Shoulder Muscle Fatigue During Repetitive Tasks as Measured by Electromyography and Near-Infrared Spectroscopy

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Objective: The objective of this study was to quantify shoulder muscle fatigue during repetitive exertions similar to motions found in automobile assembly tasks.

Background: Shoulder musculoskeletal disorders (MSDs) are a common and costly problem in automotive manufacturing.

Method: Ten subjects participated in the study. There were three independent variables: shoulder angle, frequency, and force. There were two types of dependent measures: percentage change in near-infrared spectroscopy (NIRS) measures and change in electromyography (EMG) median frequency. The anterior deltoid and trapezius muscles were measured for both NIRS and EMG. Also, EMG was collected on the middle deltoid and biceps muscles.

Results: The results showed that oxygenated hemoglobin decreased significantly due to the main effects (shoulder angle, frequency, and force). The percentage change in oxygenated hemoglobin had a significant interaction attributable to force and repetition for the anterior deltoid muscle, indicating that as repetition increased, the magnitude of the differences between the forces increased. The interaction of repetition and shoulder angle was also significant for the percentage change in oxygenated hemoglobin. The median frequency decreased significantly for the main effects; however, no interactions were statistically significant.

Conclusions: There was significant shoulder muscle fatigue as a function of shoulder angle, task frequency, and force level. Furthermore, percentage change in oxygenated hemoglobin had two statistically significant interactions, enhancing our understanding of these risk factors.

Application: Ergonomists should examine interactions of force and repetition as well as shoulder angle and repetition when evaluating the risk of shoulder MSDs.

Keywords: shoulder muscle fatigue, NIRS, EMG, musculoskeletal disorders

INTRODUCTION

A review of workers' compensation claims in the state of Ohio revealed that shoulder injury claims ranked second behind lumbar spine injury claims with an average cost per claim of $6,668 (Dunning et al., 2010). The auto industry is one of several industries with reported high incidence of musculoskeletal disorders (MSDs; Bureau of Labor Statistics, 2010; Punnet, 1999; Ulin & Keyserling, 2004). Sadi, MacDermid, Chesworth, and Birmingham (2007) reported that shoulder injuries were the most-often-treated disorder among those working in an auto plant. In order to prevent these costly shoulder MSDs in automotive manufacturing, one must first have an understanding of the fatigue implications of these physically demanding tasks.

The shoulder is a complex joint with a multitude of mechanisms to cause pain symptoms, the etiology of which may be poorly understood in patients (Cailliet, 1991). In general, MSD risk factors include repetition, force, and posture (Bernard, 1997; Gerr et al., 2002; National Research Council, 2001). It is suspected that these same risk factors apply to shoulder MSDs; however, the epidemiological literature does not provide strong evidence (Bernard, 1997) of these pathways. The lack of evidence may be attributable to the interaction of these risk factors and the complex nature of shoulder injuries. There is a void in the literature examining the interactions of force, posture, and repetition on the shoulder. The large number of shoulder injury claims suggests that there may be a significant problem existing within industry (Sadi et al., 2007). It is hypothesized that quantifying the interactions of force, repetition, and posture may provide a greater understanding of the physiological demands in automotive manufacturing tasks.

It is thought that shoulder injuries may be the result of reduced tissue tolerance and that tissue tolerance may change in response to exposure to the interaction of repetition, force, and posture.

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HUMAN FACTORS
Vol. 55, No. 6, December 2013, pp. 1077–1087
DOI: 10.1177/0018720813482328

Tissue tolerance may be related to oxygenation levels in the tissue (Boushel et al., 2001). Near-infrared spectroscopy (NIRS) can quantify changes in hemoglobin (oxygenated, deoxygenated, total, and saturated) in a specific muscle and has been used to evaluate the physical demands of exercise and work within a person (Ferrari, Mottola, & Quaresima, 2004; Lin, Maikala, McGorry, & Burnette, 2010; Perrey, Thedon, & Rupp, 2010; Yang, Chany, Parakkat, Burr, & Marras, 2007). In theory, decreasing levels of hemoglobin may lead to a deficiency in tissue oxygen levels, in turn resulting in reduced tissue tolerance, which, when combined with tissue load, may lead to cellular damage and fatigue (Boushel et al., 2001; Heiss, 1983; Leach & Treacher, 2002; Moritani, Sherman, Shibata, Matsumoto, & Shinohara, 1992; Rolfe, 2000). Research has shown that fatigue creates increased muscle coactivation and changes in kinematics that result in increased joint loading, thereby increasing the risk of injury to the joint (Marras et al., 2006; Potvin & O'Brien, 1998; Psek & Cafarelli, 1993). Furthermore, fatigue is a key element in the development and progression of pain (Cote & Hoeger Bement, 2010). Shoulder pain symptoms attributable to muscle fatigue may lead a worker to seek medical attention, potentially resulting in a diagnosed MSD. Quantifying changes in oxygenated hemoglobin in the muscle would allow us to examine the earliest phase of the MSD injury pathway attributed to fatigue.

