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ORIGINAL RESEARCH

Influence of Posture Variation on Shoulder Muscle Activity, Heart Rate, and Perceived Exertion in a Repetitive Manual Task

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OCCUPATIONAL APPLICATIONS In repetitive work, more physical variation is believed to reduce the risk of eventually developing musculoskeletal disorders. We investigated the extent to which workstation designs leading to more variation in upper arm postures during a pick-and-place task influenced outcomes of relevance to musculoskeletal disorder risk, including muscle activity, cardiovascular response, and perceived exertion, measured through the maximal acceptable work pace. Posture variation to the extent obtained in our experiment had only minor effects on these outcomes, and considerably less impact than a moderate change in working height. Apparently, substantial manipulations of the workstation or of the work task will be needed to accomplish variation to an extent that can significantly change outcomes of relevance to occupational musculoskeletal disorders and, thus, represent a potential for reduction in musculoskeletal disorder risk.

TECHNICAL ABSTRACT ***Background***: Repetitive light assembly work is associated with an increased risk for developing work-related musculoskeletal disorders. More exposure variation, for instance by redesigning the workstation, has been proposed as an effective intervention. ***Purpose***: We investigated the effect of upper arm posture variation in a 1-hour repetitive pick-and-place task on shoulder muscle activity, heart rate, and perceived exertion, measured on the Borg CR-10 scale and in terms of maximal acceptable work pace (MAWP).

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Methods: Thirteen healthy participants performed the task in three workstation designs where the hand was moved either horizontally (H30/30), diagonally (D20/40), or vertically (V10/50), with a mean upper arm elevation of ~30°. In a fourth design, the hand was moved horizontally at ~50° mean arm elevation (H50/50). ***Results***: As intended, upper arm posture variation, measured by the upper arm elevation standard deviation and range of motion, differed between H30/30, D20/40, and V10/50. However, MAWP (10.7 cycles·min^{-1} on average across conditions; determined using a psychophysical approach), mean upper trapezius activity (54% reference voluntary exertion [RVE]), and heart rate (69 bpm) did not differ between these workstation designs. In H50/50, MAWP was lower (9.3 cycles·min^{-1}), while trapezius activity (78% RVE) and perceived exertion (Borg CR-10) tended to be higher. ***Conclusions***: Our results indicate that posture variation to the extent achieved in the current experiment leads to less effects on muscle activity and perceived exertion than a moderate change in working height.

KEYWORDS Arm elevation, exposure variation, maximal acceptable work pace, muscle activity, repetitive work

NOMENCLATURE

MAWP	Maximal acceptable work pace
H30/30	Horizontal hand movements at 30° arm elevation
D20/40	Diagonal hand movements between 20° and 40° arm elevation
V10/50	Vertical hand movements between 10° and 50° arm elevation
H50/50	Horizontal hand movements at 50° arm elevation
% RVE	Percent reference voluntary electrical activation
MSD	Musculoskeletal disorders
MTM	Measurement-time-method system
EMG	Electromyography
ECG	Electrocardiography
RPE	Rating of perceived exertion
$angle_{MEAN}$	Mean angle
$angle_{SD}$	Within-cycle variation (*SD*) of the angle
RoM	Range of motion
v_{MEAN}	Mean velocity
v_{PEAK}	Peak velocity
RMS	Root-mean-square of EMG
RMS_{MEAN}	Mean RMS
RMS_{SD}	Within-cycle variation (*SD*) of the RMS
RMS_{CV}	Coefficient of variation of the RMS
RMSSD	Root mean squared successive differences between inter-beat interval values

INTRODUCTION

Repetitive work, such as in light industrial assembly, is associated with an increased risk of musculoskeletal disorders (MSD) in the neck, shoulders, and upper extremities (Andersen, Haahr, & Frost, 2007; Punnett & Wegman, 2004). Such increased risk is often explained as a result of a relatively high exposure to constrained postures and similar movements, and, therefore, more exposure variation is suggested as an effective intervention both by researchers (Fallentin, Viikari-Juntura, Wærsted, & Kilbom, 2001; Mathiassen, 2006) and by public authorities (e.g., Swedish Work Environment Authority, 2012).

Exposure variation refers to changes in exposure across time (Mathiassen, 2006). Increased variation in biomechanical exposures may be obtained by changing the content of individual tasks, by changing the time pattern of these tasks, or by introducing new tasks. Examples of interventions include the design of workstations or other equipment, introduction of additional breaks (Galinsky et al., 2007; Henning, Jacques, Kissel, Sullivan, &

Alteras-Webb, 1997; Luger, Bosch, Hoozemans, De Looze, & Veeger, 2015), re-arrangement of breaks through the working day (Balci & Aghazadeh, 2003; Dababneh, Swanson, & Shell, 2001), and job rotation (Luger, Bosch, Hoozemans, Veeger, & De Looze, 2016; Rissén, Melin, Sandsjö, Dohns, & Lundberg, 2002; Roquelaure et al., 1997). A recent review of studies investigating biomechanical exposure variation by Luger, Bosch, Veeger, and De Looze (2014) concluded that the evidence for positive effects of increased exposure variation on indicators of fatigue is limited. Initiatives specifically promoting job rotation also showed limited scientific support according to another recent review (Leider, Boschman, Frings-Dresen, & Van Der Molen, 2015). In both cases, a major reason for concluding that the evidence is, at present, limited, was that very few studies are available that focus on the relationships between aspects of variation and outcomes of relevance to muscle fatigue and MSD. In a review of occupational factors influencing intrinsic motor variability (Srinivasan & Mathiassen, 2012), specifically the variability in postures and muscle activity originating in the sensorimotor control system, the authors found indications for positive effects of increased motor variability in short-cycle repetitive activities on outcomes relevant to the development of MSD (e.g., pain and fatigue), while concluding that research is, at present, also limited in this area. All three reviews reflect an increasing interest among researchers to investigate the short-term effects of variation in posture and muscle activity on potential precursors of MSD, such as muscle fatigue.

One approach to increase biomechanical variation is to redesign a workstation. Obviously, a changed workstation design is likely to influence postures and movements while working, and thus also biomechanical exposure variation. An illustrative example was shown in a study by Könemann, Bosch, Kingma, Van Dieën, and De Looze (2014). Workers reached sideward to bins closer to or further away from the body, but at the same vertical level. Upper arm elevation more often exceeded 20° when reaching to bins at a larger distance. However, like most other studies of workstation designs, Könemann et al. (2014) did not explicitly address potential effects on exposure *variation*. One study, however, did investigate the effect on variation of different desk and computer display designs, concluding that a curved desk led to more variation in working postures and muscle activity compared to a regular desk, while display height did not have any significant effects (Straker, Burgess-Limerick, Pollock, & Maslen, 2009). These two studies, among others, demonstrate that a changed workstation design can, indeed, influence posture and muscle activity, although the effectiveness of redesigning a workstation as a means to increase exposure variation has received very limited attention.

