Postural and muscular adaptations to repetitive simulated assembly line work

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Abstract
Few studies have shown the process of adaptation in joint kinematics during prolonged repetitive work involving complex tasks. Fifteen healthy men performed 61 cycles that were one minute in duration of automotive-related tasks, which included a finger pull, knob turn, drill press and hose connector push. Kinematics of the upper extremity and trunk were collected at 60 Hz using a 3D motion capture system. Marker data were imported and modeled using Visual3D software (C-Motion, Inc., Rockville, Maryland, USA). Data were analyzed at 12-minute intervals, with data divided into the work cycle (start to finish of 4 sub-tasks) and drill task. The mean, peak, minimum and coefficient of variation (COV) were computed for all 3D joint angles. Results showed the time to complete the work cycle decreased by 6.3 s over the trials. Peak shoulder flexion decreased and peak elbow flexion increased during the work cycle. This study found adaptations to highly repetitive but light work in only one hour. This study is one of the first to examine adaptations to a highly repetitive simulated assembly work and has provided new insights into the evaluation of complex repetitive jobs as a whole.

Keywords: Repetitive Movement, Posture, Upper Extremity, 3D Kinematics.

1. Introduction
In the industrial workplace, numerous jobs require employees to make repetitive upper extremity exertions. These repetitive exertions pose a unique challenge for the shoulder complex and may lead to the development of shoulder musculoskeletal disorders. Shoulder injuries in the workplace may result in pain and lost income for the worker, and also create a financial burden to the employers due to lost productivity and compensation. It has been shown that upper extremity work-related musculoskeletal disorders (WMSD) have greater health care and rehabilitation costs compared to acute injuries and disorders that affect other body regions (Silverstein et al., 1998). Greater knowledge about how injuries develop, and what factors play a role in their development, is key to the prevention of such injuries.

Task rotation has been considered for workplace intervention to reduce the incidences of WMSDs. The premise of task rotation is that by alternating the use of different muscle groups, it will provide rest and reduce overall muscle activity (Mathiassen, 2006). Previous research has shown that consecutive tasks using the same muscle groups resulted in greater effects than when the muscle groups were alternated (Raina and Dickerson, 2008; Keir et al, 2011). Although job rotation has been shown to alter muscle activity, this poses a new concern for ergonomic assessments. Few studies have explored the process of adaptation in the upper extremity during prolonged repetitive work.

The purpose of this study was to understand the effects of highly repetitive work on joint kinematics and muscle activity of the upper extremity. The main objective was to relate changes in task performance to the kinematics of the upper body and upper extremity. We hypothesized that, over a one hour task, the joint range of motion would decrease in order to reduce moments at the shoulder and the time to complete work cycle would increase.

2. Materials and Methods

2.1 Participants
Fifteen healthy right hand dominant men with no manufacturing work experience were recruited from the university population (age 21.9 ± 2.7 years; height 1.76 ± 0.07 m; mass 73.3 ± 10.9 kg). Participants were excluded if they had upper limb or shoulder pain/injury within the last year. The

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Hamilton Health Sciences/Faculty of Health Sciences Research Ethics Board at McMaster University has approved this study.

2.2 Task Overview

Participants performed 61 cycles of simulated automobile assembly tasks. Each cycle was one minute in duration and included four different tasks: a finger pull, knob turn, simulated drilling into a vertical plate and hose connector push. Participants were required to complete six finger pulls, six full rotations at the knob, maintain a 50% of maximum drill press force for 10 seconds, followed by six hose connector pushes. Tasks one, two and four were pass/fail completions with clear target criterion. In order to complete task three, subjects were required to sustain the push force at 50% of their maximum push force for 10 seconds. Visual feedback was provided for the participants on a monitor using custom software (LabView, National Instruments, Austin, TX). Force levels for tasks 1 and four were set at 50% of their maximum effort. The experimental set up was centered with tasks placed at 30 cm on either side of the midline with tasks 1 and 4 set at umbilicus level and tasks 2 and 3 at shoulder level (Figure 1). Participants were required to stand at 60% of their total reach distance from the workstation frame.