Muscle fatigue may also be examined with the use of electromyography frequency spectral shift (Chaffin, 1973; de Looza, Bosch, & van Dieen, 2009; Ebaugh, McClure, & Karduna, 2006; Hagg, 1992; Jensen, Schibye, Sogaard, Simonsen, & Sjogaard, 1993; Lindstrom, Kadefors, & Petersen, 1977; Lindstrom, Magnussen, & Petersen, 1970), which may correspond with changes in the NIRS measures. However, it is a pre-exposure versus post-exposure measure. Thus, the objective of this study was to quantify shoulder muscle fatigue as a function of shoulder posture, force, and repetition in order to examine the interaction of these risk factors in tasks similar to those found in automotive manufacturing.

METHOD

Approach

A certified professional ergonomist visited an auto assembly plant to evaluate the physical demands on the shoulder during typical auto assembly tasks. The on-site evaluations revealed a variety of shoulder flexion-extension, abduction and adduction angles, and numerous force levels and directions of force as well as a multitude of shoulder task frequencies. The physical demands of automotive assembly work on the shoulder were quite variable and complex; therefore, our approach was to design a practical study that focused on shoulder flexion demands. The goal of this study was to quantify muscle fatigue using a combination of NIRS and EMG as a function of task force, repetition, and shoulder flexion angle. This approach permitted the examination of the interactions of the exposure measures.

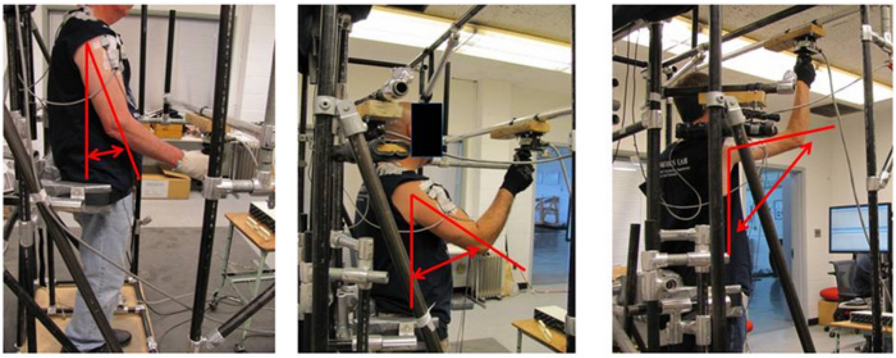
Study Population

Ten automotive assembly workers were recruited to be subjects in the study. Three subjects were female and seven subjects were male. This ratio of females to males was based on the population of workers at the auto-assembly plant that provided the subjects. The average age of the participants was 43.1 years with a standard deviation of 6.1 years. The average height and weight of the participants was 176.0 cm ($SD = 10.6$) and 82.6 kg ($SD = 20.6$), respectively. The workers had an average of 18.2 ($SD = 4.6$) years of experience in automotive manufacturing.

Experimental Design

Independent measures. There were three independent measures based on the field observations. First, shoulder angle was set at three levels: <45°, 45° to 90°, and >90°. Figure 1 illustrates the shoulder angle for each of the three conditions. Less than 45° was approximately 25°, 45° to 90° was approximately 60°, and >90° was approximately 110° for all participants. The flexion angle was measured with a goniometer at the acromion process. The height of the force transducer dictated the shoulder angle. This height was recorded and remained the same for each condition. The second independent measure was frequency, which included 2, 6, and 10 exertions per minute. The final independent measure was force level, which was set to 2.27 kg or 4.54 kg. This created a total of 18 testing conditions.

