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Observed differences in upper extremity forces, muscle efforts, postures, velocities and accelerations across computer activities in a field study of office workers

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This study, a part of the PRedicting Occupational biomechanics in OFfice workers (PROOF) study, investigated whether there are differences in field-measured forces, muscle efforts, postures, velocities and accelerations across computer activities. These parameters were measured continuously for 120 office workers performing their own work for two hours each. There were differences in nearly all forces, muscle efforts, postures, velocities and accelerations across keyboard, mouse and idle activities. Keyboard activities showed a 50% increase in the median right trapezius muscle effort when compared to mouse activities. Median shoulder rotation changed from 25 degrees internal rotation during keyboard use to 15 degrees external rotation during mouse use. Only keyboard use was associated with median ulnar deviations greater than 5 degrees. Idle activities led to the greatest variability observed in all muscle efforts and postures measured. In future studies, measurements of computer activities could be used to provide information on the physical exposures experienced during computer use.

Practitioner Summary: Computer users may develop musculoskeletal disorders due to their force, muscle effort, posture and wrist velocity and acceleration exposures during computer use. We report that many physical exposures are different across computer activities. This information may be used to estimate physical exposures based on patterns of computer activities over time.

Keywords: office ergonomics; biomechanics; task analysis; human–computer interaction

Introduction

Although computer use is considered to be an important risk factor for musculoskeletal disorder (MSD) development (Bergqvist *et al.* 1995, Gerr *et al.* 2002), the pathways through which computer use affects MSDs are unclear. One hypothesis is that computer use might affect a user's upper extremity physical exposures such as forces, muscle efforts, postures, velocities and accelerations, which may lead to musculoskeletal damage that could accumulate over time. However, while some studies have shown associations between force (Feuerstein *et al.* 1997) or posture (Marcus *et al.* 2002) and MSDs, other studies have reported no association (Andersen *et al.* 2011), and thus the overall evidence for associations between physical exposures and MSDs limited.

The variation in physical exposures experienced throughout work is thought to be associated with MSDs (Mathiassen 2006). However, using variation in physical exposure as an outcome measure in epidemiological studies requires measurements over long periods of time in large populations of workers, which is expensive, time-consuming and often impractical (Winkel and Mathiassen 1994). So far, the association between variation in physical exposures and MSDs has not been examined in computer users.

Computer use is an action that is composed of keyboard, mouse and idle activities (Chang *et al.* 2008). Computer interaction monitoring software can directly record these activities as they are performed during computer use, and can be used over an extended period of time (Blangsted *et al.* 2004, Chang *et al.* 2008). If the activities performed during computer use lead to different physical exposures, computer interaction monitoring software could provide information on the physical exposures experienced by computer users that could be used in epidemiological studies.

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Although a laboratory study has shown that different computer activities are associated with different physical exposures (Dennerlein and Johnson 2006a), it is unclear whether the results from the laboratory remain true in the field. Physical exposures measured during computer use in the field have been shown to be different than those measured in the laboratory (Asundi *et al.* 2010a). This could explain why Ijmker *et al.* (2011) did not find a relationship between duration of software-recorded mouse use and MSDs in a prospective field study despite previous belief that the constrained and non-neutral postures observed during mouse use in the laboratory my lead to MSDs. If the potentially harmful physical exposures observed during mouse use in the laboratory are not found in a field setting, an increase in mouse activities compared to keyboard or idle activities during actual computer work may not incur any additional harmful physical exposures. Factors such as working technique (Homan and Armstrong 2003), workstation setup (Simoneau *et al.* 2003, Dennerlein and Johnson 2006b) and individual factors (Won *et al.* 2009) may provide additional sources of variability that may alter or eliminate the association between physical exposures and computer activities in a field setting.

In this study, we developed a system to measure physical exposures continuously and simultaneously, including upper extremity forces, muscle efforts, postures, velocities and accelerations, and computer activities in a field study of computer workers. We wanted to test the hypothesis that there are differences in field-measured forces, muscle efforts, postures, velocities and accelerations across keyboard, mouse and idle activities to determine if this result, which has already been reported using data from the laboratory (Dennerlein and Johnson 2006a), is robust to the additional sources of variability that may be observed in the field. If there are differences in these field-measured physical exposures across activities, this result would provide support for a method for measuring physical exposures during computer use based on measurements of computer activities, which could be used to investigate associations between physical exposures and MSDs in future studies.

Methods

Experimental design and set-up

The data used for this study were taken from the larger PRedicting Occupational biomechanics in OFfice workers (PROOF) study, which is aimed at investigating the effects of psychosocial stressors at work on biomechanical loading of office workers in the field. The 120 (34 males and 86 females) participants recruited for this study ranged in age from 23 to 63 (mean = 40 years) and worked at the VU University or the VU University Medical Center, both in Amsterdam, the Netherlands. All participants self-reported that they had a working contract between 20 and 40 hour/week (61 participants reported working 36 hours or more per week) and held jobs that involved mainly computer work. All participants were comfortable operating the mouse with their right hand during the measurement period. Measurements were scheduled on a day that was reported by the participants to be representative of a regular workday, and balanced so that there were equal measurements on each weekday and in the morning/afternoon. As part of their regular health and safety programme, all participants had access to ergonomic resources. All participants had their own designated workstation. Participants were free of musculoskeletal complaints for the week prior to the measurements. The Harvard School of Public Health Human Subjects Committee, the Medical Ethics Committee of the VU University Medical Center Amsterdam and the Ethics Committee of the VU University Faculty of Human Movement Sciences all approved all protocols and consent forms.