A central assumption when recommending increased exposure variation in constrained and repetitive tasks is that fatigue will be reduced when performing the work, which may, in turn, decrease the risk of MSD (Mathiassen, 2006). In reverse, this would mean that with a more varying exposure, a particular level of fatigue would appear at a higher work pace (Bechtold, Janaro, & Sumners, 1984). Following this idea, some studies have determined the maximal acceptable work pace (MAWP) of individuals performing repetitive work under different working conditions, as a method for setting ergonomics guidelines and for addressing the general influence of these conditions on perceived exertion and expected fatigue. Thus, MAWP has been established using psychophysical approaches in a drilling task (Davis & Fernandez, 1994; Kim & Fernandez, 1993; Marley & Fernandez, 1995), a lateral pinching task (Klein & Fernandez, 1997), a simulated riveting task (Fredericks & Fernandez, 1999), a shaver assembly task (de Looze, Van Rhijn, Schoenmaker, Van Der Grinten, & Van Deursen, 2005), and a fastening task (Cort, Stephens, & Potvin, 2006). In these studies, the MAWP was determined at different working heights (de Looze et al., 2005), wrist postures (e.g. Cort et al., 2006; Davis & Fernandez, 1994), and task durations and forces (Klein & Fernandez, 1997). MAWP significantly decreased with an increase in wrist flexion or extension angle, working height, task duration, and force. Several experimental studies have demonstrated that, for a given upper extremity task, any particular individual is highly consistent in selecting his or her MAWP (e.g., Ciriello, Snook, & Hughes, 1993; Marley & Fernandez, 1995; Snook & Irvine, 1967).

To date, however, no study to our knowledge has addressed the effects of changes in exposure variation that are obtained by manipulating workstation design on fatigue and upper extremity exertion. The present study of a repetitive pick-and-place task was, therefore, planned to examine the extent to which workstation designs, intended to lead to differences in upper arm posture variation, influence activity in selected shoulder muscles, cardiovascular responses, and perceived exertion as measured through MAWP.

METHODS

Participants

Thirteen healthy participants completed the study, with mean age = 26.1 years (standard deviation [*SD*] 3.2), mean body mass = 62.4 kg (*SD* 10.8) and mean height = 173.3 cm (*SD* 9.9). Six participants were female and two were left-handed. None of the participants reported any history of MSD. All participants signed an informed consent after having been informed about the objectives of the experiment. The study was approved by the Ethical Committee of the Department of Human Movement Sciences in Amsterdam.

Task

The participant was seated on a chair with back support and performed a highly repetitive pick-and-place task using the dominant hand in the frontal plane, simulating common occupational activities such as order picking and mail sorting. A fixture was mounted on the wall in front of the participant and their glenohumeral joint center was aligned with the middle of the fixture. One work cycle consisted of: (1) picking one pin (1.3 g) from a central container and placing it in a hole to the left; (2) picking a second pin (1.3 g) from the central container and placing it in the hole to the right; and (3) picking the pins from the holes and returning them to the central container first from the left, then from the right. During an initial laboratory visit, the distance between the two target holes in the fixture was adjusted while the fixture was vertical (Figure 1C) to give upper arm elevation angles for a given participant as close as possible to 10° and 50° relative to the trunk. These angles were measured using a goniometer, and the central container was placed between the two levels (i.e., at an arm elevation of 30°). This approach resulted in a median target hole distance across participants of 0.21 m (range = 0.16 – 0.26 m). This distance between target holes, determined for each participant, was used in all subsequent testing for that participant.

In addition to the vertical workstation design described above (V10/50), the task was performed with the fixture in three additional designs: (1) horizontal at ~30° arm elevation (H30/30, Figure 1A); (2) diagonal at an ~45° angle relative to horizontal, where the targets corresponded to 20° and 40° arm elevation (D20/40, Figure 1B); and (3) horizontal at an arm elevation angle of ~50° (H50/50, Figure 1D). Thus, for each participant, the traveled distance of the hand in a work cycle was equal in all workstation designs. The H30/30, D20/40, and V10/50 designs were intended to differ in upper arm posture variation, but not in the mean arm elevation, while the H50/50 design was included to represent a

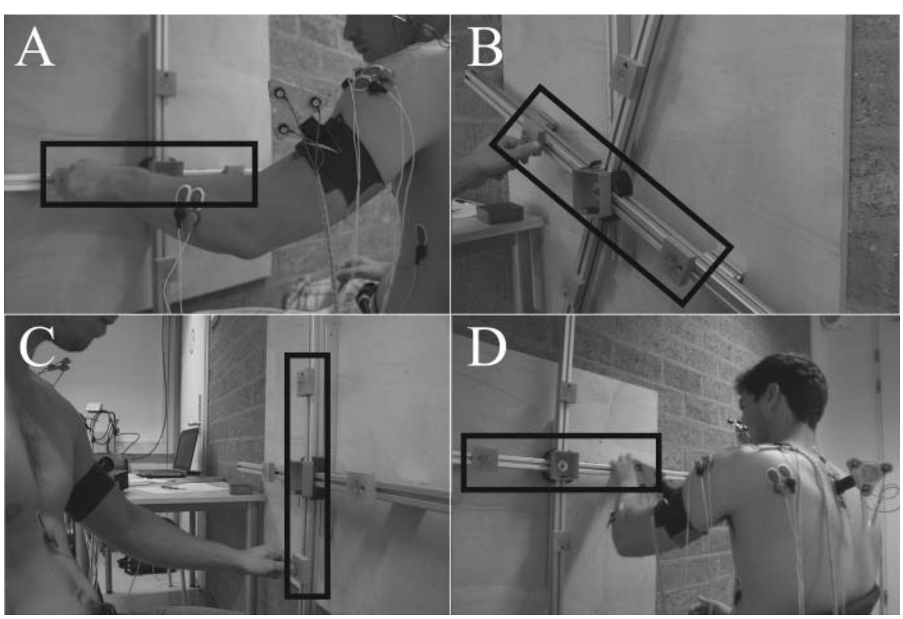

FIGURE 1 **Participant performing the four experimental conditions A: H30/30, B: D20/40, C: V10/50, and D: H50/50.**

more "extreme" mean posture than H30/30, but with the same extent of upper arm posture variation. Thus, H50/50 was included to compare the effect of reconfiguring the workstation for the purpose of increasing variation with that of a "classic" reconfiguration of the workstation (i.e., changing the vertical placement of components).

Procedures

Participants visited the laboratory on three occasions, and were asked not to perform any heavy arm exercises for 24 hours prior to each of these visits. At the first visit, participants were informed about the task protocol, the fixture set-up was individually adjusted, and participants completed a training session of at least 30 minutes to familiarize them with the task and to practice work at various paces for at least 2 minutes. On the latter two visits, participants performed the four experimental conditions in a randomized but balanced order (randomized, controlled crossover scheme); two at each visit, with a 40-minute break between each. During all three visits, which were performed within 1 week with at least 1 day in between, participants received verbal instructions on how to perform and evaluate the task, using a standard template (Appendix A).

Determination of MAWP

The pick-and-place task was performed for a total of 60 minutes at each of the four workstations (Figure 2). The first *standard phase* lasted for 24 minutes and was based on the "staircase method" for arriving at a MAWP for an 8-hour workday, where different work paces are applied in consecutive descending and ascending steps (Cornsweet, 1962; Ehrenstein & Ehrenstein, 1999). Studies determining maximal acceptable levels of work pace, object weight, or force are mainly performed for the purpose of setting guidelines for occupational tasks (Fernandez & Marley, 2014). In the present study, however, we used the MAWP as a response measure, integrating the participant's perception of exertion and expected fatigue when performing the task. In total, seven different work paces (7–13 cycles·min^{-1}) were presented in consecutive 2-minute bouts during the standard phase, some in replicate (see Figure 2). A work pace of 7 cycles·min^{-1} is considerably lower than what would be expected in industrial work (see below), and pilot experiments showed that a pace of 13 cycles·min^{-1} was faster than what participants found to be acceptable. Work pace was controlled by a metronome giving an auditory signal to the participant.