Dependent measures. NIRS was measured on the anterior deltoid as well as trapezius



<45° 45°-90° >90°

Figure 1. Shoulder angles <45°, 45° to 90°, and >90°.

muscles. NIRS reporting included change in oxygenated hemoglobin, deoxygenated hemoglobin, total hemoglobin, and saturation. The percentage change between the first 10-min baseline period and the last half hour of the session served as one dependent measure.

EMG data were collected on the anterior deltoid, middle deltoid, trapezius, and biceps muscles. The differences in spectral frequency content between prior to and immediately following the 2-hr task median frequency were calculated and used as a dependent measure in the statistical analysis for each muscle.

Equipment

An INVOS® 4100 Cerebral Oximeter (Somanetics Corportation, Troy, MI) developed for both brain and body tissue oxygenation measurement was used as the gold standard to develop a custom two-channel NIRS device. The two-channel NIRS system developed was calibrated with a two-point linear fit for each sensor-device pair. NIRS technology is based on the absorption of light by oxygenated and deoxygenated hemoglobin in the tissue (Yang et al., 2007). The INVOS sensors were placed on the muscles to identify the hemoglobin and red-colored oxygenated hemoglobin in the tissue directly beneath the sensor using two wavelengths, 730 nm and 810 nm (INVOS System, n.d.). The change in oxygenated hemoglobin and deoxygenated hemoglobin are outputs of the systems as well as total hemoglobin and saturation index. The INVOS sensors have two detectors: a shallow detector at 3 cm and a deep detector at 4 cm from the infrared light source. The mean photon path is banana shaped from the light-emitting source to each detector. Both detectors sample the shallow tissue layers beneath the light source equally; however, the far-spaced photon detector reaches the deep layers of tissue. The system subtracts the near signal from the far signal, resulting in output specific to the deeper tissue under the sensor. The estimated measuring depth was 1 to 2 cm below the sensor (INVOS System, n.d.). The NIRS system connected to the computer via USB, and data were collected at 85 Hz.

A Delsys wired EMG system was used to collect surface electromyography on shoulder muscles. Electrodes were placed on the trapezius, anterior deltoid, middle deltoid, and biceps muscles. Surface electrodes were placed on the dominant arm and shoulder. The amplifier gain was set at 1,000 for each muscle. EMG and force transducer data were collected at 1000 Hz with the use of Matlab.

A force transducer was used to measure the force level of 2.27 kg and 4.54 kg. The force was displayed on a computer screen as shown in Figure 1 greater than 90°. There was also a dual screen for the data collection team to monitor the quality of exertions.

A pipe structure was used to keep the participant in a controlled posture. The participant was belted in at the waist. The pipe structure provided a constant moment arm of 22 in. This measure was three quarters of the average arm length of all participants.

A pestle-shaped tool with a 1 in.-diameter handle was used to exert an upward force on the transducer at either 2.27 kg or 4.54 kg.

Procedure

After arrival to the testing facility, participants signed the university's institutional review board consent form. Participants were tested 2 days a week for 9 weeks for a total of 18 testing sessions. The 18 testing conditions were completely randomized for each participant. There was 1 day for each testing condition.

The skin was cleaned and surface electrodes were placed on the trapezius, anterior deltoid, middle deltoid, and biceps muscles according to Zipp (1982) and Konard (2005). The trapezius electrode was placed one third of the distance between the C7 spinous process and the acromion in line with the muscle fibers. The anterior deltoid electrode was placed over the muscle belly below the acromion approximately one fifth the distance to the epicondyle humerus lateral. The middle deltoid electrode was placed over the belly of the muscle approximately one fourth the distance down from the acromion to the epicondyle humerus lateral. The biceps electrode was placed two thirds of the distance between the acromion and fossa cubiti in line with the muscle fibers. The response was tested for each muscle. Two types of maximum effort trials were collected, one for the task and a second trial for the trapezius muscle up directly into the force transducer above the shoulder. Three maximum efforts were collected with 2-min rest breaks between each one. The three maximum exertions had to be within 10% of one another to proceed to the next step. An additional 2-min rest break was given after the last maximum exertion. This break was followed by a 70% maximum voluntary contraction (MVC) exertion. The target force level was displayed on a computer screen for the worker. In addition, the target force display had a tolerance of 5% displayed for the individual. The 70% exertion had to be controlled within 5% of the exertion level. If the quality was not good, the trial was repeated after a 2-min rest break.