In order to separate the force, muscle effort, posture, velocity and acceleration data into keyboard, mouse and idle activities, we measured keyboard and mouse events using custom-designed computer interaction monitoring software (Chang *et al.* 2008). Simultaneously, we continuously measured the forces applied to the keyboard and sides of the mouse, muscle effort of the left and right trapezius and extensor carpi radialis, and postures of the left and right wrist and shoulder, the head, neck and trunk. All measurements were performed while participants completed their own work at their own workstations. Set-up and instrumentation of the worker, as well as instrumentation removal, took approximately 75 min, and the measurement period took approximately 115 min, for a total of approximately three hours spent with each participant. All instrumentation used either wireless technology or data loggers with onboard memory to allow the workers to move freely while at their workstation and to leave their workstation when necessary (Figure 1). The same experimenter performed all of the instrumentation set-up and removal for all participants in the study.

Activity monitoring

Computer interaction monitoring software, once installed onto a participant's computer, automatically recorded the beginning and end times of any keyboard or mouse activity by monitoring the keyboard and mouse events

Figure 1. Instrumentation set up on a participant at her workstation. The systems used to measure the biomechanical exposures were chosen to be unobtrusive and allow the participant to perform her regular work without interruption or restriction. Participants were able to move freely at their workstation and to leave the workstation without restraint.

captured by the Windows operating system. For 13 participants who could not load the software onto their computers due to computer security or use of a non-Windows operating system, the keyboard and mouse events were monitored through an external USB tracker (Model 110b; Ellisys Inc., Geneva, Switzerland). From the event data we calculated keyboard activity, mouse activity and idle activity. Keyboard activities were defined as any series of keyboard events (keystrikes) that had less than two seconds of inactivity between successive keystrikes. Similarly, mouse activities were defined as a series of mouse events (mouse movement, scrolling or button clicks) that had less than two seconds of inactivity between successive mouse events. While there is no extant standard for defining keyboard or mouse activities, two seconds were chosen as being a long enough time period to separate keyboard and mouse activities from idle activities. The definitions chosen are the same as in the laboratory study (Dennerlein and Johnson 2006a). Cut-offs between 1.5 and 4.5 s have been validated as having low relative error compared to direct observation (Yeh *et al*. 2009, Hwang *et al*. 2010). Idle activities were defined as any time there were no keyboard or mouse activities for at least two seconds but less than 30 s. The 30 s cut-off has also been validated (Hwang *et al*. 2010) and has been used in previous studies (Ijmker *et al*. 2011). The combination of keyboard activities, mouse activities and idle activities together were considered a period of computer activity, and any period without computer activity for at least 30 s was considered a period of non-computer activity (Blangsted *et al*. 2004, Chang *et al*. 2008). Since the computer activity data had to be aligned with the force, muscle effort, posture and wrist velocity and acceleration data, a sampling rate of 40 samples per second was chosen as fast enough to capture the time domain and frequency content of all data of interest.

Force

We measured keyboard force using a keyboard force plate (Asundi *et al*. 2009). Each participant's keyboard was placed on the keyboard force plate, which had three miniature compression load cells (ELFF-B4-10L; Measurement Specialties, Hampton, VA) mounted underneath it in a triangular pattern. Participants used their own keyboard during the measurement period.

We measured mouse grip force using a modified USB mouse with scroll wheel (Model 3902C693; Microsoft, Inc., Redmond, WA) modelled after the one designed by Johnson *et al*. (2000). The modified mouse had three compression load cells (ELW-D1-10L; Measurement Specialties, Hampton, VA) mounted inside and measured the thumb forces applied to the left side of the mouse. All participants were required to use the force-sensing mouse instead of their own mouse, and to use the mouse with their right hand during the measurement period.

The load cells in the keyboard and the mouse were connected to USB backplanes (NI cDAQ-9172; National Instruments, Austin Texas) that sampled the data at 10,000 samples per second using LabView (LabView v.8.5; National Instruments, Austin, TX). These data were then low-pass filtered at 20Hz (6th order Butterworth filter) and down-sampled to 40 samples per second before being saved on the personal computer. Keyboard and mouse grip force were recorded during all activities. To avoid drift over time both forces signals were automatically zeroed whenever the standard deviation of the force signal over a one second window was close to zero.