The second *adjustment phase* lasted for 26 minutes and was based on the "method of adjustment," during which the participant is encouraged to give feedback on every work pace presented, and the experimenter adjusts it accordingly (Fernandez, Fredericks, & Marley, 1995; Marley, 1990; Marley & Fernandez, 1995). Thus, for each 2-minute bout in this phase, the participant was requested to assess whether that particular pace was consistent with the instruction "work as hard as you can for an 8-hour working day where you will not develop unusual discomfort in the neck, shoulder, arm, and hand" (complete instructions are provided in Appendix A). Thus, in the *standard phase* participants were presented with a predetermined, limited range of work paces, while in the *adjustment phase* the participants were free to choose both higher and lower paces, if needed, than those occurring in the standard phase. At the end of the *adjustment phase* (i.e., after 50

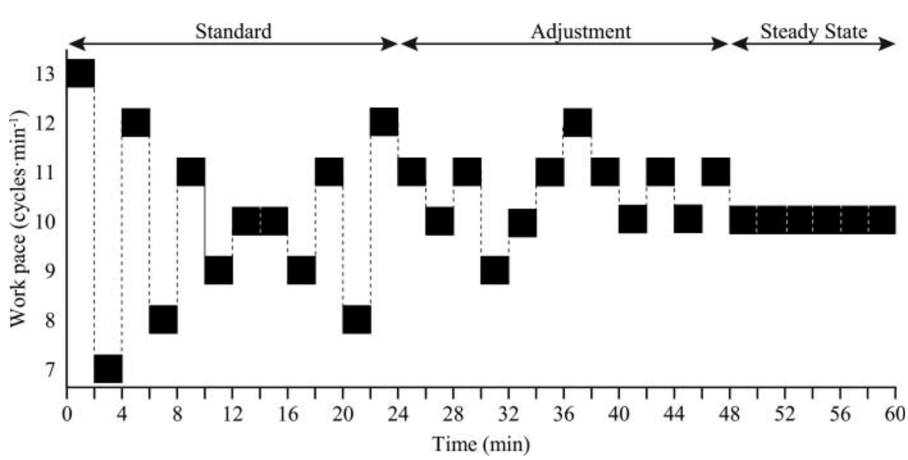

FIGURE 2 **An example illustrating the standard, adjustment, and steady state phases of the 60-minute pick-and-place task protocol.**

minutes of work), the MAWP was settled. The third and final *steady state phase* lasted for 10 minutes, during which the participant continued working at the MAWP. Previous studies have shown that maximal acceptable levels of work pace can be successfully established using this psychophysical procedure (see Fernandez & Marley, 2014 for an overview), and that the MAWP can be reliably determined within a period of about 60 minutes (Muppasani & Fernandez, 1996; Nussbaum & Johnson, 2002).

Work Pace According to the MTM-1 System

The MTM-1 system is a predetermined motion-time system used in various industrial settings to describe human motion in a standardized way. The system analyzes movements and actions in a task, and converts them into micro time elements. Using predetermined standards from MTM-1 (Maynard, Stegmerten, & Schwab, 1948), we created a detailed table based on one work cycle of the current experiment (Appendix B). Each work cycle comprised a combination of the five basic actions of reach, grasp, move, position, and release. In MTM-1, each of these five basic actions is assigned a certain number of time measurement units, one unit corresponding to 0.036 second, which can then be modified to accommodate, for example, different distances of hand movement. Thus, we determined the total number of time measurement units for a complete work cycle for each individual participant, adjusted to the specific distances between central and distant targets in the experimental task for that particular participant. The corresponding pace (cycle time) is labeled MTM-100. Any other pace, including the individual MAWP, can be expressed on the MTM scale. As an example, a MAWP of 10 cycles$\cdot$min^{-1} for an individual moving 14 cm between the central and distant targets would correspond to MTM-104, since MTM-100 for this distance corresponds to 9.6 cycles$\cdot$min^{-1} (Appendix B).

Measurements

Kinematics

In order to track the extent of upper arm posture variation, we recorded upper body kinematics at 100 Hz using the Optotrak system (Northern Digital Inc., Waterloo, Ontario, Canada) with two camera bars, one on each side of the participant. Before each experiment, we placed one marker cluster on the upper part of the trunk (upper back) and one on the dominant upper arm (lateral side), and we visually probed anatomical landmarks corresponding to those proposed by Wu et al. (2005). The glenohumeral rotation center was estimated from recordings of a circular arm movement using an instantaneous helical axis algorithm (Veeger, Yu, An, & Rozendal, 1997).

Prior to work at each of the four workstations, we determined a postural reference for the experimental recordings by collecting data while the participant was seated with their back straight, upper arms alongside their body, elbows flexed in 90°, and thumbs pointing upward. During the entire 60-minute experiment, kinematic recordings lasting for 60 seconds were made every 2 minutes in a regular pattern, beginning with the second minute of the standard phase.

Muscle Activity

We recorded muscle activity using surface electromyography (EMG) from five muscles on the dominant side (upper trapezius, infraspinatus, anterior deltoid, medial deltoid, extensor digitorum), as well as from the upper trapezius on the non-dominant side. We placed pre-gelled Ag/AgCl surface electrodes (Blue Sensor ECG Electrodes, AMBU®, Ballerup, Denmark) in a bipolar configuration with an inter-electrode distance of 20 mm according to the SENIAM guidelines (Hermens, Freriks, Disselhorst-Klug, & Rau, 2000). A common reference electrode was placed over the C7 cervical vertebra. Prior to electrode placement, we shaved and scrubbed the skin and cleaned it with alcohol. The quality of the raw EMG signals was visually confirmed.

Prior to work at each of the four workstations, we collected EMG during 10 seconds of rest while the participant was sitting with their hands in their lap, as well as during a reference contraction in which the participant held their arms abducted and straight in the frontal plane for 20 seconds (Mathiassen, Winkel, & Hägg, 1995). This reference posture was visually checked by the experimenter. EMGs were then recorded continuously during the entire 60-minute experiment. EMG signals were amplified with a 16-channel amplifier (Porti, TMS International B.V., Enschede, the Netherlands) and sampled at 2,000 Hz. All signals were filtered offline with a bidirectional, second-order, bandpass (30–400 Hz) Butterworth filter to remove heart rate (HR) artefacts (Drake & Callaghan, 2006; Marker & Maluf, 2014; Willigenburg, Daffertshofer, Kingma, & Van Dieën, 2012). We root mean square (RMS) converted the filtered signal using a

100-millisecond moving window with 99.5-millisecond overlap.

Cardiovascular Responses

Electrocardiographic (ECG) signals were recorded from the thorax derivation (midaxillary sixth left rib—distal end of sternum; Mathiassen, Hallman, Lyskov, & Hygge, 2014) using pre-gelled Ag/AgCl electrodes (Blue Sensor ECG Electrodes, AMBU®, Ballerup, Denmark). As for EMG recordings, the skin was shaved, scrubbed, and cleaned with alcohol prior to electrode placement. ECG signals were amplified using a 16-channel amplifier (Porti, TMS International B.V., Enschede, the Netherlands) and sampled at 2,000 Hz. Offline, the signals were filtered with a bidirectional, second-order bandpass (0.5–200 Hz) Butterworth filter (Mathiassen et al., 2014).

Rating of Perceived Exertion (Borg)

Participants rated their perceived exertion (RPE) while working at their MAWP. This was done using a Borg CR-10 scale (Borg, 1982) for the neck, dominant shoulder, upper arm, lower arm, and wrist as shown on a printed body map. Ratings were obtained immediately after the steady state phase.

Data Analysis

The metronome controlling work pace also provided a digital signal which was continuously sampled throughout the 60-minute protocol. We were, therefore, able to extract data specific to each single work cycle from the 60-second kinematic recordings, as well as from the continuous EMG and ECG recordings.

