subjects



instance, Santy and Dawal (2010) showed that left and right upper trapezius (after 90 minute), anterior deltoid (after 95 minutes), brachioradialis (after 100 minutes), and bicep brachii (after 110 minutes) experienced muscle fatigue during light assembly task performed for duration of two hours. This type of task is also considered as light muscle activation with dynamic and repetitive movements. However, the difference between the time-to-fatigue as well as the order of the muscles experiencing fatigue found in their study and our study can be due to the different nature of welding and assembly tasks. In addition, a few other studies have shown that prolonged repetitive tasks can be the cause of wrist, hand and forearm disorders (Hansson et al., 2000; Muggleton et al., 1999; Thomsen et al., 2002). It has been shown that these types of work-related musculoskeletal disorders in upper limbs are caused by muscle fatigue (Lomond & Cote, 2011; Nussbaum et al., 2001). Moreover, shoulder disorders, as one of the most serious work-related musculoskeletal disorders, have been found to be associated with prolonged and repetitive tasks which require precise movements (Christensen, 1986; Kvarnstrom, 1983; Walker-Bone & Cooper, 2005). Using surface EMG, Beauchamp et al. (Christensen, 1986) found that the activity of the anterior deltoid increases in overhead welding by decreasing the angle between the wire tip and the weld gun handle. However, during the horizontal welding position, the anterior cubital was found to be most active.

FATIGUE IN LOWER-LIMB AND LOWER BACK MUSCLES

DET% of both left and right lower erector spine was found to be significantly different ($p < 0.05$) for the first and last 10 minutes of the experiment. This was also the case for left and right medial gastrocnemius. Right lower erector spine was found to be the third muscle to start experiencing fatigue after 47.1 minutes of the experiment. For left lower erector spine, however, the time-to-fatigue was 51 minutes. Left and right medial gastrocnemius were the lower-limb muscles which started experiencing fatigue after 60.5 and 62.1 minutes of the experiment, respectively. The authors believe that the lower-limb and lower back muscles experience fatigue due to the fact that welding tasks in this experiment are performed in a standing position for relatively long period of time. In this case, the lower-limb and lower back muscles have to tolerate the load of the upper body and undergo the forces which result from holding awkward postures to perform the task. As a result, this type of working position can contribute to musculoskeletal disorders in these muscles. In other studies, it has been reported that prolonged standing was the cause of foot or lower leg pain in 83% of the United States industrial workers (Zander et al., 2004), and muscle fatigue was found to be one of the main reasons for this type

of pain associated with the tasks which require lengthen standing positions (Madeleine et al., 1998). Halim and et al. (2012) studied the time-to-fatigue of the lower back, and anterior and posterior legs muscles during metal stamping which was performed in a standing position. They evaluated the muscle fatigue three times at the beginning (1st session), middle (2nd session), and the end (3rd session) of the work day using sEMG. Their study showed that right gastrocnemius experienced fatigue before other muscles at all sessions. They also found a decrease in muscle performance for all the tested muscles after two hours standing. They showed that all the tested muscles experienced fatigue at the end of working day earlier than the beginning and mid-day. In addition, they stated that regardless of the type of jobs, muscle fatigue takes place as a result of prolonged standing.

Recommendations For Preventing Muscle Fatigue

The repetitive and prolonged nature of welding tasks can impose fatigue on a welder's muscles, which can as a result lead to musculoskeletal disorders. Therefore, in order to improve working condition of welders to reduce muscle fatigue, these awkward postures have to be eliminated or at least minimized prior to the state of muscle fatigue. Moreover, improvements should focus on minimizing the load on upper-limb and lower-limb as well as lower back muscles. Feedback about impacts of these postures can help welders reduce awkward body postures, minimize the repetitive movements, and limit the amount of load on different muscles.

In some cases, employee rotation might be effective method to avoid muscle fatigue by reducing the amount of exposure time to awkward postures and repetitive movements. Moreover, micro breaks can be another helpful method to rest the muscles before the time-to-fatigue. This allows the muscles to recover and as a result to avoid performance reduction. According to the time-to-fatigue results, our study suggests a break time before the first muscle (right deltoid) starts experiencing fatigue which was 41.2 minutes after the task started. Depending on the nature of the tasks, sufficient time should be allocated for breaks to minimize the risk of muscle fatigue. Studies indicate that in prolonged low to medium force activities, muscles need more time to recover and obtain their initial force capacity (Kroon & Naeije, 1991; Sjøgaard et al., 1988). Studies have recommended sufficient recovery time to avoid myalgic disorders in trapezius muscles during prolonged muscle activation (Henneman et al., 1965; Rolander et al., 2005). Furthermore, it has been shown that longer breaks can be more effective to reduce risk of leg swelling caused by prolonged standing (Hansen et al., 1997).