After the 70% exertion, the oxygenation sensors were placed on the participants' shoulder muscles. The trapezius sensor was placed adjacent to the trapezius electrodes along the line of action of the muscle. The anterior deltoid sensor was placed in the line of action of the anterior deltoid electrodes medial to the electrodes. The participants performed a 10-min baseline period. The baseline period consisted of marching in place as well as stretching the shoulder muscle, but no force was exerted during the baseline. After the baseline period, the data collection session was started. A tone was sounded at a rate for the given condition (2 exertions per minute, 6 exertions per minute, or 10 exertions per minute). Participants were provided a display of force level with a target at either 2.27 kg or 4.54 kg as required by the test condition for the day. The participants performed the exertions for 2 hr. The 2 hr duration was based on the rotation scheme at the facility of the workers. The participants were required to maintain the 2.27 kg or 4.54 kg force level for 2 s. The 2 s duration was based on data from the facility sponsoring the project. Immediately after the 2 hr session, two post-exertion 70% MVCs were collected, one for the task and a second for the trapezius muscle. The 70% MVC exertion was approximately 2 s. The order of the two 70% exertions was counterbalanced. The first exertion was always used in this case. All participants were encouraged verbally to maintain the 70% of maximum force level displayed on the computer screen.

The second participant was the quality control person making sure that each exertion was 2 s and at the appropriate force level. The 2 participants switched roles in the second session of the day. The participants had a day at the plant between each testing session. Finally, the 2 participants switched off between who went first each day.

Data Analysis

Preliminary data analysis was done to calculate the percentage change in NIRS data between the average of the 10 min initial baseline period and the average of the last 30 min of data collection. During the initial baseline period, participants were instructed to march in place in order to elevate their heart rate as well as stretch the shoulder, but no force was exerted with the shoulder.

The preliminary analysis of the EMG data was performed with the use of Matlab. The pre-amplified, raw EMG data were filtered using a Butterworth with a band pass of 20 Hz to 450 Hz and a notch filtered at 60 Hz as well as aliases. The entire 10 s of data was displayed, and 1,000 data points were selected for data analysis just as the force level was rising into the 70% window. The EMG median power frequency was calculated for the 1,000 data points selected for the pre- and post-trials. The force level between the pre- and post-exertions had to be within 1 lb for the data to be considered. The difference between the pre- and post-activity median frequencies for each muscle was calculated, and further statistical analysis was completed on the differences (Soderberg, 1992).

Statistical Analysis

Correlations were run among the four oxygenation variables. Proc GLM was used to develop a model (SAS Institute, 1990) for each dependent measure to determine whether there was a statistically significant change attributable to repetition, force, and shoulder angle as well as interactions of repetition and force, repetition and shoulder angle, and shoulder angle and force as well as the three-way interaction. A post hoc test was used to determine significant differences among the levels for the main effects.

RESULTS

The correlation analysis showed several very high correlations between three NIRS variables. The correlation coefficient between percentage change in oxygenated hemoglobin and total hemoglobin was 0.9869 and 0.9863 for the anterior deltoid and trapezius muscles, respectively. The correlation between the percentage change in oxygenated hemoglobin and the deoxygenated hemoglobin was 0.8442 and 0.8001 for the anterior deltoid and trapezius muscles, respectively. Since these correlations among percentage change in oxygenated hemoglobin, percentage change in total hemoglobin, and percentage change in deoxygenated hemoglobin were so high and the GLM results were very similar among these three variables, the results for NIRS data will focus on percentage change in oxygenated hemoglobin. Finally, the saturation measure was not highly correlated to the other NIRS measures; therefore it will be presented.

NIRS Results

Table 1 lists the *p* values for the statistical differences in percentage change in oxygenated hemoglobin and the saturation. The table indicates that percentage changed in oxygenated hemoglobin was statistically significant for the main effect of repetition in both anterior deltoid and trapezius muscles. Figure 2 illustrates the percentage decrease in oxygenated hemoglobin for both anterior deltoid and trapezius muscles. The figure indicates there was a statistically significant greater decrease in anterior deltoid muscle percentage change in oxygenated hemoglobin as the number of repetitions per minute increased. The figure illustrates that the trapezius muscle percentage change in oxygenated hemoglobin was not statistically significantly different between 2 and 6 repetitions per minute, but there was a statistically significant greater decrease at 10 repetitions per minute. The patterns were similar for percentage change in total hemoglobin and percentage change in deoxygenated hemoglobin.