In order to normalise the force readings to each individual's strength, three 5-second maximal force contraction measurements were collected from each force-sensing device to determine the participant's maximum voluntary forces (MVFs). Separate, MVF-sensing devices with different compression load cells (Mouse Model LSB200 L2357, Range 0-875lb, Keyboard Model LSB200, Range 0-100lbs, Futek Advanced Sensor Technology Inc., Irvine, CA) were used for the MVFs so that the MVFs did not overload the load cells of the force-sensing mouse and keyboard. A static, typing maximal force measurement was collected by having participants press down as hard as they could on the 'J' key of the MVF-sensing keyboard with their right index finger. A static, mouse-based maximal force measurement was collected by having subjects squeeze the MVF-sensing mouse using the same hand and mousing posture that they used during their actual work. The MVF values were the highest one-second averages of the force signals collected from the three 5-second maximal force measurements for each force-sensing device. Subjects had approximately one minute of rest in between each contraction.

Muscle effort

Using surface electromyography (EMG), we measured muscle effort from the right and left upper trapezius (TRAP) and the right and left extensor carpi radialis (ECR) using a wireless logger system (Mega WBA; Mega Electronics LTD, Kupio, Finland). After abrading the target areas of the skin and washing these areas with alcohol, 12-mm diameter Ambu Bluesensor N-00-S surface electrodes containing highly conductive wet gel were mounted over the muscles of interest with 20 mm interelectrode spacing in accordance with published guidelines for the surface EMG of the ECR (Basmajian 1989) and of the TRAP (Jensen *et al.* 1993). The wireless EMG pre-amplifier was attached to the two electrodes and a third ground electrode. While the sensors were being applied, participants sat with their forearms pronated and perpendicular to the ground, hovering above the table, and their shoulders relaxed, to imitate the postures that would be assumed during computer use. Data were recorded at 1000 samples per second after amplification (bandwidth of 10–500 Hz). The bipolar signal was converted to an EMG amplitude signal by smoothing its absolute value through a 3 Hz second-order, zero phase, low-pass Butterworth filter. The signals were then down-sampled to 40 samples per second using a mean filtering procedure.

In order to normalise the EMG signal amplitude, prior to data collection three 5-second maximal muscle contraction measurements were collected from each muscle to determine each participant's maximum voluntary contractions (MVCs). Each muscle's MVC was the highest one-second average of the EMG amplitudes collected from the three measurements. Within each muscle, there was approximately one minute of rest in between each MVC. For the TRAP MVCs, participants sat with their arms abducted to 90 degrees and elbows flexed to 90 degrees and then attempted to abduct their arms upwards against resistance applied by the experimenter. For the ECR, participants attempted to extend and radially deviate their wrists against resistance by the experimenter while their lower arms rested on a table.

Posture, wrist velocity and wrist acceleration

We measured right and left wrist postures using twin axis electrogoniometers (Model SG65; Biometrics Ltd, Gwent, UK) that recorded wirelessly at 1000 samples per second via the same MegaWin WBA data logging system used for the muscle effort data collection. Data were digitally filtered through a 5 Hz second-order, zero phase, low-pass Butterworth filter and down-sampled to 40 samples per second. Wrist angles were the angle deviations in degrees, relative to the reference wrist posture angles defined as the position of approximately zero wrist flexion and wrist deviation determined by the experimenter while the participant's hand was open and relaxed. Wrist joint velocities and accelerations were calculated by digitally differentiating the posture data. The root mean squared (RMS) value was taken to represent each parameter.

We measured shoulder flexion, shoulder abduction, torso, neck and head postures using five data-loggers containing triaxial accelerometer data-loggers (G-Link Data Loggers; Microstrain, Inc; Williston, VT). The postural data loggers were placed on each participant's right and left arm as close to the shoulder as possible, on the torso centred above the acromial notch, on the neck centred above the C7 vertebrae, and centred on the participant's forehead (see Figure 1). Due to the 2 Mb onboard memory limitation of the data loggers, data were recorded at 25 samples per second. Once downloaded, data were passed through a 5Hz second-order, zero phase, low-pass Butterworth filter and were converted from acceleration units to degrees. Angles were calculated with respect to the reference posture defined as the posture recorded while participants stood erect looking straight ahead with their arms resting at their sides. The accelerometer axes were aligned with flexion and extension by recording data during a pure bowing motion (flexion at the hips only).

To measure shoulder rotation, we used a custom video system that calculated angles based on the projected position of black and white markers taped at the dorsal side of the wrist, the lower biceps brachii and on the acromion at the shoulder onto a video image (Bruno *et al*. 2011). Laboratory comparisons of this system with a 3D motion analysis system demonstrated good accuracy (average error of 1 degree for right rotation) for computer-related postures. Video images were collected at 30 frames per second. Position data from the images were filtered using a 5Hz fourth-order, low-pass filter.

To match recording rates of the other systems, all postural data were upsampled to 40 samples per second using a linear interpolation method.

Data processing and statistical analysis

Data processing included two steps: (1) synchronising the data collected from the different systems and (2) parsing the data to identify the data sections that corresponded to the different computer activities.