Kinematics

Using customized functions in Matlab™ (version 2015a, The Mathworks Inc., Natwick, MA, USA), we calculated humerus elevation relative to the thorax according to Wu et al. (2005). For each work cycle, we calculated the mean ($angle_{MEAN}$) and *SD* ($angle_{SD}$) of this upper arm elevation angle, as well as the angular range of motion (RoM). Using the differentiate function of the symbolic Math Toolbox™ in Matlab™ (i.e., "diff"), we calculated the first derivative of the angular time series. This resulted in a time series of angular velocity, from which we obtained the mean (v_{MEAN}) and peak (v_{PEAK}) angular velocity of the upper arm.

Muscle Activity

For each work cycle, we calculated the mean (RMS_{MEAN}) and the *SD* (RMS_{SD}) of the RMS-converted EMG signal. Mean RMS values for both reference and experimental recordings were adjusted for RMS values obtained during rest. This procedure involved first subtracting the squared RMS value during rest from the squared RMS value of the reference or experimental recordings, and then taking the square root of the result. Within-cycle variation in muscle activity was assessed for all muscles by calculating the coefficient of variation (CV), or RMS_{SD}/RMS_{MEAN}. For the trapezius recordings, the adjusted RMS values during each work cycle were also normalized to the adjusted RMS values of the middle 10 seconds of the reference recording and expressed as percent of reference voluntary electrical activation (% RVE; Mathiassen et al., 1995). Thus, normalized values of RMS_{MEAN} and RMS_{SD} were calculated for the trapezius muscle, but were not available for the other muscles due to the lack of relevant reference contractions.

Cardiovascular Responses

ECG recordings were visually inspected for artefacts, but none were identified. Using a customized Matlab™ script, inter-beat (R-R) intervals (IBIs) were detected from the ECG recordings. HR, in beats per minute (bpm), was determined by dividing 60 seconds by the IBI. RMS successive differences between IBI values (RMSSD) were calculated as a representation of HR variability in the time domain (Hallman, Srinivasan, & Mathiassen, 2015).

Further Processing and Statistical Analysis

In order to examine the effects of different workstation designs on exposure, we compared results for the part of the standard phase during which participants were working at a work pace of 10 cycles·min^{-1} (cf. Figure 2). To identify possible associations between biomechanical exposures and MAWP, we also compared results while the participants worked at the MAWP during each of the four experimental conditions, specifically between minutes 51 and 60 during the steady state phase (cf.

Figure 2). Summary biomechanical exposure metrics both for the standard pace and for MAWP were mean exposure levels across the work cycles, specifically mean of (1) RMS_{MEAN} [% RVE] for muscle activity of the dominant upper trapezius; (2) $angle_{MEAN}$ [°]; (3) v_{MEAN} [$°\cdot s^{-1}$]; and (4) v_{PEAK} [$°\cdot s^{-1}$] for the kinematics; and (5) HR [bpm] for cardiovascular response; as well as variables describing exposure variation, which included means across cycles of (6) RMS_{SD} [% RVE] of the dominant upper trapezius; (7) CV for muscle activity of all six muscles; (8) RoM [°]; and (9) $angle_{SD}$ [°] for the kinematics; and (10) RMSSD [ms] for cardiovascular response.

Due to non-normal distributions of the majority of parametric model residuals, effects of workstation design both during the standard pace and during MAWP were analyzed using Friedman's non-parametric test for repeated measures. We considered possible sex difference in the responses to the different workstation designs, but inspection of the results clearly suggested that no such effect were present (as reviewed below), and thus no formal tests addressing gender were implemented. Post-hoc pairwise comparisons were performed using Wilcoxon signed-rank tests. Statistical analyses were implemented in SPSS (IBM SPSS Statistics 22.0). Statistical significance was concluded when $p < 0.05$ (Friedman's test) or $p < 0.00833$ (Wilcoxon signed-rank tests Bonferroni corrected for six pairwise comparisons; $p < p/n = 0.05 / 6 = 0.00833$).

RESULTS

At the standard pace, EMG recordings were available from all 13 participants, while kinematic recordings were corrupted for one participant. At MAWP, EMG recordings from all participants and kinematics from 12 were available (as above), excepting the H50/50 design in which only 10 participants were able to complete the protocol (3 had to stop prematurely because they found the mechanical load to be so high that none of the offered work paces was acceptable).

Kinematics at the Standard Pace

Upper arm elevation variables are summarized in Figure 3. The figure illustrates that we were successful in designing exposure protocols that differed in kinematic variation but not in mean arm posture (designs H30/30, D20/40, and V10/50), and that H30/30 and H50/50 differed, as intended, in mean arm posture but not in upper arm posture variation. These results were confirmed by statistical tests (Table 1). We did, though, observe slight deviations from the intended mean upper arm elevation angles of 30° and 50°; the actual angles were ~5° larger and almost 5° smaller, respectively. Visual inspection of the data revealed no indication of a systematic difference between males and females (cf. Figure 3).

Workstation design had a main effect on upper arm elevation velocity (v_{MEAN}), and post-hoc tests indicated that V10/50 yielded significantly higher v_{MEAN} than H30/30 and D20/40 (Table 1). Upper arm peak velocity (v_{PEAK}) was also significantly influenced by workstation, with D20/40 and V10/50 causing higher v_{PEAK} than H30/30 and H50/50 (Table 1). In keeping with the arm elevation data, we found no indication of a sex difference in muscle activity and cardiovascular responses at the standard pace.

Mean activity (RMS_{MEAN}) of the dominant upper trapezius differed significantly between workstation designs at the standard pace (Table 1). Post-hoc tests indicated that H50/50 resulted in a significantly higher RMS_{MEAN} than H30/30, with median values of 94% RVE and 47% RVE, respectively. Variation

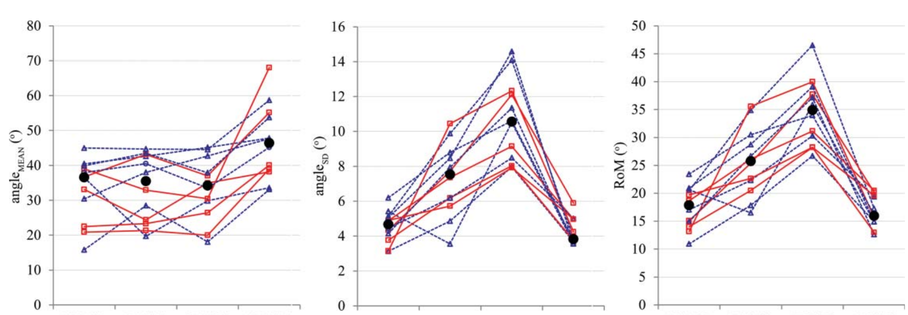

FIGURE 3 **Upper arm elevation variables for the four workstation designs at the standard pace: $angle_{MEAN}$ (left), $angle_{SD}$ (middle), and RoM (right). Lines show individual results for females (n = 5, red squares, solid lines) and males (n = 7, blue triangles, dashed lines); median values across all participants are marked by black circles.**

TABLE 1 **Median kinematic ($n = 12$) and EMG ($n = 13$) variables during the standard pace, with *p*-values obtained from the Friedman tests and from the post-hoc univariate Wilcoxon signed-rank tests.**

