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To determine the number of direct measurements needed to obtain a representative estimate of typing force and wrist kinematics, continuous measures of keyboard reaction force and wrist joint angle were collected at the workstation of 22 office workers while they completed their own work over three days, six hours per day. Typing force and wrist kinematics during keyboard, mouse and idle activities were calculated for each hour of measurement along with variance in measurements between subjects and between day and hour within subjects. Variance in measurements between subjects was significantly greater than variance in measurements between days and hours within subjects. Therefore, we concluded a single, one-hour period of continuous measures is sufficient to identify differences in typing force and wrist kinematics between subjects. Within subjects, day and hour of measurement had a significant effect on some measures and thus should be accounted for when comparing measures within a subject.

Practitioner Summary: The dose response relationship between exposure to computer related biomechanical risk factors and musculoskeletal disorders is poorly understood due to the difficulty and cost of direct measures. This study demonstrates a single hour of direct continuous measures is sufficient to identify differences in wrist kinematics and typing force between individuals.

Keywords: exposure assessment; upper extremities; musculoskeletal disorders; electrogoniometers; force plate

Introduction

While the association between computer use and musculoskeletal disorders is well documented (Tittiranonda *et al.* 1999, Gerr *et al.* 2002, Marcus *et al.* 2002), the dose response relationship between exposure to biomechanical risk factors associated with computer work and musculoskeletal disorders is poorly understood (Gerr and Fethke 2011, Ijmker *et al.* 2011). In a review by Gerr *et al.* (2004), it was concluded that many epidemiologic studies evaluating the association between upper extremity musculoskeletal symptoms and computer user joint angles are limited by imprecise or biased measures of exposure.

Biomechanical exposures of the upper extremity are best measured directly (Spielholz *et al.* 2001), however a major limitation of direct measures is their cost and complexity. Trask *et al.* (2007) estimated cost per direct measurement was 10–20 fold greater compared to interview based measurements. Thus, before direct measures of computer-related biomechanical exposures are implemented on a large scale, typical of epidemiologic studies, effective and cost efficient sampling methods need to be identified.

Epidemiologic studies on computer work aim to explain differences in health outcomes through differences in computer-related exposures. An effective sampling strategy would sufficiently sample an individual's computer exposure to account for within subject variability (e.g. variability across time, activities and other factors) such that differences in computer exposures between subjects can be identified. A cost effective sampling strategy would obviously minimise the duration and frequency of the samples needed per subject to achieve an effective sampling strategy.

Variability of physical risk factors during computer use in the office environment has been examined in a few studies. Johnson *et al.* (2000) studied the variability of mouse grip and button forces associated with computer use. From their results, they concluded that mouse force variability was random across hours and days and that only 43 grip episodes generated within a 42 minutes window accurately represent a subject's mechanical exposure to forces applied to the mouse. Ortiz *et al.* (1997) examined variability in upper extremity, head and neck joint angle

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measurements among 19 video terminal display (VDT) operators. Using a manual goniometer, joint angles were measured by two observers, on three different days, at two different times of the day. They reported the variance in joint angle measurements between subjects was significantly greater than the variance in joint angle measurements within a subject (across the different observers, days and times of day) and therefore they concluded a single measure of joint angle provided a representative sample for the joint angle.

In this study, we characterised variability in force during typing and wrist kinematics (joint angle, range of motion and joint acceleration) during keyboard, mouse and idle activities, across subjects, days and hours of the day. We evaluated force and wrist kinematics as these biomechanical factors have been associated with computer-related musculoskeletal complaints (Hunting *et al.* 1981, Feuerstein *et al.* 1997, Rempel *et al.* 1999, Liu *et al.* 2003). We evaluated wrist kinematics during keyboard, mouse and idle computer activities separately as these activities have different biomechanical exposure profiles (Dennerlein and Johnson 2006).