To synchronise the force, muscle effort and postural data, after all of the instrumentation was mounted and before returning to their work participants performed a series of distinctive movements that would show in the datastream of multiple systems, including bowing, abducting their shoulders and tapping on the keyboard using flexion movements of their wrist. These movements were repeated at the end of the data collection period before instrumentation was removed. These synchronisation events were readily identifiable via visual inspection and were used to align all force, muscle effort, posture and computer interaction data through cross-correlations calculated from the signals.

Once synchronised, the force, muscle effort and postural data were parsed and grouped by keyboard activities, mouse activities and idle activities. For each force, muscle effort and postural measure within each computer activity, summary statistics were calculated including the 10th, 50th and 90th percentiles of the signal amplitude, which provided a measure of the distribution of the postural data and EMG data (Jonsson 1988). The difference between the 90th and 10th percentiles provided a measure of variability. For wrist velocity and acceleration, the root mean square values were calculated as described in Marras (1992).

To test the hypothesis that forces, muscle effort, postures, velocities and accelerations differed by computer activity, one-way repeated-measures analysis of variance (ANOVA) models were fitted to the 10th, 50th and 90th percentiles and variability (90th–10th) of each summary statistic (dependent parameters). The independent parameters in each model were keyboard activity, mouse activity and idle activity, with subject set as a random variable. Post-hoc analyses used *t*-tests with Bonferroni correction for multiple comparisons to test for differences between each computer activity. All statistical analysis was performed in SAS version 9.2 (SAS Institute Inc., North Carolina).

Results

Of the 120 participants recruited and measured in this study, 118 were included in the data analysis. The remaining two participants were removed from the analysis because of technical failure of the measurement equipment.

Activity monitoring

Participants in this study spent an average of 84 min (standard deviation $= 40$ min) or 73% (standard deviation $= 16\%$) of the data collection period, interacting with their computers. Participants on average spent half as much of their time using the keyboard as using the mouse, and similar amounts of time engaging in mouse and idle activities (Table 1).

Table 1. Duration (in minutes and as percent of total time) of computer activity, non-computer activity, keyboard, mouse, and idle activity during the study period, averaged across all participants [$n = 118$], with standard deviations.

	Duration in minutes	Percent of total time	Percent of computer activity
Total time	115 (12)	–	–
Non-computer activity	31 (19)	27 (16)	–
Computer activity	84 (39.8)	73 (16)	–
Keyboard activity	18 (0.7)	16 (11)	21 (11)
Mouse activity	35 (0.7)	30 (9)	42 (11)
Idle activity	31 (0.4)	27 (8)	37 (9)

Force

Both keyboard and mouse grip forces were different across computer activity, with the applied mean and peak keyboard forces during keyboard activities averaging 1.8% (0.60 N) and 5.7% (1.95 N) of the participants' maximum force and the mean and peak mouse forces during mouse activities averaging 1.7% (0.70 N) and 3.9% (1.60 N) of the participants' maximum force (Table 2). In many cases, participants still exerted force on the keyboard during mouse or idle activities (e.g. resting the non-mousing hand on the keyboard or resting both hands on the keyboard while not typing) and forces on the mouse during keyboard or idle activities (e.g. gripping the mouse during typing or while idle). Not surprisingly, however, the keyboard forces were highest during keyboard activities and the mouse grip forces were highest during mouse activities. For keyboard forces, there were no differences in applied keyboard forces between the levels of forces experienced during mouse and idle activities. However, higher mouse grip forces were recorded during idle activities than during keyboard activities (Table 2).

Muscle effort

All right and left ECR and TRAP muscle effort parameters were different across keyboard, mouse and idle activities ($p < 0.001$). The highest muscle effort values for all right and left ECR parameters and for the 10th and 50th percentiles of right and left TRAP EMG were observed during keyboard activities. When compared to mouse activities, there was close to a 50% increase in the 10th and 50th percentiles of right trapezius muscle effort during keyboard activities. The 90th percentiles of right and left TRAP muscle efforts were largest for idle activities. Static (10th percentile) muscle effort levels during keyboard activities were almost double the levels observed during idle activities for all muscles, and mouse muscle effort levels tended to be intermediate (Figure 2). Mouse activities were associated with the lowest variability in muscle effort for all four muscles measured. The greatest muscle effort variability was observed for the left and right TRAP during idle activities.

Posture, wrist velocity and wrist acceleration

There were differences in all wrist postural values across keyboard, mouse and idle activities ($p < 0.001$). Keyboard activities were associated with the greatest right and left wrist ulnar deviation. The 50th and 90th percentiles of left and right ulnar deviation both exceed 5 degrees during keyboard use. The lowest variability and the greatest wrist extension in the right wrist were observed during mouse activities, while the lowest variability and greatest wrist extension in the left wrist were observed during keyboard activities (Figure 3). Mouse activities and idle activities promoted similar postural exposures for the left hand.

There were also significant differences in wrist velocities and accelerations across the computer activities ($p < 0.001$). Keyboard activities were associated with the greatest RMS velocity and acceleration values. Mouse activities were associated with intermediate velocity and acceleration values. The smallest RMS velocity and acceleration values were observed during idle activities (Table 3).