	Median value					Univariate Wilcoxon signed-rank tests					
Standardized pace (10 cycles·min^{-1})	H30/30	D20/40	V10/50	H50/50	Friedman Main effect *p*-value	H30/30, D20/40	H30/30, V10/50	D20/40, V10/50	H30/30, H50/50	D20/40, H50/50	V10/50, H50/50
Upper arm elevation											
$angle_{mean}$ (°)	36.6	35.5	34.2	46.4	<0.001*	0.807	0.807	0.753	0.003*	0.002*	0.002*
$angle_{sd}$ (°)	4.7	7.5	10.6	3.8	<0.001*	0.004*	0.001*	0.001*	0.530	0.003*	0.002*
RoM (°)	17.9	25.7	34.9	15.9	<0.001*	0.004*	0.002*	0.002*	0.583	0.002*	0.002*
v_{mean} (°·s^{-1})	16.8	19.9	24.9	14.7	<0.001*	0.010	0.002*	0.002*	0.071	0.010	0.002*
v_{peak} (°·s^{-1})	67.2	95.2	112.8	64.2	<0.001*	0.002*	0.002*	0.012	0.388	0.003*	0.002*
Dominant upper trapezius											
RMS_{mean} (% RVE)	46.9	48.8	63.1	94.0	0.002*	0.221	0.028	0.463	0.003*	0.041	0.209
RMS_{sd} (% RVE)	15.6	26.6	37.3	26.5	<0.001*	0.009	0.001*	0.039	0.002*	0.239	0.023
CV	0.42	0.50	0.58	0.34	<0.001*	0.064	0.002*	0.007*	0.182	0.004*	0.002*
Non-dominant upper trapezius											
CV	0.33	0.42	0.39	0.39	0.801	0.311	0.196	0.917	0.583	0.433	0.272
Dominant infraspinatus											
CV	0.44	0.45	0.37	0.45	0.272	0.701	0.507	0.279	0.583	0.239	0.754
Dominant anterior deltoid											
CV	0.50	0.50	0.48	0.47	0.296	0.600	0.101	0.311	0.875	0.239	0.012
Dominant medial deltoid											
CV	0.56	0.63	0.60	0.49	0.018*	0.133	0.196	0.382	0.050	0.005*	0.005*
Dominant extensor digitorum											
CV	0.52	0.57	0.56	0.56	0.849	0.917	0.552	0.463	0.695	0.347	0.814
Cardiovascular response											
HR (bpm)	68.4	68.0	71.0	70.0	0.840	0.722	0.534	0.790	0.333	0.721	0.285
RMSSD (ms)	33.8	32.9	35.0	37.3	0.516	0.131	0.182	0.657	0.203	0.445	0.241

*$p < 0.05$ (Friedman) and 0.00833 (Wilcoxon).

TABLE 2 Median MAWP and MTM pace for each workstation design, and ratings of perceived exertion (RPE; Borg CR-10) directly after the steady state phase, with *p*-values obtained from the Friedman test and from the post-hoc univariate Wilcoxon signed-rank tests.

	Median value					Univariate Wilcoxon signed-rank tests					
	H30/30	D20/40	V10/50	H50/50	Friedman Main effect *p*-value	H30/30, D20/40	H30/30, V10/50	D20/40, V10/50	H30/30, H50/50	D20/40, H50/50	V10/50, H50/50
Pace											
MAWP	11	10	10	9	0.030*	0.803	0.782	0.480	0.066	0.021	0.034
MTM	122	118	118	103	0.030*	0.906	0.609	0.588	0.068	0.013	0.068
RPE											
Neck	3.5	3.0	2.0	2.5	0.382	0.271	0.441	0.811	0.368	0.886	0.752
Shoulder	3.5	3.0	3.0	3.5	0.447	0.366	0.510	0.726	0.755	0.287	0.312
Upper arm	1.5	2.0	2.5	2.5	0.067	0.214	0.230	0.941	0.012	0.071	0.108
Lower arm	2.0	1.0	1.5	2.0	0.121	0.161	0.492	0.856	0.258	0.589	1.000
Wrist	1.0	0.5	0.8	0.8	0.535	0.750	0.429	0.150	0.674	0.465	0.863

*$p < 0.05$ (Friedman) and 0.00833 (Wilcoxon).

in muscle activity (RMS_{SD}) of the dominant upper trapezius also showed a significant main effect of workstation design, with both V10/50 and H50/50 having significantly larger RMS_{SD} than H30/30. When variation was expressed in terms of the CV, the dominant upper trapezius muscle still exhibited a main effect of workstation design, and several pairwise comparisons were statistically significant (Table 1). Of the other five investigated muscles, only the dominant medial deltoid showed any significant dependence on workstation design, with the D20/40 and V10/50 protocols having more relative variation than H50/50.

At the standard pace, HR and RMSSD were, on average, 69 bpm and 35 ms. Neither of these variables differed significantly between workstation designs.

MAWP

MAWP differed significantly between workstation designs (main effect $p = 0.030$; Table 2). Post-hoc tests did not reveal any significant pairwise differences (Table 2), though H50/50 resulted in a lower MAWP than H30/30, D20/40, and V10/50 (Figure 4).

At the group level, the MAWP for H30/30, D20/40, and V10/50 corresponded to MTM-122, MTM-118, and MTM-118 paces, respectively, and the lower MAWP in H50/50 corresponded to MTM-103. Since, for a particular participant, the MTM-paces are proportional to the MAWP values, the statistical results when testing effects of workstation design are equivalent to those obtained when comparing the MAWP values (Table 2).

Kinematics at MAWP

Upper arm elevation variables when working at the MAWP (Figure 5) were similar to those found at the standard pace (cf. Figure 3). Overall, the same main effects and pairwise comparisons were significant in both cases (Table 3 versus Table 1), and kinematics did not appear to differ between females and males at MAWP (Figure 5).

Muscle Activity, Cardiovascular Responses, and Ratings of Perceived Exertion at MAWP

We found a significant main effect of workstation design on RMS_{MEAN} of the dominant upper trapezius but, in contrast to our findings at the standard pace (Table 1), none of the pairwise differences between workstation designs were significant (Figure 6; Table 3). RMS_{SD} of the dominant upper trapezius showed a

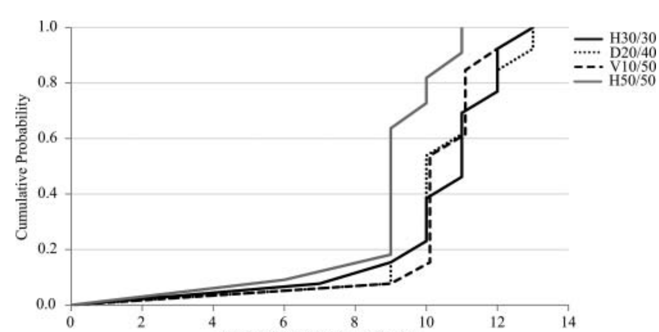

FIGURE 4 Cumulative probability distribution of the maximal acceptable work pace for the four workstation designs.

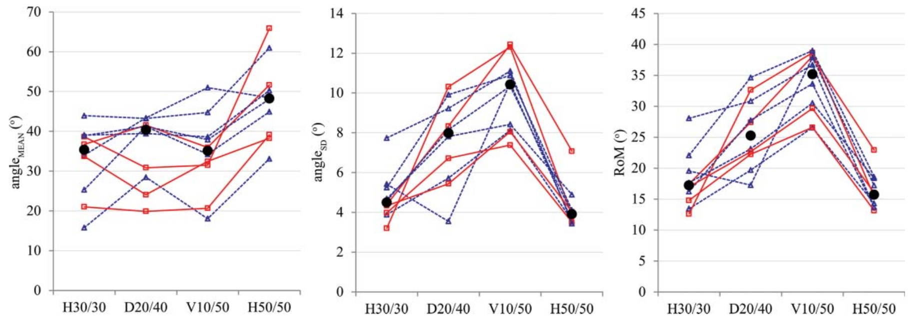

FIGURE 5 Upper arm elevation variables for the four workstation designs at the MAWP: angle$_{MEAN}$ (left), angle$_{SD}$ (middle), and RoM (right). Lines show individual results for females ($n = 4$, red squares, solid lines) and males ($n = 6$, blue triangles, dashed lines); median values across all participants are marked by black circles.

significant main effect of workstation design, with less absolute variation for this muscle in H30/30 than in D20/40 and V10/50. CV of the dominant upper trapezius also differed between designs, with significantly more relative variation in V10/50 than in H30/30 and H50/50. None of these effects differed between males and females (Figure 6). One participant showed, for unknown reasons, a higher RMS_{MEAN} and RMS_{SD} in some of the workstation designs than all other participants (Figure 6); however, the CVs for this participant were not extraordinary. For the other five muscles, CV did not differ significantly between workstation designs (Table 3).