From the data, we tested two hypotheses. The first hypothesis was: for each activity, variance in exposure magnitude measures of typing force and wrist kinematics between subjects is significantly greater than variance in exposure magnitude measures of typing force and wrist kinematics across multiple days and multiple hours of the day within subjects. If the variance in measurements between subjects is greater than the variance within subjects, then a single measurement, chosen from any day and any hour of the day, is sufficient to characterise differences in exposure magnitudes between individuals.

The second hypothesis was: for each activity, exposure magnitude measures of typing force and wrist kinematics of an individual do not vary significantly between days or hours of the day. If an individuals exposure magnitude measurements vary across days or hours (i.e. it is not stable over time), then the day and/or hour of measurement would need to be accounted for in studies which collect multiple measurements from the same subject (e.g. studies with a repeated measures design).

Methods

A total of 10 men and 12 women, ranging in age from 23 to 66 (mean = 33.4, SD = 11.0), recruited from a single worksite, agreed to participate in this study. Participants included faculty, graduate student researchers and research associates. As the study focused on computer use, measurements were limited to days in which the user expected to be at their computer for more than four hours. This cut-off was selected based on the findings of Marcus *et al.* (2002) in which four hours of self-reported computer use was associated with an increased risk of reporting hand and wrist complaints.

Subject workstations featured height and angle adjustable support surfaces (which supported their mouse and keyboard) for all but two of the subjects. The two other subjects had fixed height support surfaces. All workstations included height adjustable chairs and monitors. Mean anthropometric measures for the participants are presented in Table 1. The Harvard School of Public Health's Office of Human Research Administration approved all protocols and participant consent forms. All participants read and signed the written consent form prior to participation in the study.

Table 1. Mean (SD) participant anthropometry and workstation set up ($n = 22$).

	Mean (SD)
Anthropometry	
Age (year)	33 (11)
Height (cm)	169 (10)
Weight (kg)	68 (14)
Shoulder breadth (cm)	35 (3)
Right arm length (cm)	30 (3)
Right forearm length (cm)	25 (2)
Right hand length (cm)	18 (1)
Right hand width (cm)	8 (1)
Workstation set up	
Vertical keyboard height relative to elbow (cm)	11 (4)
Horizontal keyboard position relative to edge of desk (cm)	14 (4)
Angle of keyboard/mouse platform (°)	12 (5)

Experimental design

The experimental design was a repeated-measures study in which we quantified typing forces and wrist kinematics over three days for six continuous hours per day at the participant's own workstation as they completed their actual work tasks. In order to capture days consisting mostly of computer work, the three days of measurement were not necessarily consecutive. Participants were instructed to work as they would normally, including attending meetings, honoring breaks and going to lunch. No adjustments were made to the participant's workstation; chair height, monitor height and the adjustable support surface were left as set by the participant (Table 1).

Keyboard reaction force data and bilateral wrist kinematics data, collected over six hours (HOUR) on three different days (DAY), were divided into one hour blocks for a total of 18 observations per participant and 396 (18×22) total observations. The one hour minimum time window was selected based on practicality and human subject-based constraints. Instrumenting subjects is most feasible when it corresponds with the workers' natural breaks in the work-day (e.g. break to break, half-day or full-day). Furthermore, based on pilot data and previous studies (Johnson *et al*. 2000, Chang *et al*. 2008), the one hour time frame was shown to be long enough to reliably include periods of keyboard, mouse and idle interactions during actual work.

Sample size calculation

Since individuals are being compared to themselves (repeated measures design) in testing the primary hypotheses, we anticipated needing 20 subjects, in order to have 84% power ($\alpha = 0.05$) to detect a difference in the mean exposures of 0.7 standard deviations between times of the day and days of the week. We increased the sample size by 10% (22 subject's total) to account for drop outs.