For the head, neck and torso, flexion/extension exposures were more non-neutral than lateral tilt exposures. Keyboard activities were associated with the greatest head extension and the smallest variability in neck and torso

Table 2. Results of F-tests for differences in keyboard force and mouse grip force in Newtons and %MVF across computer activities for the mean and peak keyboard and mouse grip forces, averaged across all participants ($n = 118$).

	Computer activity (N)			Computer activity (%MVF)		
	Keyboard	Mouse	Idle	Keyboard	Mouse	Idle
Keyboard forces						
Mean	0.60 (0.06)^{A}	0.23 (0.04)^{B}	0.23 (0.04)^{B}	1.8 (0.19)^{A}	0.7 (0.12)^{B}	0.7 (0.12)^{B}
Peak	1.95 (0.12)^{A}	0.75 (0.09)^{B}	0.86 (0.09)^{B}	5.7 (0.46)^{A}	2.2 (0.30)^{B}	2.5 (0.31)^{B}
Mouse grip forces						
Mean	0.02 (0.01)^{C}	0.70 (0.03)^{A}	0.15 (0.01)^{B}	0.03 (0.02)^{C}	1.7 (0.12)^{A}	0.4 (0.04)^{B}
Peak	0.14 (0.02)^{C}	1.60 (0.05)^{A}	0.66 (0.04)^{B}	0.3 (0.06)^{C}	3.9 (0.28)^{A}	1.5 (0.11)^{B}

Note: Significant differences were found for all parameters tested ($p < 0.001$). Different letters indicate that those computer activities differ based on post-hoc analyses. "A" represents the highest force or force MVF parameter values, with "B" and "C" representing smaller values. Values in parentheses are standard errors.

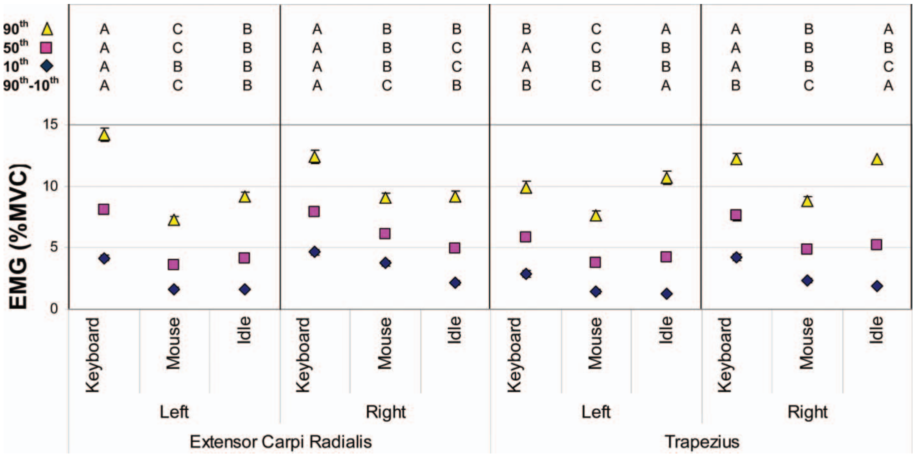

Figure 2. Mean (standard error) 10th (diamond), 50th (square) and 90th (diamond) percentiles of left and right extensor carpi radialis and trapezius muscle effort expressed as a %MVC averaged across all participants ($n = 118$). Letters (A, B, C) indicate that significant differences across computer activities were found based on an F-test from a repeated measures ANOVA. Different letters indicate which computer activities were different from one another. 'A' represents the highest muscle effort values for each muscle effort parameter and muscle, with 'B' and 'C' indicating smaller values. When no significant differences were found, it is indicated by p-values greater than 0.05.

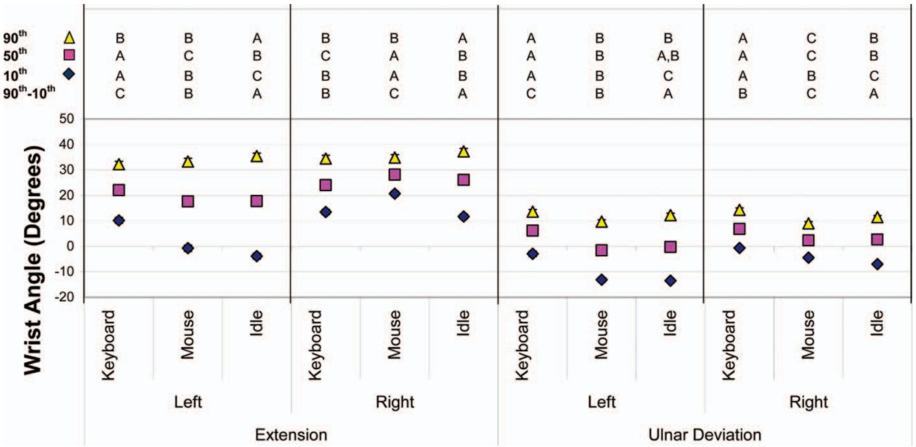

Figure 3. Mean (standard error) 10th (diamond), 50th (square) and 90th (diamond) percentiles of wrist postures averaged across all participants ($n = 118$). Letters (A, B, C) indicate that significant differences across computer activities were found based on an F-test from a repeated measures ANOVA. Different letters indicate which computer activities were different from one another ($p < 0.001$). 'A' represents the values for each wrist posture parameter, with 'B' and 'C' representing smaller values. When no significant differences were found, it is indicated by p-values greater than 0.05.

exposures. Mouse activities were associated with the smallest variability in head flexion/extension and lateral tilt, while the greatest variability in all head, neck and torso postures was observed during idle activities (Figure 4).