At MAWP, mean HR and RMSSD were 69 bpm and 29 ms, respectively, and did not differ significantly between workstation designs. Inspection of the results did not suggest any sex difference either. Perceived exertion (Borg CR-10) did not differ between the four workstation designs for any body region (Table 2), with mean values across the workstation designs of 2.8 (neck), 3.3 (shoulder), 2.1 (upper arm), 1.6 (lower arm), and 0.8 (wrist).

DISCUSSION

Changing Variation by Workstation Design

We were successful in creating three workstation designs that led to similar mean upper arm elevation angles close to 30° (actual mean = 35.4°), but differences in kinematics variation, as indicated by angle$_{SD}$ (increasing from 4.7° to 10.6° between H30/30 and H10/50) and RoM (increasing from 17.9° to 34.9°). Thus, we successfully managed to manipulate *how much* arm elevation changed between these workstation designs, while strictly controlling *how often* it changed (by employing the same work pace scheme for all protocols), and even the extent of *similarity* between work cycles (by designing a standardized repetitive task). We were, therefore, able to investigate the effect of changing only one of the three fundamental aspects of variation as proposed by Mathiassen (2006), who also emphasized the need for disentangling the relative importance of these three aspects to performance, fatigue and health. Our controlled manipulations of variation in movement patterns were, as expected, accompanied by changes in the variation of upper trapezius muscle activity. While the upper trapezius has been more of a focus than other muscles in discussions about interventions promoting biomechanical variation in constrained and repetitive jobs (Ciccarelli, Straker, Mathiassen, & Pollock, 2014; Ostensvik, Veiersted, & Nilsen, 2009), we emphasize the current finding that the examined workstation designs did not show any notable differences in variation for the other upper extremity muscles investigated.

Posture Variation and MAWP

In addition to a "background" exposure involving an upper arm elevation of ~35° and muscle activity ranging between 47% and 63% RVE in the dominant upper trapezius, increased variation to the extent accomplished here did not significantly influence the MAWP. Participants arrived at similar MAWPs for H30/30, D20/40, and V10/50. The effect of increased variation on MAWP was less than that observed when working height was increased to give an average arm elevation of ~50° during a horizontal hand movement (9.0 cycles·min^{-1} in median). The non-significant effect on MAWP of increased upper arm posture variation (indicating similar exertion and fatigue across workstation designs) stands in contrast to the results of Yung, Mathiassen, and Wells (2012), who showed that the extent of force variation around a constant average

TABLE 3 **Median kinematic (n = 12, excepting n = 10 for H50/50) and EMG (n = 13, excepting n = 10 for H50/50) variables during the MAWP with p-values obtained from the Friedman's test and from the post-hoc univariate Wilcoxon signed-rank tests.**

	Median value					Univariate Wilcoxon signed-rank tests					
MAWP	H30/30	D20/40	V10/50	H50/50	Friedman Main effect p-value	H30/30, D20/40	H30/30, V10/50	D20/40, V10/50	H30/30, H50/50	D20/40, H50/50	V10/50, H50/50
Upper arm elevation											
$angle_{mean}$ (°)	35.4	40.3	35.1	48.3	0.001*	0.861	0.600	0.507	0.005*	0.005*	0.007*
$angle_{sd}$ (°)	4.5	8.0	10.4	3.9	<0.001*	0.004*	0.001*	0.002*	0.241	0.007*	0.005*
RoM (°)	17.2	27.6	35.2	15.7	<0.001*	0.003*	0.002*	0.010	0.386	0.005*	0.005*
v_{mean} ($°\cdot s^{-1}$)	15.7	20.1	24.4	13.9	<0.001*	0.015	0.002*	0.002*	0.114	0.009	0.005*
v_{peak} ($°\cdot s^{-1}$)	66.8	100.1	112.6	66.8	<0.001*	0.002*	0.002*	0.002*	0.575	0.005*	0.005*
Dominant upper trapezius											
RMS_{mean} (% RVE)	47.1	59.8	56.2	77.9	0.029*	0.507	0.023	0.701	0.013	0.241	0.445
RMS_{sd} (% RVE)	22.4	29.4	37.0	27.8	<0.001*	0.006*	0.001*	0.064	0.009	0.878	0.017
CV	0.42	0.48	0.61	0.38	0.004*	0.011	0.005*	0.033	0.445	0.028	0.007*
Non-dominant upper trapezius											
CV	0.38	0.43	0.37	0.37	0.187	0.382	0.075	0.753	0.508	0.386	0.241
Dominant infraspinatus											
CV	0.46	0.48	0.49	0.47	0.356	0.552	0.753	0. 807	0.169	0.386	0.114
Dominant anterior deltoid											
CV	0.49	0.49	0.55	0.52	0.253	0.221	0.011	0. 087	0.139	0.508	0.333
Dominant medial deltoid											
CV	0.58	0.61	0.62	0.55	0.131	0.013	0.033	0. 650	0.445	0.059	0.047
Dominant extensor digitorum											
CV	0.52	0.55	0.52	0.57	0.048*	0.507	0.173	0. 463	0.074	0.203	0.169
Cardiovascular response											
HR (bpm)	69.2	68.2	70.1	70.0	0.583	0.790	0.790	0.929	0.575	0.779	0.889
RMSSD (ms)	28.4	36.5	28.1	22.3	0.586	0.286	0.929	0.534	0.110	0.139	0.314

*p < 0.05 (Friedman) and 0.00833 (Wilcoxon).

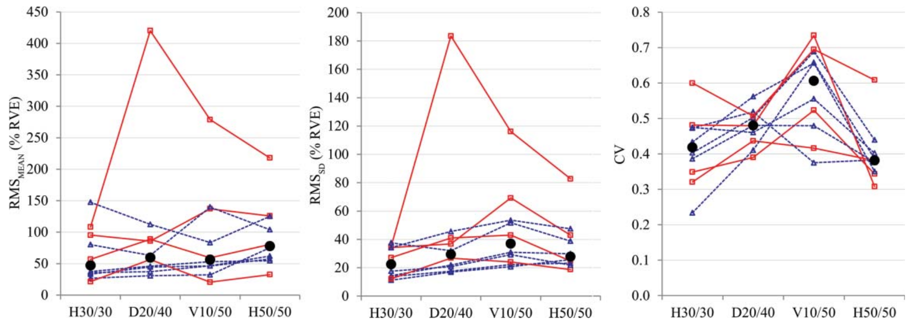

FIGURE 6 EMG variables for the dominant upper trapezius muscle in the four workstation designs at the MAWP: RMS_{MEAN} (left), RMS_{SD} (middle), and CV (right). Lines show individual results for females ($n = 4$, red squares, solid lines) and males ($n = 6$, blue triangles, dashed lines); median values across all participants are marked by black circles.

exertion was associated with several manifestations of muscle fatigue. However, they based their findings on isometric elbow extensions and a considerably larger dispersion between alternating force levels than that occurring in the present experiment according to the dispersion in trapezius muscle activity; one condition in the study by Yung et al. (2012) even included rest (0% MVC). While the strictly controlled experiment of Yung et al. (2012) suggested that larger variation is more effective in alleviating fatigue, we emphasize that a trade-off will be present in an occupational context between introducing tasks, operations, or loads with a large diversity, so that variation will increase for the better, and the chance that some of these loads become so large that they will be psychophysically unacceptable or even hazardous.