Instrumentation and data processing

Vertical forces applied to the keyboard were measured using a thin profile force plate, placed under the keyboard (Asundi *et al*. 2009). Force values were sampled at 200 Hz by a digital data acquisition card (NI cDAQ-9172; National Instruments; Austin, TX) and recorded onto a personal computer. The force data were then low pass filtered with a cut-off frequency of 20 Hz, re-sampled to 40 Hz and processed to minimise inertial artefacts (Asundi *et al*. 2009). The baseline force was continually corrected throughout the data collection to account for drift in the force sensors due to changes in temperature over the day, shifts in the location of the keyboard on the force plate and other physical perturbations (e.g. paper resting on the keyboard). The algorithm calculated 1st percentile force value over a two seconds moving window and subtracted that value from the force signal. This algorithm was validated in the laboratory by simulating such disturbances and through visual inspection of the data.

Extension/flexion and radial/ulnar deviation of the wrists were measured using twin axis electro-goniometers (SG65 Biometrics Ltd, London, UK) affixed to the back of the right and left hand of each participant. The system had a resolution of less than 0.1°, accuracy of $\pm 2^\circ$ measured over a range of $\pm 90^\circ$ with minor crosstalk between flexion/extension and radial/ulnar movement planes when place over the wrist (Johnson *et al*. 2002). Joint angles were digitally recorded at 250 Hz to a datalogger (ME 6000, Mega Electronics, Finland), low pass filtered with a 10 Hz cut-off and re-sampled to 40 Hz. Zero radial/ulnar deviation was defined when the third metacarpal aligned with the capitate and the lateral epicondyle, while zero flexion/extension was defined when the lateral side of the 5th metacarpal, aligned with the ulnar styloid and the lateral epicondyle. Filtered joint angle data were digitally double differentiated to obtain joint accelerations.

Input device activities were monitored using a custom written software program installed on each participant's computer (Dennerlein and Johnson 2006). The program, written in LabView (National Instruments, Austin, TX), recorded the start time and duration of each discrete key-strike and mouse event (moving the mouse, clicking any of the buttons or operating the scroll wheel). Keyboard activities were defined as isolated key-strikes (i.e. key-strikes that were not proceeded or followed by any event within two seconds) or episodes of multiple key-strikes occurring with no more than two seconds between successive key-strikes. Mouse activities were defined in a similar manner as either isolated mouse events or as episodes of multiple mouse events occurring with no more than two seconds between successive events. Idle computer activities were defined as those periods greater than two seconds but less than 30 seconds in which no keyboard or mouse activities occurred. Periods greater than 30 seconds in which no keyboard or mouse activities occurred were categorised as non-computer activities. The cut-off limits used above were defined based on the work of Chang *et al*. (2008).

Data analysis

Each continuous, hour long block of wrist joint angle and joint acceleration data were parsed according to keyboard, mouse and idle computer tasks as described above. Each continuous hour long block of force data were parsed according to keystrokes.

Parsed typing force data were collapsed into two summary measures: median (50th percentile) and peak (90th percentile) force values; parsed wrist kinematics data were collapsed into three summary measures: median (50th percentile) wrist joint angle, range of motion (ROM = 95th – 5th percentile) and root mean square (RMS) of wrist joint accelerations. For presentation purposes, mean and standard deviations across participants were calculated for each exposure metric for each type of activity (keyboard, mouse and idle). Mean and standard deviations across all participants were also calculated for each exposure metric, for each type of task, for each day of measurement (DAY) and for each hour of measurement (HOUR).

Wrist kinematics summary measures (median joint angle, joint ROM and RMS joint acceleration) during keyboard, mouse and idle computer activity were compared by repeated measures analysis of variance. Post hoc Tukey HSD follow-up tests were used to complete pair-wise comparisons if a significant group effect was found.