Table 1 indicates that there was a significant decrease in trapezius muscle percentage change in oxygenated hemoglobin as a function of shoulder angle. Figure 3 shows the percentage change in trapezius muscle oxygenated hemoglobin as a function of task shoulder angle. The figure shows a nearly 12% drop at a shoulder angle <45° and a significantly greater drop at 45° to 90° but no statistically significant difference between 45° to 90° and >90° of shoulder angle. Table 1 also shows a statistically significant change in anterior deltoid muscle percentage change in saturation as a function of shoulder angle. The post hoc test indicated that the percentage change in saturation increased 2.88% at a shoulder angle <45° and significantly changed to a percentage change of 1.36% at >90°; however, neither were significantly different than 45° to 90°.

Table 1 indicates there were statistically significant differences in anterior deltoid and trapezius muscles percentage change of oxygenated hemoglobin as a function of force level. The anterior deltoid muscle had an approximately 15% decrease in oxygenated hemoglobin for the 2.27 kg conditions, compared with an approximately 22% decrease for the 4.54 kg conditions.

TABLE 1: *P* Values for Median Frequency Differences and Muscle Oxygenation Percentage Changes

	Gender	Reps	Shoulder Angle	Force	Reps × Force	Force × Shoulder Angle	Reps × Shoulder Angle	Reps × Shoulder Angle × Force
% change in oxygenated hemoglobin (HbO_2)								
Anterior deltoid	.9842	.0001*	.1701	.0111*	.0322*	.5141	.8915	.2206
Trapezius	.6434	.0002*	.0063*	.0154*	.1120	.4727	.0020*	.3636
% change in saturation								
Anterior deltoid	.8563	.2715	.0330*	.8029	.6548	.2746	.1942	.2608
Trapezius	.6946	.0562	.7616	.6367	.0325*	.7339	.6559	.4441
Difference in EMG								
Anterior deltoid	.8730	.0039*	.0600	.0269*	.5985	.0939	.0977	.8105
Trapezius	.4643	.0201*	.0089*	.0830	.2329	.5734	.8074	.4530
Middle deltoid	.8335	.0095*	.0824	.1910	.8254	.2736	.7216	.7216
Biceps	.3203	.5016	.6183	.1086	.4184	.2389	.8178	.0963

Note. Reps = repetitions; EMG = electromyography.
*Indicates statistical significance at alpha = .05.

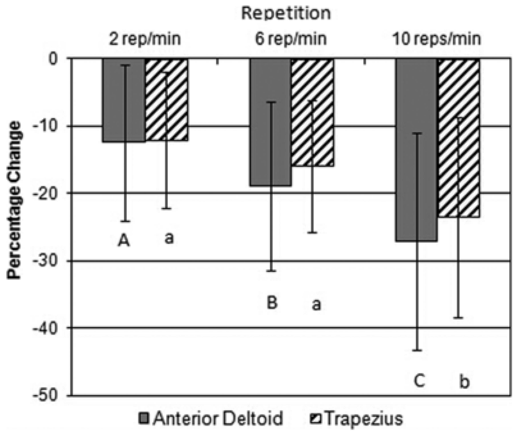


Figure 2. Percentage change in anterior deltoid and trapezius muscles oxygenated hemoglobin as a function of repetitions per minute.

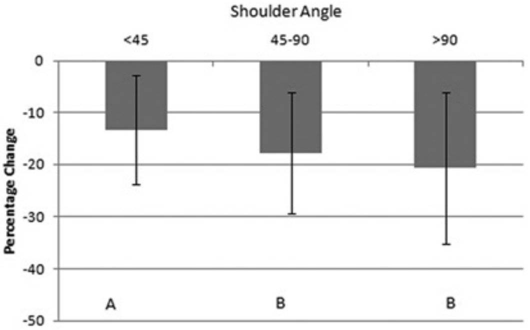


Figure 3. Percentage change in anterior deltoid muscle oxygenated hemoglobin as a function of shoulder angle.

There was a similar pattern in the trapezius muscle for force.