To this end, we deliberately focused on modifications in the range of upper arm posture, whereas in real occupational settings tasks may differ not only in this respect (*how much*) but also in *frequency* or *similarity*. Our task did not impose any major cognitive demands, which may be consistent with some industrial assembly tasks, while others may entail considerable requirements for decision making. Whether combined physical and mental demands would influence MAWP more than physical demands alone needs to be investigated further; some studies suggest that combined demands in upper extremity work may, indeed, lead to larger exposures in the shoulder region, and, therefore, likely to a different level of fatigue development and performance from that observed for only physical demands (Leyman, Mirka, Kaber, & Sommerich, 2004; Shaikh, Cobb, Golightly, Segal, & Haslegrave, 2012; Wang, Szeto, & Chan, 2011).

Determinants of MAWP

During work at MAWP, the current workstation designs still differed with respect to variation in trapezius muscle activity (Table 3; Figure 6), while differences in the mean activity level were less pronounced than at the standard pace. More pronounced differences while working at MAWP were particularly obvious when examining the results during work with horizontal hand movements (H50/50 and H30/30). At the standard pace (10 cycles·min^{-1}), H50/50 was associated with clearly larger mean muscle activity levels in the dominant upper trapezius compared to H30/30 (i.e., 94 and 47% RVE, respectively). A larger RMS_{MEAN} in H50/50 was expected, since several earlier studies have shown that increased upper arm elevation is associated with increased upper trapezius EMG amplitude (Jakob, Liebers, & Behrendt, 2012; Lee, Lu, Sung, & Liao, 2015; Mathiassen & Winkel, 1990). Working at MAWP was associated with a moderate slowdown compared to the standard pace in H50/50, but a slight increase in H30/30, and these changes in pace led to changes in trapezius activity to the extent that it did not differ significantly anymore between the workstation designs, even if it was numerically larger in H50/50.

These findings suggest that muscle activity variation within the range covered in the present experiment is not a distinct determinant of acceptable work pace in strictly controlled, short-cycle, repetitive tasks, while the mean muscle activity level may be of some importance, even at moderate exertions and within a rather narrow range (47% to 63% RVE in the present study). Thus, as a speculative hypothesis, subjects may adjust work pace so as to arrive at a MAWP with an "acceptable level" of mean muscle activity. Another possible driver of MAWP could be the attempt to select a pace where movements feel smooth and rhythmical (i.e., neither too slow, which would feel awkward, nor too fast, which would feel forced and stressed). In other words, "motor flow" may be an important factor. In an experiment where participants were requested to work both at a self-selected pace and in protocols where pace was strictly controlled, Dempsey, Mathiassen, Jackson, and O'brien (2010) showed that participants selected the work pace they were used to, even if it was relatively high (about MTM-110). The authors suggested that participants had developed an automated motor strategy during the course of the experiment, which could not be changed without the need for new motor learning.

MTM Ratings of MAWP

Assembly work in Swedish industries is often paced between MTM-110 and MTM-120 (Mathiassen & Winkel, 1996; Sundelin & Hagberg, 1992). Since, in an MTM context, movements in the present work cycle were equal in all four workstation designs, participants should, according to the MTM system, be able to work at paces between MTM-110 and MTM-120, irrespective of movement direction or working height. Converting MAWP values into MTM paces using the MTM-1 system (Appendix A) showed that the self-selected paces for H30/30, D20/40, and V10/50 corresponded, in median, to common standards in Sweden, specifically MTM-122, MTM-118, and MTM-118, respectively (Table 2). The MTM-pace at MAWP decreased considerably (MTM-103) when the working height was increased to H50/50, though this difference was not statistically significant. It appeared that H50/50 was too demanding for the participants to accept a pace between MTM-110 and MTM-120. This finding suggests that the present MTM-1 system is not sufficiently sensitive to effects of working height on perceived workload.

Strengths and Limitations

To our knowledge this is the first study to examine, in a controlled experiment, whether an increased exposure variation, here in terms of the range of upper arm postures, leads to a more tolerant perception of work pace in the working participant. We expected this to happen *a priori*, since more variation is generally believed to alleviate fatigue. However, changes in variation were implemented here on top of an average exposure, the latter of which may already have been so pronounced that the different levels of variation we implemented had only marginal effects. It is possible that more pronounced contrasts in variation would have shown an effect on MAWP. In other words, more exposure variation could allow for a higher work pace (MAWP) before reaching a level of perceived exertion, discomfort, and fatigue judged by the participant to be acceptable for an 8-hour workday. Larger contrasts in variation could be achieved in several ways, such as by letting a participant move their hand only to the central bin versus moving to bins even more distal than the ones we used. We sacrificed this opportunity, though, to ensure that the distance covered by the hand was constant across workstation designs, since differences in this distance could confound the MAWP. Workstation designs leading to larger contrasts in variation could also identify whether the cardiovascular response would remain closely correlated to perceived exertion, as it appears from our results, or whether HR would increase at a larger MAWP even though exertion stays constant. In any case, our results suggest that exposure variation needs to be considerable for any major effects on perceived effort and HR to occur, supporting an earlier impression that moderate variation has only inconclusive effects (Luger et al., 2014). While our workstation designs led to differences in RoM, movements were very similar, and substantial effects may be obtained only by mixing operations or tasks with larger exposure diversity (Mathiassen, 2006).

The upper arm elevation RoM was expected to be $\sim 0^{\circ}$ in H30/30, $\sim 20^{\circ}$ in D20/40, and $\sim 40^{\circ}$ in V10/50. The results showed that these expectations were, however, not met; RoMs were approximately 18, 26, and 35° in these three workstation designs. Dynamic movements associated with performing the task appeared to modify the range of arm elevation determined during adjustments of the fixture, which were done with the arm in static postures.

The order of workstation designs in the experiment was determined using a balanced scheme (i.e., a randomized, controlled crossover scheme) across participants, so that any particular workstation design would occur with the same likelihood at a certain position in the order. Thus, half of the participants performed the H50/50 design as the first one at one of the experimental days. Since work at this protocol workstation was considered quite difficult, we were aware of the possible concern that the 40 minutes of recovery offered before the next work bout would not allow for complete recovery of muscles to a non-fatigued state. However, subsequent analyses of the EMG signal amplitudes during the reference contractions performed just before each bout suggested that muscles did, indeed, recover to a sufficient extent.

Work in the present laboratory study was strictly controlled, and thus the results should be interpreted with due caution with respect to external validity. While we claim that our repetitive task does have occupational relevance, it obviously does not exactly mimic tasks in, for instance, industrial assembly. Thus, we emphasize that the MAWP values resulting from the present experiment should not be implemented as guidelines for occupational work. We had our participants working at each workstation design for only one hour. Thus, we could not validate the participants' ability to arrive at a "correct" MAWP, specifically a pace that does not lead to "unusual discomfort in the neck, shoulder, arm and hand" after 8 hours of work. In the present study, however, we used and interpreted the MAWP as an integrated measure of perceived exertion and expected fatigue when working at different workstation designs, rather than as a way of literally determining an acceptable pace for repetitive work in industry. Thus, in the present context, the issue of whether MAWP is, indeed, valid in the long term, let alone whether it reflects the risk of developing MSD, is considered less critical.