Total variance was partitioned (Glantz 2002) into between-subject variance and within-subject variance ($\sigma_{\text{total}} = \sigma_{\text{between subjects}} + \sigma_{\text{within subjects}}$). To evaluate if variance between subjects is significantly greater than variance within subjects, variances were compared using the *F*-test statistic, calculated as the ratio of $\sigma_{\text{between subjects}}$ to $\sigma_{\text{within subjects}}$. Within-subject variance was further partitioned into variance due to DAY, HOUR, the interaction between DAY and HOUR and the residual variance for each of these variables ($\sigma_{\text{within subjects}} = \sigma_{\text{day}} + \sigma_{\text{hour}} + \sigma_{\text{day*hour}} + \sigma_{\text{res (day)}} + \sigma_{\text{res (hour)}} + \sigma_{\text{res (day*hour)}}$).

To evaluate if exposure magnitudes varied significantly across DAY of measurement or HOUR of measurement, two additional *F*-test statistics were calculated; the first as the ratio of σ_{day} to $\sigma_{\text{res (day)}}$ and the second as the ratio of σ_{hour} to $\sigma_{\text{res (hour)}}$. *F*-test statistics, with corresponding degrees-of-freedom were compared to *F* distribution tables to determine significance. For all tests, significance was set at $p < 0.05$.

Variance estimates and the analysis of variance was completed using JMP software (Version 7.0; SAS Institute, Cary, NC). *F*-test statistics were calculated in MS Excel 2003 (Microsoft, Redmond, WA).

Results

Observations

Due to scheduling conflicts, instrumentation issues or periods of no computer interaction within an hour long episode, some observations (i.e. individual hour long block of typing force data or wrist kinematics data) for each exposure metric were either excluded or lost. Specifically, 18 observations were lost due to early participant withdrawal. One participant withdrew after the first day and a second participant withdrew after the second day. Both participants withdrew due to time constraints. Eight observations contained no episodes of mouse, keyboard or idle activities. In addition to these eight observations, one observation contained no episodes of idle activities, 13 observations contained no episodes of keyboard activities and one observation contained no episodes of mousing activities. Instrumentation issues accounted for additional lost outcome measurement observations.

The total number of outcome measurement observations ranged between 252 observations (64%) of radial deviation exposures of the right wrist during keyboard activities and 364 observations (92%) of radial deviation exposures of the right and left wrist during mousing activities. Degrees of freedom were adjusted accordingly.

On average, each hour long observation included 29.7 (SD = 6.6) minutes of computer use, consisting of 4.9 (SD = 3.1) minutes of keyboard activities, 15.1 (SD = 5.3) minutes of mouse activities and 9.7 (SD = 3.2) minutes of idle activities.

Typing force

Mean 50th percentile typing force across all participants was 1.2 N (SD = 0.4 N). Mean 90th percentile typing force was 3.2 N (SD = 1.0 N).

Between subject variance in median and peak typing force was significantly greater ($p < 0.1$) than within subject variance across days and hours of the day (Table 3).

A significant effect ($p = 0.05$) due to day of measurement was observed for peak typing force (up to a 0.3N difference in means between day 1 and day 3), but not for median typing force ($p = 0.07$, Table 4). No significant effect due to hour of measurement ($p > 0.77$) was observed for either median or peak typing force (Table 5).

Median wrist joint angle

Activity (keyboard, mouse and idle) had a significant effect ($p < 0.01$) on extension joint angles of the left wrist and ulnar deviation joint angles of the left and right wrist. Extension joint angles of the right wrist, however, did not differ significantly ($p = 0.47$) across keyboard, mouse and idle activities (Table 2). Median ulnar deviation joint angles for both the left and right wrist were greater (with differences between 5° and 7°) during keyboard activities compared to mouse and idle activities.

For all three activities, between subject variance in median wrist extension and ulnar deviation joint angles of both the left and right wrist was significantly larger ($p < 0.01$) than within subject variance across days and hours (Table 3).

Day of measurement had a significant effect ($p < 0.01$) on left wrist extension during mouse activities and during idle activities (Table 4). Differences in means of up to 5° were observed across days (between day 2 and days 1 and 3). Hour of measurement had a significant effect ($p < 0.01$) on right wrist extension during mouse activities (Table 5). Differences in means of up to 3° were observed across hours of the day (between hours 1 and 2 and hours 4 and 5).