Table 1 indicates statistically significant interactions for repetition and force for anterior deltoid muscle percentage change in oxygenated hemoglobin and trapezius muscle percentage change in saturation. Figure 4 illustrates the interaction of repetition and force for the anterior deltoid muscle. The figure shows an approximate 3% difference between 2.27 kg and 4.54 kg exertion at 2 and 6 repetitions per minute, whereas at 10 repetitions per minute, the difference was approximately 10%. Thus, the influence of weight increased as the number of repetitions increased. Figure 5 displays the interaction of repetition and force for the trapezius saturation levels. Note that percentage change in saturation ranges from 0.5% to 2.5% increase, compared with a 10% to 32% decrease in oxygenated hemoglobin, illustrating that the change in hemoglobin is much greater than the change in saturation. The saturation appears not to change as a function of repetition for the 2.27 kg task,

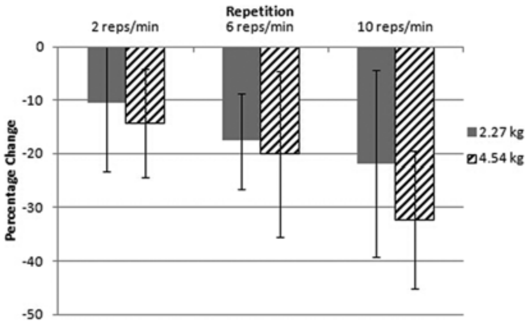


Figure 4. Percentage change in anterior deltoid muscle oxygenated hemoglobin as a function of repetition and force.

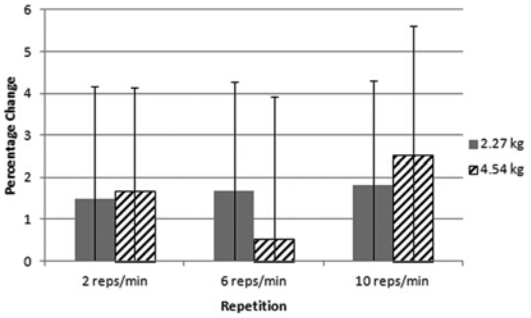


Figure 5. Percentage change in trapezius muscle oxygen saturation as a function of repetition and force.

whereas for the 4.54 kg task, the saturation was lowest at 6 repetitions per minute and increased to 1.5% change at 2 repetitions per minute and 2.5% increase at 10 repetitions per minute.

Table 1 indicates that the interaction of repetition by shoulder angle was significant for the trapezius muscle in the percentage change oxygenated hemoglobin. Figure 6 presents the interaction of repetition and shoulder angle for the trapezius percentage change in oxygenated hemoglobin. At 2 and 6 repetitions per minute, Figure 6 illustrates little difference among the three shoulder angles; however, at 10 repetitions per minute, the decrease on muscle oxygenated hemoglobin doubled as shoulder angle went from less than 45° to greater than 90°. Thus, at faster repetition levels, the influence of shoulder angle was greater.

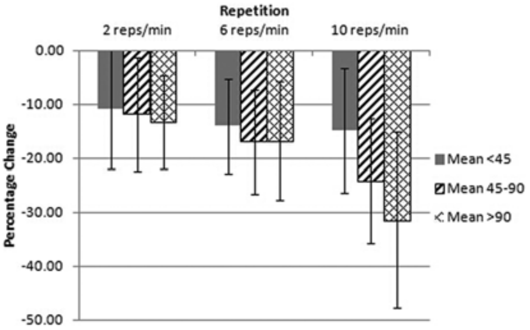


Figure 6. Percentage change in trapezius muscle oxygenated hemoglobin as a function of repetition and shoulder angle.

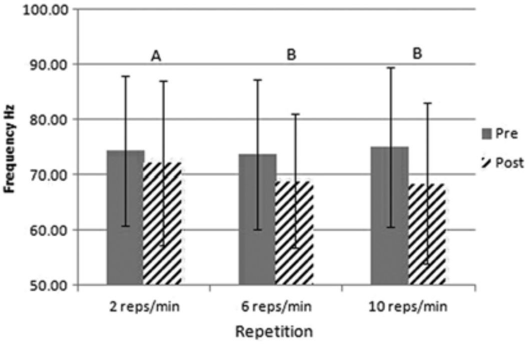


Figure 7. Anterior deltoid muscle median frequency pre- and post-task as a function of repetition.