In addition, our population of young and healthy adults was more homogeneous than the general working population. However, we had both male and female participants, and we emphasize that biomechanics and motor control may differ according to sex, including muscle architecture, muscle recruitment patterns, central organization of voluntary movements, and maximal strength (Côté, 2012).

Future Research

It is frequently suggested that more variation might counteract the development of MSDs in jobs characterized by repetitive operations and/or constrained postures (Mathiassen, 2006; Straker & Mathiassen, 2009). While associations between the extent of variation and important occupational outcomes, such as fatigue, and disorders are largely unknown, our results suggest that variation within the limits investigated here, and around the average exposures we used, are not likely to be effective in reducing risk. We encourage further studies examining the possible effects of other extents of posture variation, added "on top" of other average postures.

We specifically manipulated the "aspect of variation (Mathiassen, 2006), while keeping the "*how often*" and "*how similar*" aspects almost constant. Further studies of the effectiveness of manipulating either one of these three fundamental aspects of variation are encouraged, including identifying their mutual dependence in influencing fatigue, performance, and disorder risks. This may include research into whether the effects of variation on motor control and fatigue, for example, depend on body region and muscle group.

CONCLUSIONS

We successfully manipulated upper arm posture variation, by implanting different workstation designs. The workstation designs also led to differences in movement velocity and in variation in trapezius muscle activity. However, neither cardiovascular responses nor perceived exertion, as indicated through MAWP, differed between the workstation designs. Changing the working height, however, did have an effect on MAWP. Apparently, more radical manipulations of the workstation or the work task than those implemented in this experiment would be needed to accomplish variation to an extent sufficient to substantially change outcomes, such as perceived exertion and cardiovascular responses.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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APPENDIX A: Instructions Given to Subjects at the Beginning of Each Experimental Day (Translated from Dutch)

General instructions:

- Your task is to move your hand back and forth, picking pins from the central bin and placing them in the outer bins;
- You will hear a metronome at the start of every cycle, which comprises picking and placing two pins from the central bin to the outer bins, and picking and placing the same two pins in the same order from the outer bins to the central bin;
- Try to move consistently, meaning slower when there is a longer time in between two metronome beeps, and faster when the time between two metronome beeps is shorter;
- When picking and holding the pins, try not to apply a lot of pinch force;
- During the experimental conditions, it is important that you concentrate on the task and try to avoid errors such as dropping a pin; therefore, you are not allowed to read or talk while performing the task;
- I encourage you to complete the full 1-hour experimental conditions.

Specific instructions:

- Imagine that you are on piecework getting paid for the amount of work that you do, but working a normal 8-hour shift that allows you to go home without unusual discomfort in the neck, shoulder, arm, and hand;
- In other words, I want you to imagine a job where you work as hard as you can (or as fast as possible) for an 8-hour shift without straining your neck, shoulder, arm, and hand;
- The 1-hour protocol includes three phases:
  - Phase 1, the standard phase, lasting for 24 minutes. You will work at various predetermined work paces that are cued by a metronome beep at the start of every work cycle; each work pace lasts for 2 minutes and I will indicate when the work pace will change;
  - Phase 2, the *adjustment phase*, lasting for 26 minutes. At the end of each 2-minute work pace period, I will ask you to judge that work pace. I will adjust the work pace

according to your judgement. At the end of this phase (i.e., after 50 minutes), I will settle on your maximal acceptable work pace;
  - Phase 3, the *steady state phase*, lasting for 10 minutes. You will continue working at the maximal acceptable work pace settled at 50 minutes.
- When I ask for your judgement about a work pace, always remember that your judgement should reflect your maximal acceptable work pace for an 8-hour working day where you will not develop unusual discomfort in the neck, shoulder, arm, and hand;
- Judging a work pace is not an easy task. Only you know how you feel, so please stay concentrated;
- If you think the pace is too high (too fast), let me know; but I don't want you to work too lightly (too slowly) either, so if you think you could work faster, as you maybe would on piecework, let me know;
- Do not be concerned if you are not sure whether you have reached your maximal acceptable work pace; I will help you during this process; you will try as many (modifications to) work paces as necessary to settle on your maximal acceptable work pace after 50 minutes;
- If, by accident, you make an error (e.g., you drop a pin, leave it, and take a new pin), do not worry about running out of pins, I will make sure you have enough pins in stock;
- Remember that it is not a contest; everyone is not expected to do the same amount of work by or to work at the exact same pace;
- I need your accurate judgement about how hard (or how fast) you think you can work without developing unusual discomfort in your neck, shoulder, arm, and hand.

APPENDIX B: MTM-paces

	Action	Abbr.	Class.	TMU at different distances between central and distant target (cm)							
				12	12.5	13–15	15.5–17.5	18–20	20.5–22.5	23–25	25.5–27.5
1	Grasp	G	1C3	10.8	10.8	10.8	10.8	10.8	10.8	10.8	10.8
2a	Move	M	C	8.0	9.2	9.2	10.3	11.1	11.8	12.7	13.5
2b	Position	P	2	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6
3	Release	RL	1	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
4	Reach	RE	D	8.4	9.4	9.4	10.1	10.8	11.5	12.2	12.9
5	Grasp	G	1C3	10.8	10.8	10.8	10.8	10.8	10.8	10.8	10.8
6a	Move	M	C	8.0	9.2	9.2	10.3	11.1	11.8	12.7	13.5
6b	Position	P	2	26.6	26.6	26.6	26.6	26.6	26.6	26.6	26.6
7	Release	RL	1	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
8	Reach[a]	RE	D	12.2	12.2	12.9	14.2	15.6	17.0	18.4	19.8
9	Grasp	G	1C3	10.8	10.8	10.8	10.8	10.8	10.8	10.8	10.8
10	Move	M	C	8.0	9.2	9.2	10.3	11.1	11.8	12.7	13.5
11	Release	RL	1	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
12	Reach	RE	D	8.4	9.4	9.4	10.1	10.8	11.5	12.2	12.9
13	Grasp	G	1C3	10.8	10.8	10.8	10.8	10.8	10.8	10.8	10.8
14	Move	M	C	8.0	9.2	9.2	10.3	11.1	11.8	12.7	13.5
15	Release	RL	1	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Total TMU				165.4	172.2	172.9	180.0	186.0	191.6	198.0	204.0
CT—MTM-100				6.0	6.2	6.2	6.5	6.7	6.9	7.1	7.3
WP—MTM-100				10.1	9.7	9.6	9.3	9.0	8.7	8.4	8.2
CT—MTM-110				5.4	5.6	5.7	5.9	6.1	6.3	6.5	6.7
WP—MTM-110				11.1	10.6	10.6	10.2	9.9	9.6	9.3	9.0
CT—MTM-120				5.0	5.2	5.2	5.4	5.6	5.7	5.9	6.1
WP—MTM-120				12.1	11.6	11.6	11.1	10.8	10.4	10.1	9.8

Note. The table shows MTM assessment of the task. The complete work cycle consisted of 15 separate actions with an abbreviation (Abbr.) and a classification (Class.) which, depending on the individually pre-set distance between middle and distant target, corresponds to a certain amount of time measurement units (TMU). The sum of the TMU per action is converted into the cycle time (CT) at MTM-100 (total TMU $\times$ 0.036 s) and into the work pace corresponding to MTM-100 (WP; 60 / CT). Additionally, the CT (s) and WP (cycles$\cdot$min^{-1}) for MTM-110 and MTM-120 are provided.

[a]Step number 8 in the work cycle included reach at the double distance from the one side target to the other.