Range of motion

Activity had a significant effect ($p < 0.01$) on extension and ulnar deviation range of motion for both the left and right wrist. Range of motion of the right wrist was largest during idle activities and smallest during mouse activities ($p < 0.05$). Range of motion of the left wrist was smallest during keyboard activities ($p < 0.05$), and similar between mouse activities and idle activities ($p > 0.05$).

For all three activities, between subject variance in extension and ulnar deviation range of motion of both the left and right wrist was significantly larger ($p < 0.01$) than within subject variance across days and hours (Table 3).

Day of measurement had a significant effect ($p < 0.01$) on ulnar deviation range of motion of the right wrist during keyboard activities (Table 4). Differences in means of up to 2° were observed across days (between day 1 and days 2 and 3). There did not appear to be an order effect associated with day of measurement. Hour of measurement did not have a significant effect on range of motion (Table 5).

Wrist joint accelerations

Activity had a significant effect ($p < 0.01$) on extension and ulnar deviation accelerations for both the left and right wrist (Table 2). Joint accelerations were greatest during keyboard activities, with values approximately 2–4 times greater than joint accelerations during mouse activities.

For all three activities, between subject variance in extension and ulnar deviation joint acceleration of both the left and right wrist was significantly larger ($p < 0.01$) than within subject variance across days and hours (Table 3).

Neither day nor hour of measurement had a significant effect on joint accelerations (Tables 4 and 5).

Table 2. Mean (SD) wrist kinematics during keyboard, mouse and idle activities.

	Left wrist				Right wrist			
	Keyboard	Mouse	Idle	*p*-values*	Keyboard	Mouse	Idle	*p*-values*
Extension		($n = 21$)				($n = 20$)		
50th$^{\%tile}$ posture (°)	35 (14)^A	27 (15)^B	26 (14)^B	**<0.01**	35 (11)^A	37 (8)^A	35 (8)^A	0.47
Range of motion (°)	38 (12)^B	64 (12)^A	68 (11)^A	**<0.01**	32 (6)^B	23 (7)^C	48 (11)^A	**<0.01**
RMS acceleration (°/sec^2)	515 (138)^A	249 (98)^C	349 (137)^B	**<0.01**	830 (258)^A	200 (60)^C	363 (134)^B	**<0.01**
Ulnar deviation		($n = 22$)				($n = 22$)		
50th$^{\%tile}$ posture (°)	11 (17)^A	4 (17)^B	5 (17)^B	**<0.01**	16 (9)^A	11 (9)^B	11 (9)^B	**<0.01**
Range of motion (°)	25 (6)^B	39 (14)^A	41 (14)^A	**<0.01**	21 (5)^B	19 (3)^C	25 (5)^A	**<0.01**
RMS acceleration (°/sec^2)	339 (116)^A	181 (128)^C	242 (155)^B	**<0.01**	392 (168)^A	144 (36)^B	194 (73)^B	**<0.01**

Notes: *p-values from repeated measures analysis of variance (ANOVA). Bold values indicate significant main effects of activity type ($p < 0.05$). ^{A}Superscripts indicate results of Tukey HSD follow-up test. Values with common superscripts are not significantly different ($p > 0.05$). For each wrist, means with different superscripts are significantly different.

Table 3. Variances between subjects and variances across day and hour within subjects in typing force and wrist kinematic measures during keyboard, mouse and idle activities.