EMG Results

Table 1 lists the *p* values of statistically significant differences for change in median frequency before exposure and immediately following exposure. Repetition was statistically significantly different for the anterior deltoid, trapezius, and middle deltoid muscles. Figure 7 displays the median frequency of the anterior deltoid muscle pre- and post-activity during the standard exertion. The figure demonstrates that the difference between pre- and post-activity median frequency was significantly greater at 6 and 10 repetitions compared with 2 repetitions. There was no statistically significant difference between 6 and 10 repetitions per minute. A similar pattern was found in the middle deltoid. The post hoc results for the trapezius showed significantly greater median frequency shift at 10 repetitions compared with 2 repetitions, but

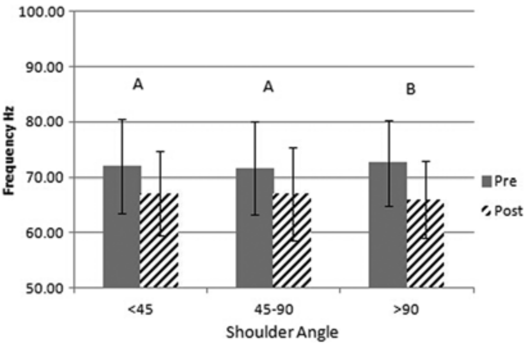


Figure 8. Trapezius muscle median frequency pre- and post-task.

neither was statistically significantly different from 6 repetitions. There was a statistically significantly greater drop in median frequency at 4.54 kg compared with 2.27 kg of force for the anterior deltoid muscle. The average decrease in anterior deltoid muscle median frequency was 5.52 Hz for 4.54 kg and 3.48 Hz for 2.27 kg. Table 1 indicates a statistically significant change in trapezius muscle median frequency pre- and post-task attributable to shoulder angle. Figure 8 exhibits the median frequency pre- and post-task as a function of shoulder angle. The post hoc results revealed significantly greater fatigue at a shoulder angle greater than 90° but no difference between the other two angles, as indicated in the figure. The table shows that none of the interactions was statistically significantly different.

DISCUSSION

In theory, a decrease in hemoglobin may possibly lead to a lack of oxygen and nutrients to the muscle, which may lead to fatigue and potentially culminate in an MSD (Kumar, 2001; Moritoni et al., 1992; Perrey, Thedon, & Bringard, 2010; Perrey, Thedon, & Rupp, 2010; Rolfe, 2000). In the current study, large changes occurred in the oxygenated hemoglobin with changes of up to 30%. Furthermore, changes in total hemoglobin and deoxygenated hemoglobin exhibited similar magnitudes of change. In comparison, the saturation percentage change score was relatively small, with a maximum magnitude of approximately 2.5%. Thus, percentage change in hemoglobin measures may provide a sensitive measure of the earliest phase of muscle fatigue.

One of the more interesting findings of this study may be the interaction of repetition and force for the trapezius percentage change in oxygen saturation and how these findings relate to MSD risk. Oxygen saturation represents the dynamic balance between oxygen supply and oxygen consumption in the tissue (Ferrari et al., 2004). The 2.27 kg tasks showed the same level of oxygen saturation for all three repetition levels. In comparison, the 4.54 kg tasks had the lowest saturation at 6 repetitions per minute and increased percentage change in saturation at both 2 and 10 repetitions per minute. These results may suggest an optimal balance of oxygen supply and consumption for energy metabolism at a moderate exposure level. Yang et al. (2007) also found this optimal pattern in the erector spine muscle oxygen saturation levels as a function of repetition during lifting tasks. Marras (2008) has suggested a *J*-shaped relationship for the dose response for risk of musculoskeletal injury, whereby too little as well as too much exposure increases the risk of injury. Thus, the minimum percentage change in oxygen saturation at 4.54 kg at 6 repetitions per minute (moderate exposure) may provide some physiological measure supporting the theory of a *J*-shaped curve for risk of injury.

There was a statistically significant difference in the pre- and post-task median frequency among the repetitions, shoulder angles, and forces. The shift in median frequency was statistically significant; however, the largest average shift in the median frequency was only 5.5 Hz. The concept of examining the shift in median frequency has been in the literature for decades (Lindstrom et al., 1970). Unfortunately, there are no published standards for the amount of median frequency shift that defines fatigue (Szucs, Navalgund, & Borstad, 2009) or how much of a shift may result in an injury to the muscle. Knardahl (2002) suggested that surface EMG may not be sensitive enough to record low-level muscle activity levels even though these activities may result in muscle pain. Since the median frequency changes found in the current study were small in magnitude and the oxygenated hemoglobin changes were much greater in magnitude, it is hypothesized that change in oxygenated hemoglobin may represent a more sensitive measure for preventing fatigue in tasks that have relatively low force levels, such as those found in automotive manufacturing.