Rotation of the shoulder was the shoulder posture most affected by computer activity, with a change from approximately 25 degrees internal rotation during keyboard activities to approximately 15 degrees external rotation during mouse activities ($p < 0.001$). Keyboard activities were associated with the smallest variability for all shoulder postures on the left side. During mouse activities, the greatest external rotation and the smallest variability were observed in the right shoulder. Idle activities were associated with the greatest variability for all right and left shoulder postures (Figure 5).

Discussion

The goal of this study was to determine if there were differences in forces, muscle efforts, postures, velocities and accelerations across keyboard, mouse and idle activities, based on direct measurements of these physical exposures

Table 3. Mean (standard error) right and left wrist velocities and accelerations across all participants ($n = 118$).

	Keyboard	Mouse	Idle
Left wrist			
Flexion/extension			
Velocity (°/s)	28 (9)^{A}	24 (4)^{B}	13 (7)^{C}
Acceleration (°/s^2)	408 (151)^{A}	265 (50)^{B}	146 (82)^{C}
Radial/Ulnar deviation			
Velocity (°/s)	16 (5)^{A}	15 (3)^{B}	8 (4)^{C}
Acceleration (°/s^2)	214 (67)^{A}	156 (93)^{B}	93 (44)^{C}
Right wrist			
Flexion/extension			
Velocity (°/s)	36 (13)^{A}	27 (6)^{B}	13 (9)^{C}
Acceleration (°/s^2)	568 (239)^{A}	315 (79)^{B}	169 (116)^{C}
Radial/Ulnar deviation			
Velocity (°/s)	21 (6)^{A}	16 (3)^{B}	10 (4)^{C}
Acceleration (°/s^2)	297 (100)^{A}	180 (43)^{B}	127 (52)^{C}

Note: Letters (A, B, C) indicate that significant differences across computer activities were found based on an F-test from a repeated measures ANOVA. Different letters indicate which computer activities were different from one another ($p < 0.001$). "A" represents the highest wrist velocity or acceleration values for each parameter, with "B" and "C" representing smaller values. Significant differences were found across all computer activities for all velocities and accelerations.

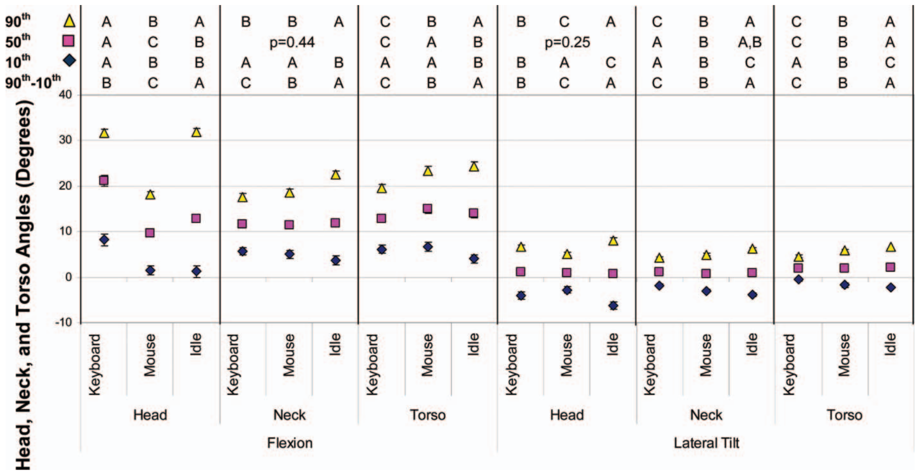

Figure 4. Mean (standard error) 10th (diamond), 50th (square) and 90th (diamond) percentiles of head, neck and torso postures averaged across all participants ($n = 118$). Letters (A, B, C) indicate that significant differences across computer activities were found based on an F-test from a repeated measures ANOVA. Different letters indicate which computer activities were different from one another ($p < 0.001$). 'A' represents the highest values for each parameter, with 'B' and 'C' representing smaller values. When no significant differences were found, it is indicated by p-values greater than 0.05.

collected in a field study of computer workers. We observed differences across activities in nearly all of the forces, muscle efforts, postures, velocities and accelerations studied. Keyboard activities were associated with increased muscle efforts of all muscles measured, and the smallest variability of left wrist postures. Mouse activities were associated with the greatest right external shoulder rotation. The smallest variability of all muscle efforts and right wrist postures was also observed during mouse activities. Idle activities led to the largest variability of muscle effort of the right and left TRAP, and of all postures. The observation that there are differences in physical exposures across activities, which has already been reported using data from the laboratory (Dennerlein and Johnson 2006a), has now also been reported using physical exposures collected in a field setting.