		Left wrist			Right wrist		
		Between subjects	Within subjects	*p*-value*	Between subjects	Within subjects	*p*-value*
Keyboard activities	*Typing force*	Both hands ($n = 22$)					
	50th$^{\%tile}$ force $(N)^2$	**3.1**	**0.1**	**<0.01**			
	90th$^{\%tile}$ force $(N)^2$	**17.8**	**0.5**	**<0.01**			
	Extension		($n = 21$)			($n = 20$)	
	50th$^{\%tile}$ posture $(°)^2$	**2763**	**88**	**<0.01**	**2010**	**51**	**<0.01**
	Range of motion $(°)^2$	**2319**	**248**	**<0.01**	**668**	**81**	**<0.01**
	RMS acceleration $(°/sec^2)^2$	**295,511**	**18,330**	**<0.01**	**1,139,462**	**21,298**	**<0.01**
	Ulnar deviation		($n = 22$)			($n = 22$)	
	50th$^{\%tile}$ posture $(°)^2$	**3808**	**84**	**<0.01**	**1314**	**43**	**<0.01**
	Range of motion $(°)^2$	**651**	**150**	**<0.01**	**400**	**24**	**<0.01**
	RMS acceleration $(°/sec^2)^2$	**194,142**	**26,113**	**<0.01**	**459,487**	**5698**	**<0.01**
Mouse activities	*Extension*		($n = 21$)			($n = 20$)	
	50th$^{\%tile}$ posture $(°)^2$	**3786**	**161**	**<0.01**	**1147**	**36**	**<0.01**
	Range of motion $(°)^2$	**2070**	**356**	**<0.01**	**842**	**91**	**<0.01**
	RMS acceleration $(°/sec^2)^2$	**155,642**	**9897**	**<0.01**	**58,340**	**3499**	**<0.01**
	Ulnar deviation		($n = 22$)			($n = 22$)	
	50th$^{\%tile}$ posture $(°)^2$	**5120**	**104**	**<0.01**	**1518**	**45**	**<0.01**
	Range of motion $(°)^2$	**3476**	**162**	**<0.01**	**166**	**11**	**<0.01**
	RMS acceleration $(°/sec^2)^2$	**289,551**	**13,515**	**<0.01**	**19,172**	**3941**	**<0.01**
Idle activities	*Extension*		($n = 21$)			($n = 20$)	
	50th$^{\%tile}$ posture $(°)^2$	**3444**	**142**	**<0.01**	**992**	**55**	**<0.01**
	Range of motion $(°)^2$	**1553**	**282**	**<0.01**	**1700**	**175**	**<0.01**
	RMS acceleration $(°/sec^2)^2$	**275,679**	**18,884**	**<0.01**	**277,866**	**16,922**	**<0.01**
	Ulnar deviation		($n = 22$)			($n = 22$)	
	50th$^{\%tile}$ posture $(°)^2$	**5221**	**88**	**<0.01**	**1259**	**42**	**<0.01**
	Range of motion $(°)^2$	**3214**	**154**	**<0.01**	**338**	**31**	**<0.01**
	RMS acceleration $(°/sec^2)^2$	**416,893**	**21,358**	**<0.01**	**82,205**	**7086**	**<0.01**

Note: *p*-values determined from *F*-distribution tables. Bold values indicate between subject variance is significantly larger ($p < 0.05$) than within subject variance.

Table 4. Mean (SD) typing force and wrist kinematics by day of measurement for keyboard, mouse and idle activities.