Combining measures of NIRS and EMG provides a method to examine the theoretical fatigue process. In theory, decreasing hemoglobin may lead to a lack of muscle oxygenation, which may lead to fatigue (Kumar, 2001; Moritoni et al., 1992; Perrey, Thedon, & Bringard, 2010; Perrey, Thedon, & Rupp, 2010; Rolfe, 2000). In the current study, NIRS provided a measure of percentage change in total hemoglobin, percentage change in oxygenated hemoglobin, and percentage change in deoxygenated hemoglobin as well as percentage change in saturation. In the study, we observed large changes in oxygenated hemoglobin that correspond to the earliest phase of the theoretical model of muscle fatigue. These large changes in oxygenated hemoglobin resulted in only small changes in muscle saturation, which may illustrate how the energy metabolism of the system attempts to resist fatigue. Finally, there were small shifts in the EMG median frequency, which provide a quantitative measure of a shift from fast-twitch fatigable muscle fibers to slow-twitch fatigue-resistant muscle fibers. NIRS and EMG appear to be measuring very different aspects of the physiological process of fatigue. Thus, by measuring both, we may gain an appreciation of the fatigue process. The NIRS measures identified an important interaction that was not revealed with the EMG measure, suggesting that the NIRS measure may be more sensitive.

Silverstein, Fine, and Armstrong (1986) showed an interaction between force and repetition in an epidemiological study of the hand-wrist disorders. The current laboratory study on the shoulder showed similar force and repetition interactions as the epidemiological study on the wrist. Thus, we may be gaining an understanding of the fatigue process and unraveling the causal processes of MSDs. In the current study, we examined relatively low force levels that may not lead to extensive fatigue; however, the NIRS percentage change in hemoglobin data was very responsive to these tasks. Thus, NIRS change in hemoglobin measures may provide a sensitive measure to understand the development of the fatigue process, which may lead to prevention of fatigue and potential musculoskeletal injury.

Applications

The significant interaction in the NIRS measures may be especially important to practicing ergonomists. These interactions illustrate the need for ergonomists to consider not only the force, repetition, and shoulder angle individually but also the combinations and how these risk factors may combine to influence the risk of shoulder injury. Understanding that at 10 repetitions per minute, the impact of the force level is much greater than at reduced levels of repetition may assist ergonomists as well as engineers designing the jobs to prevent shoulder injuries in the design of the job. Thus the results of this study may provide insight for designing working conditions in automotive manufacturing tasks that may reduce the risk of shoulder injuries. Further research would be needed to reduce the risk attributable to shoulder abduction and adduction.

Limitations

The study had a relatively small sample of participants, and there were only 3 females in the study. This was a laboratory study in a controlled environment. The fatigue levels in a plant situation where workers may switch hands or change postures would change compared with the laboratory conditions. Thus, there would be different levels of fatigue in a real-world situation.

CONCLUSIONS

The main effects of task repetition, force, and shoulder angle significantly influenced percentage change in oxygenated hemoglobin as well as EMG. The interaction of force and repetition significantly influenced percentage change in oxygenated hemoglobin for the anterior deltoid muscle. The interaction of repetition and shoulder angle significantly influenced percentage change in oxygenated hemoglobin for the trapezius muscle. By measuring both EMG and

NIRS, we are gaining a better understanding of the fatigue process.

ACKNOWLEDGMENTS

Funding for this study was provided by Honda of America. We would like to thank Jose Banaag for his assistance with this project.

KEY POINTS

- The influence of task force or weight increased at higher levels of task repetition. This finding was similar to that of epidemiological studies.
- The influence of shoulder angle increased at higher levels of task repetition.
- Near-infrared spectroscopy (NIRS) measures appear to be more sensitive than surface electromyography (EMG) measures for evaluating muscle fatigue.
- The combination of NIRS and EMG provided a greater understanding of the fatigue process.

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Date received: June 21, 2012
Date accepted: February 13, 2013