The information reported here may provide some insight into the relationship between computer activities, physical exposures and MSDs. A consistent finding in this study was that we observed the greatest variability in all muscle efforts and postures during idle activities. Similarly, we also reported that the left wrist and shoulder postures experienced more variability during mouse activities than keyboard activities. This may be explained by considering

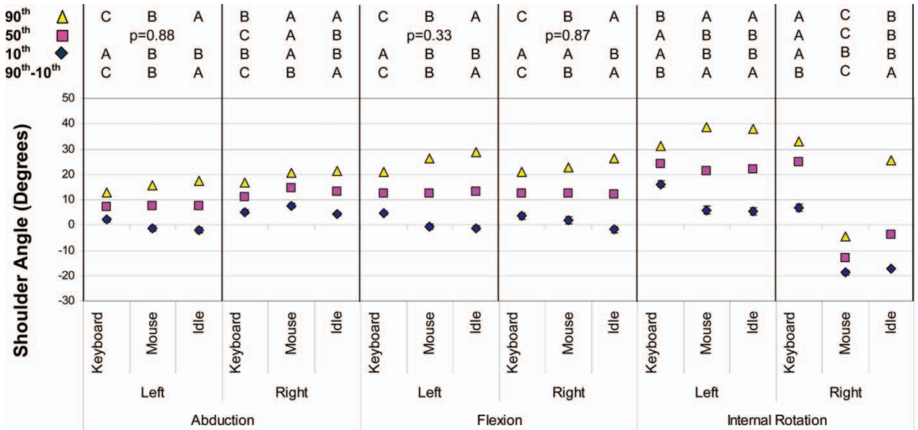

Figure 5. Mean (standard error) 10th (diamond), 50th (square) and 90th (diamond) percentiles of shoulder postures averaged across all participants ($n = 118$). Letters (A, B, C) indicate that significant differences across computer activities were found based on an *F*-test from a repeated measures ANOVA. Different letters indicate which computer activities were different from one another ($p < 0.001$). 'A' represents the highest values for each shoulder angle posture, with 'B' and 'C' representing smaller values. When no significant differences were found, it is indicated by *p*-values greater than 0.05.

that the left hand is only constrained during keyboard activities, while during mouse activities the left hand may have similar freedom from constraint as during idle activities. The findings of increased variability during idle activities corroborate previous findings by Richter *et al.* (2009), who observed increased variability in muscle effort during non-computer office work compared to during computer work in several wrist and shoulder muscles in a group of office workers. Biologically, it is thought that increased variability provides active muscles with a chance to reperfuse after periods of ischemia caused by higher-intensity forces or postures (Visser and van Dieen 2006), reducing damage to working tissues. For this reason, computer users who perform more idle activities during computer work or perform more non-computer work may experience protection against MSD development. Conversely, perhaps it could be the decreased variability in muscle effort, in right wrist postures or in right shoulder external rotation observed during mouse activities that is increasing this risk (Andersen *et al.* 2003, Ijmker *et al.* 2007). Others have suggested this hypothesis as well (Wahlstrom 2005, Mathiassen 2006). Based on this theory, keyboard activities may also be putting computer users at risk for MSDs for the right arm, since keyboard activity is additive to mouse activity and is reported to increase muscle activity, but also to the left arm since keyboard is the constraining activity of the left wrist. However, the relatively small amount of time spent on keyboard activities compared to mouse activities (Chang *et al.* 2008) may be why keyboard activities do not appear as a risk factor in the epidemiologic literature (e.g. Ijmker *et al.* 2007, 2011).

While idle activities may be beneficial for increasing variability within muscle efforts and postures, we also observed that participants exerted forces on the keyboard and especially on the mouse during idle activities. This may indicate that computer users rested their hands on the keyboard during mouse use and gripped the mouse during idle activities. This type of 'hovering' was also observed in a previous study (Homan and Armstrong 2003). Since keyboard and mouse activities were both shown to be associated with greater static and non-neutral wrist and shoulder postures than idle activities in this study, 'hovering' would indicate that computer users experience greater static and non-neutral wrist and shoulder postures than necessary during idle activities, reducing the recovery and intervention potential of these idle periods.

Although we saw differences in the 10th, 50th and 90th percentiles of many physical exposures across computer activities, it is difficult to draw conclusions on whether these differences were significant enough to contribute to MSD development. For example, although keyboard activities showed an almost 50% increase in the 10th and 50th percentiles of right trapezius muscle effort when compared to mouse activities, all values for trapezius muscle effort were relatively low (less than 15%). We observed the greatest postural differences in the 50th percentile of right shoulder rotation, which changed from 25 degrees internal rotation during keyboard activities to 15 degrees external rotation during mouse activities. However, there is currently no literature relating particular shoulder rotation angles to MSDs. The one physical exposure that has been associated with increased risk of MSDs based on previous studies is ulnar deviation greater than 5 degrees (Marcus *et al.* 2002). In this study, we observed that median right and left ulnar deviation was greater than 5 degrees only during keyboard activities, indicating that increased keyboard activity may put computer users at risk for developing MSDs.