		Left wrist				Right wrist			
		Day 1	Day 2	Day 3	*p*-value*	Day 1	Day 2	Day 3	*p*-value*
Keyboard activities	*Typing force*		For both hands ($n = 20$)						
	50th$^{\%tile}$ force (N)	1.2 (0.5)	1.5 (0.4)	1.1 (0.4)	0.07				
	90th$^{\%tile}$ force (N)	**3.3 (1.1)**	**3.2 (1.2)**	**3.0 (1.0)**	**0.05**				
	Extension		($n = 16$)				($n = 17$)		
	50th$^{\%tile}$ posture (°)	34 (17)	36 (10)	33 (15)	0.24	35 (12)	36 (12)	35 (13)	0.58
	Range of motion (°)	40 (16)	40 (14)	34 (13)	0.15	33 (9)	31 (8)	31 (6)	0.57
	RMS acceleration (°/sec^2)	520 (158)	528 (130)	516 (140)	0.13	826 (267)	827 (276)	823 (274)	0.68
	Ulnar deviation		($n = 20$)				($n = 20$)		
	50th$^{\%tile}$ posture (°)	11 (19)	7 (13)	12 (18)	0.15	16 (9)	15 (11)	18 (12)	0.53
	Range of motion (°)	28 (12)	27 (14)	24 (7)	0.24	**23 (7)**	**21 (5)**	**21 (4)**	**<0.01**
	RMS acceleration (°/sec^2)	369 (200)	343 (141)	337 (71)	0.28	399 (173)	390 (169)	407 (169)	0.63
Mouse activities	*Extension*		($n = 16$)				($n = 17$)		
	50th$^{\%tile}$ posture (°)	**25 (17)**	**30 (16)**	**25 (18)**	**0.01**	37 (8)	38 (9)	37 (12)	0.66
	Range of motion (°)	62 (13)	64 (16)	65 (16)	0.74	23 (10)	22 (6)	22 (10)	0.68
	RMS acceleration (°/sec^2)	260 (148)	252 (118)	240 (87)	0.50	201 (52)	209 (77)	199 (61)	0.55
	Ulnar deviation		($n = 20$)				($n = 20$)		
	50th$^{\%tile}$ posture (°)	5 (20)	3 (19)	6 (17)	0.44	11 (11)	10 (10)	13 (13)	0.70
	Range of motion (°)	40 (19)	38 (16)	40 (13)	0.75	19 (4)	18 (3)	19 (4)	0.35
	RMS acceleration (°/sec^2)	210 (219)	176 (140)	164 (96)	0.34	144 (37)	155 (52)	141 (26)	0.21
Idle activities	*Extension*		($n = 16$)				($n = 17$)		
	50th$^{\%tile}$ posture (°)	**24 (17)**	**29 (14)**	**24 (17)**	**0.01**	35 (8)	36 (9)	35 (11)	0.63
	Range of motion (°)	66 (13)	68 (14)	69 (13)	0.68	49 (11)	49 (10)	49 (13)	0.94
	RMS acceleration (°/sec^2)	368 (200)	364 (140)	332 (110)	0.28	368 (139)	381 (134)	365 (164)	0.72
	Ulnar deviation		($n = 20$)				($n = 20$)		
	50th$^{\%tile}$ posture (°)	6 (19)	4 (19)	5 (17)	0.52	11 (9)	10 (9)	12 (12)	0.59
	Range of motion (°)	43 (20)	39 (14)	42 (12)	0.33	26 (6)	25 (4)	26 (5)	0.31
	RMS acceleration (°/sec^2)	275 (258)	242 (165)	220 (118)	0.34	195 (76)	205 (65)	195 (99)	0.73

Note: **p*-values determined from *F*-distribution tables. Bold values indicate a significant effect ($p < 0.05$) associated with day of measurement.

Table 5. Mean (SD) typing force and wrist kinematics by hour of measurement for keyboard, mouse and idle activities.