2.3 Protocol

Prior to set up on day one, height, weight, maximum arm reach, shoulder and umbilicus heights were recorded and used to set the height of the apparatus. The participants then performed three maximal voluntary force trials for tasks one, third and four. Task force levels were set to normalize the force for each task and provide visual feedback for the drill push. Participants performed a familiarization protocol in which they practiced all four tasks and rehearsed the force profile required for the drilling task. Once the participants were comfortable with the protocol, they were instructed to complete the four tasks with their right arm sequentially in a clockwise direction starting and ending with a button press. They were able to complete the tasks at their own pace within a one-minute span (similar cycle time to that found on an automotive assembly line). Participants were asked to rate their level of perceived discomfort for the entire body over all four tasks every five minutes using the Borg Scale (Borg, 1990). They repeated this protocol until they reached a level of perceived discomfort of an eight or higher on the Borg Scale (Côté et al. 2002) or until they were unable to complete all four tasks within the one minute cycle in two consecutive cycles. The subjects were not made aware of the stoppage criteria; however no subjects required these criteria.

2.4 Data Collection and Analysis

Kinematics were collected at 60 Hz using a 3D motion capture system for 61 cycles (Cortex 1.3.0.475, Motion Analysis Corporation, Santa Rosa, CA). Twenty-six reflective markers were used to define and track the trunk, pelvis, upper arm, and forearm segments. Marker data were imported and modeled using Visual3D software (C-Motion, Inc., Rockville, MD). Based on palpable anatomical landmarks, virtual markers were created to define the proximal and distal endpoints for the pelvis, thorax/abdomen, shoulder, sterno-clavicular, elbow and wrist joints. Segment local coordinate systems were defined according to standard anatomical conventions and the position and orientation of each segment was estimated using global optimization in which the waist has 3 degrees of degree (DOF), sternum has 2 DOF, shoulder has 3 DOF, elbow and wrist have 2 DOF. This included a clavicle segment to model shoulder elevation. The relative angles between segments of interest were defined according to ISB standards for the upper extremity (Wu et al, 2005). Angles of interest included: shoulder flexion/extension, abduction/adduction and elevation/depression,
elbow flexion/extension, body rotation, body lean, spine rotation and spine flexion/extension (Figure 2). Raw kinematic and kinetic variables were dual-pass filtered with a second order Butterworth filter with a cut-off of 10 Hz.

Data were analyzed at 12-minute intervals, with data divided into the work cycle (start to finish of 4 sub-tasks) and drill task. The mean, peak, minimum and coefficient of variation (COV) were computed for all 3D joint angles. Repeated measures analyses of variance (ANOVA) were conducted with time as the repeated measure and joint kinematics (mean, peak and COV for each joint angle) and effort time as the independent variables (α=0.05). Significant effects were followed up with a least significance difference (LSD) post-hoc. Note that, as this study was exploratory in nature, attention was paid to denote relevant trends by using an α-level of 0.1.

3. Results

3.1 Time Parameters

The time to complete each work cycle decreased significantly by 6.3 ± 2.1 seconds over the hour (F5, 70=14.023, p<0.0005) (Figure 3).

3.2 Ratings of perceived discomfort

No participants reached the threshold rating of perceived discomfort of an eight. The ratings of perceived discomfort increased by 1.2 units throughout the experimental protocol (Figure 4) (F11,154 = 5.946, p=0.0005).

3.3 Kinematics

3.3.1 Mean Joint Angles

A significant decrease in mean shoulder abduction was found (F5, 70=2.586, p<0.033) (Figure 5a). A significant increase in mean shoulder abduction was seen during the drill task (F5, 70=2.004, p<0.089). There was also a significant decrease in mean shoulder flexion over time (F5, 70=2.449, p<0.042) (Figure 5b).

A significant increase was found for mean elbow flexion (F5, 70=2.099, p<0.076) (Figure 5c).

Mean body rotation increased from 16.2 to 17.3° (rotation to the left) during the whole task on day one (F5, 70=2.766, p<0.024) (Figure 5d). For the drill task, rotation increased significantly to the left (F5, 70=4.35, p<0.002).
3.3.1 Peak Joint Angles
There was a significant decrease in peak shoulder elevation \( (F_5, \gamma_0=2.909, p<0.019) \) and abduction \( (F_5, \gamma_0=3.043, p<0.015) \) during the work cycle (Figure 6). Peak shoulder flexion angle decreased by 7.0° over time during the work cycle from minute zero to minute 60 \( (F_5, \gamma_0=4.890, p<0.0005) \) (Figure 6c).