The information on the differences in muscle efforts, forces, postures, velocities and accelerations reported in this study could be used in future studies to generate estimates of any individual's physical exposures based on the computer activity patterns of that individual. If an individual's computer activity patterns are measured over long periods of time, this method could be used to describe the variation in exposures experienced by that individual. In order to generate estimates of physical exposures based on computer activity patterns, we rely first on the assumption that the physical exposures recorded during this two-hour measurement period are representative of physical exposures generated over longer periods of time. A number of studies have shown that this assumption is valid for field measurements of physical exposures during computer use (Johnson *et al.* 2000, Asundi *et al.* 2010a,b). We also must assume that the physical exposures are consistently the same across all periods of keyboard activities, mouse activities and idle activities over time, so that it is truly the variation in patterns of computer activities driving the variations in physical exposures. Although we have no reason to believe that this would not be the case, this question has not been specifically investigated and could be a subject for future research.

If certain computer activities are causing users to be exposed to high forces, muscle efforts, postures, velocities and accelerations that may cause MSDs, this may provide opportunities for intervention. One option would be to adjust the patterns of computer activities that computer users are performing. For example, computer users could be encouraged to perform keyboard shortcuts to reduce mouse activities. The other option would be to modify the forces, muscle efforts, postures, velocities and accelerations experienced during the different computer activities. For example, moving the mouse to the centre of the user's desk, rather than on the outside of the keyboard, could reduce external shoulder rotation (Dennerlein and Johnson 2006b). Some of the tasks required by the right arm could also be remapped to the left arm.

Because there were no differences in median shoulder flexion, shoulder abduction, neck flexion, and head tilt across computer activities, these physical exposures cannot be determined based on computer usage patterns. The finding for shoulder posture is different than what was expected based on the previous laboratory study, which found increased shoulder abduction and flexion during tasks requiring mouse activities (Dennerlein and Johnson 2006a). This may indicate that during real computer work users adjust their postures within their workstation constraints so that their shoulders can assume more neutral postures during all computer activities, whereas for the laboratory study the mouse was set at a fixed area on the work surface and participants did not adjust the mouse's position.

This study benefits from several strengths. We were the first to measure forces, muscle efforts, postures, velocities and accelerations of computer workers performing different computer activities directly, for long periods of time, in a real work environment. The data collection equipment was chosen to be unobtrusive to participants during the study period so that our measurements were taken during a realistic work period (Figure 1). By identifying and selecting our data based on computer activity, we were able to test the hypothesis that forces, muscle efforts, postures, velocities and accelerations were different across computer activities within the computing task, including idle activities. Finally, the participants recruited for this study were chosen because they had the same types of jobs and performed similar tasks as participants in the studies used to validate the definitions for activity used in this study, and therefore we believe that the previous definitions can be applied to the current study.

The results and conclusions of this study should be taken with consideration of the study's limitations. This study was designed to measure forces, muscle efforts, postures, velocities and accelerations only during computer work. Wireless systems were chosen to allow participants to move freely and to leave their workstations, but for this reason data were only collected while participants were close to their computers. Participants were also recruited because they spent most of their time working at a computer, and were asked to choose a time for the measurement that would be representative of a normal work day. Therefore, we cannot test any hypotheses about differences between forces, muscle efforts, postures, velocities and accelerations during computer use compared to during other, non-computer activities. The hypotheses that we did test using the data that we collected required many individual statistical tests, and therefore we might expect occasional falsely-positive results. However, many of the difference that we found were highly significant ($p < 0.001$), and thus we do not expect these differences to be a consequence of type I error. We recruited office workers in an academic setting, but expect that our results could be generalised to other groups of computer workers. However, our results are likely not generalisable to specialised computer workers, such as radiologists, data entry typists or graphic designers, who may have different workstation set-ups, input devices or computer activity demands during their computer use. Finally, we required all of our participants to use our external force-sensing mouse during the data collection. Some participants mentioned that this mouse was larger or heavier than the mouse they were accustomed to using, which could have affected their exposures during mouse activities. Also, it is possible that alternative pointing devices would lead to different forces, muscle efforts, postures, velocities and accelerations during mouse activities than those reported here.

In conclusion, we determined that many field-measured forces, muscle efforts, postures, velocities and accelerations were different during keyboard activities, mouse activities and idle activities, with keyboard activities associated with increased muscle efforts of all muscles measured and the smallest variability of left wrist postures and mouse activities associated with the largest external shoulder rotation and decreased variability of right wrist postures. The greatest variability of all muscle efforts and postures was observed during idle activities. Since these physical exposures are different across computer activities, information about a computer user's patterns of computer activities could be used to characterise changes in many physical exposures associated with computer use, providing data that could be used in epidemiological studies on computer use and MSDs as well as opportunities for intervention.

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