Other engineering techniques to reduce the risk of muscle fatigue and WMSDs include optimizing workstations and equipment by implementing new designs and processes. Jarvholm and et al. (1991) studied the effect of arm support on supraspinatus muscle load using intramuscular pressure measurement and EMG in nine subjects. They found that an arm support device reduced the muscle load in welding task with reduction in pressure of 22% and normalized EMG of 17%. Although the muscle force reduction was significant, average muscle pressure was still high. In prolonged standing jobs, for example, anti-fatigue floor mats and proper footwear can improve work conditions and minimize muscle fatigue in lower-limb muscles (King, 2002). Ergonomic improvements that minimize overexertion, the main reason for WMSDs, should be implemented at construction sites (Wang et al., 2017).

KEY CONTRIBUTIONS OF THE STUDY

This study was designed to evaluate the capability of a nonlinear data analysis method (RQA) in assessing EMG signals during light muscle activation to detect vulnerable muscles and their time-to-fatigue. To the best of our knowledge, it was the first time that a light muscle activation performed for a relatively long duration of time was evaluated using RQA and EMG sensors. In addition, the authors believe that for the first time welding tasks were analyzed as light muscle activations utilizing a novel method which was in close correlation with subjective results. This study showed that RQA

data analysis method can be used in ergonomic studies to evaluate different construction tasks to improve work conditions as well as tools and equipment.

FUTURE STUDIES

None of the subjects participated in this study had any previous welding experience. The effect of skill level on muscle fatigue should be evaluated in order to identify differences between expert and novice welders. This might help novice welders learn how to properly perform welding tasks with the least amount of awkward postures and muscle load. Future studies should also evaluate muscle activation of subjects during different types of common welding tasks with different welding equipment. In addition, the authors believe that it is worthwhile to investigate different durations of break time and other engineering techniques and their effect on muscle fatigue. Certain exercises can also be incorporated to those break times to help the muscles recover faster and regain their initial force capacity. Although the duration of experiment in this study was three hours, as also suggested by Santos and et al. (2016) who conducted a systematic review study to show the influence of task design on upper limb muscles during low-load repetitive work, future studies should extend the duration of the experiments to better represent real work conditions. Finally, recruiting left-hand-dominant and female subjects can provide a more comprehensive assessment of muscle fatigue in welding activities.

CONCLUSION

To the best of our knowledge, muscle activation in dynamic and low force contraction, such as welding task, has not been previously analyzed using a quantitative evaluation and non-stationary data analysis method during a long experimental study. In this study, surface electromyography (sEMG) was used to capture the muscle activation of six right-hand-dominant subjects while performing different welding tasks for three hours. RQA, as a non-stationary data analysis method, was used to analyze the EMG data to detect the determinism percentage (DET%) as an indication of muscle fatigue. In addition, a subjective fatigue assessment was conducted to draw comparisons with the DET results. According to the DET results, all the tested muscles experienced fatigue by showing significant difference in DET values (p -value < 0.05) between the first and last 10 minutes of the experiment, except left and right bicep and triceps. For both left and right bicep and triceps, the subjective fatigue score remained zero meaning that no fatigue was reported by any of the subjects throughout the experiment. Both RQA and subjective fatigue analysis methods were also used to find the time-to-fatigue for the muscles which displayed significant difference in DET values between the first and last 10 minutes of the experiment. According to the results, right deltoid was the first muscle which experienced fatigue with the time-to-fatigue of 41.2 minutes. The results indicated that RQA and subjective fatigue results of time-to-fatigue for seven muscle groups were in close correlation. The methodology used in this study was shown to be an effective quantitative method to evaluate muscle activation during welding activity and to provide real-time feedback about how working condition affects muscle fatigue. This feedback can help welders to avoid awkward postures and to minimize the amount of loads applied to their muscles. As a result, this can have positive impact on welders' occupational safety and can reduce the risk of WMSDs. The potential of RQA for a low force muscle activation was shown in this study. The authors believe that this methodology can be used for ergonomic research to investigate different aspects of occupational jobs, especially to identify vulnerable muscles and specific causes of WMSDs during different tasks. In addition, it can be utilized to ergonomically optimize tools and equipment used for different construction jobs in order to reduce the risk of WMSDs.

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