Peak elbow flexion increased significantly over time \( (F_5, \gamma_0=2.168, p<0.067) \) (Figure 6d).

For the drill task, peak rotation increased significantly \( (F_5, \gamma_0=2.125, p<0.072) \) (Figure 6e). There was a significant change in peak body lean (forward) from -13.7 to -16.4° \( (F_5, \gamma_0=3.423, p<0.008) \) during the whole task (Figure 6e).
4. Discussion

This study represents an attempt to evaluate the process of adaptation of the upper limb to highly repetitive cyclical work. It is also one of the first studies to combine the analysis of all sub-tasks involved in one complex job. The examination of the combined effects of a complex job is important for assessing injury risk. Assessing sub-tasks in isolation may not provide proper insight; however it is the cumulative effects from all the tasks that may be important for injury risk. This study provides new insights on how the effects combine to contribute to risk of musculoskeletal injury.

Although we hypothesized that the work cycle time would increase over the hour, our results showed a significant decrease in length of time to complete the task. First, it may suggest that participants capitalized on increasing rest between cycles (the time between the end of one cycle and beginning of the next). We conducted an EMG gaps analysis over the course of the hour to determine the number and amount of rest for each muscle within the work cycle. It is well known in the workplace that workers will work faster in order to receive longer rest periods. This is supported by our findings where no gaps were found for any subjects throughout the work cycle. Secondly, this decrease in time to complete the work cycle may reflect a learning effect. This learning effect may potentially be hazardous for the workers as they choose to work faster, thus creating higher muscular demands to complete the job.

As hypothesized, shoulder flexion decreased over the course of the hour. There was a maximum of decrease (up to 6°) in peak and mean shoulder flexion and an increase in elbow flexion (up to 5°) over the course of the hour. This suggests that the arm is moving closer towards the body (decrease in reach distance) and decreasing the moment created by the weight of the extended arm. Participants in this study were not allowed to move their feet throughout the experimental protocol and in order to decrease the reach distance. When examining changes in body position, mean body rotation to the left increased over time. This change in body position allows for the shortening the right lever and thus decreasing the moment at the shoulder.

A secondary purpose of this project was to determine whether a learning effect occurred after an hour of the experimental protocol by examining participant behaviour one day later. We found that the time to complete the task on day two was statistically different from the first minute on day one. This suggests that for time to complete the work cycle, a learning effect occurred as day two was more similar to the final minute of day one. Additionally, we compared joint angles on day one to those on day two. Contrary to what was expected, shoulder abduction, shoulder flexion, body rotation and trunk rotation angles on day two were significantly different from the end of day one. This suggests that the changes in body angles that occurred over time on day one did not persist to day two. This is contrary to what was hypothesized as greater flexion and abduction angles increase the load at the shoulder. Moreover, the present study only lasted 61 minutes so a longer protocol may have induced more significant robust adaptations.

There are a few limitations to the current study. A relatively small number of young, healthy male adults participated and thus, generalizing to workers of all ages and training should be done with caution. The participants were from the university population and had no experience working on a manufacturing line, thus they may react differently than workers in the manufacturing plants. An examination of work tasks on-site over time would provide a better insight to whether these changes occur with those individuals actually performing the jobs. Additionally, research has shown that novices and experts exhibit different motor and EMG variability (Madeleine et al. 2008). On-site examinations with both expert and novice workers could further our knowledge on how individuals adapt to work-related stresses as well as evaluate learning effects. All task force values were set at 50% of the participants’ maximum.
This may not be as generalizable to the industrial workplace as forces required to perform jobs tend to be absolute. The organization of the tasks and the tasks themselves are different than those found in the workplace. For example, while you will find the use of the drill in the workplace, our task involved an inactive drill, thus we would expect the results to be different.

5. Conclusion

This is one of the first studies to examine adaptations to a highly repetitive simulated assembly line work. We found significant adaptations to highly repetitive but light work in only one hour. By adapting a relatively simple model to incorporate a clavicle segment, we were able to better evaluate shoulder function. While the work was not as difficult as expected, we were able to demonstrate adaptations in posture and other kinematic variables in an hour of simulated work. By evaluating both the work cycle as a whole and the sub-tasks individual, we aim to develop new methods for evaluating the risk of complex tasks in prolonged repetitive work.

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