		Left wrist							Right wrist						
		Hour 1	Hour 2	Hour 3	Hour 4	Hour 5	Hour 6	*p*-value*	Hour 1	Hour 2	Hour 3	Hour 4	Hour 5	Hour 6	*p*-value*
Keyboard activities	*Typing force*				For both hands ($n = 20$)										
	50th$^{\%tile}$ force (N)	1.2 (0.4)	1.2 (0.5)	1.1 (0.4)	1.2 (0.5)	1.2 (0.5)	1.2 (0.6)	0.92							
	90th$^{\%tile}$ force (N)	3.2 (1.2)	3.3 (1.2)	3.3 (1.2)	3.1 (1.0)	3.1 (1.1)	3.1 (1.1)	0.77							
	Extension				($n = 16$)							($n = 17$)			
	50th$^{\%tile}$ posture (°)	34 (13)	35 (15)	35 (14)	35 (17)	36 (14)	37 (15)	0.40	35 (11)	35 (11)	34 (13)	36 (12)	35 (12)	37 (11)	0.22
	Range of motion (°)	36 (14)	35 (15)	37 (13)	36 (15)	42 (17)	40 (17)	0.21	32 (12)	32 (7)	33 (9)	30 (7)	31 (7)	32 (6)	0.59
	RMS acceleration (°/sec^2)	528 (146)	504 (142)	499 (146)	512 (162)	544 (160)	494 (198)	0.37	835 (242)	841 (285)	801 (325)	831 (267)	830 (276)	823 (280)	0.64
	Ulnar deviation				($n = 20$)							($n = 20$)			
	50th$^{\%tile}$ posture (°)	9 (14)	10 (18)	12 (18)	10 (18)	11 (18)	11 (18)	0.39	16 (8)	16 (9)	15 (9)	16 (10)	16 (10)	16 (9)	0.68
	Range of motion (°)	26 (13)	22 (7)	24 (9)	26 (9)	27 (10)	25 (8)	0.26	21 (6)	22 (5)	22 (7)	20 (5)	22 (6)	21 (6)	0.30
	RMS acceleration (°/sec^2)	359 (139)	336 (116)	311 (101)	326 (133)	371 (226)	321 (145)	0.28	398 (177)	399 (190)	389 (199)	382 (143)	390 (166)	387 (172)	0.63
Mouse activities	*Extension*				($n = 16$)							($n = 17$)			
	50th$^{\%tile}$ posture (°)	27 (12)	26 (17)	27 (15)	26 (17)	25 (17)	29 (18)	0.81	**36 (8)**	**36 (9)**	**37 (9)**	**39 (8)**	**39 (9)**	**38 (8)**	< **0.01**
	Range of motion (°)	61 (16)	63 (16)	62 (15)	64 (16)	65 (17)	66 (17)	0.98	23 (10)	20 (5)	24 (12)	23 (9)	22 (7)	23 (8)	0.29
	RMS acceleration (°/sec^2)	241 (137)	236 (90)	248 (104)	258 (110)	256 (88)	262 (107)	0.70	190 (59)	201 (61)	206 (71)	201 (65)	195 (60)	207 (80)	0.73
	Ulnar deviation				($n = 20$)							($n = 20$)			
	50th$^{\%tile}$ posture (°)	3 (14)	6 (18)	5 (18)	3 (19)	5 (18)	5 (18)	0.06	12 (9)	11 (9)	12 (9)	11 (9)	11 (10)	11 (10)	0.72
	Range of motion (°)	35 (16)	39 (15)	39 (18)	39 (17)	41 (14)	39 (12)	0.18	19 (4)	18 (3)	19 (4)	19 (4)	19 (3)	19 (4)	0.58
	RMS acceleration (°/sec^2)	180 (172)	173 (115)	190 (146)	185 (131)	177 (103)	184 (123)	0.60	138 (29)	142 (39)	148 (40)	145 (36)	137 (34)	154 (86)	0.78
Idle activities	*Extension*				($n = 16$)							($n = 17$)			
	50th$^{\%tile}$ posture (°)	27 (11)	25 (18)	25 (15)	27 (17)	26 (14)	28 (17)	0.92	35 (8)	35 (9)	33 (12)	36 (8)	37 (8)	37 (8)	0.73
	Range of motion (°)	63 (11)	69 (14)	66 (15)	66 (15)	69 (16)	73 (14)	0.42	45 (10)	47 (14)	49 (17)	49 (15)	49 (9)	50 (13)	0.11
	RMS acceleration (°/sec^2)	329 (154)	326 (142)	333 (157)	363 (158)	373 (146)	369 (139)	0.33	348 (140)	351 (147)	353 (150)	363 (166)	377 (158)	389 (148)	0.66
	Ulnar deviation				($n = 20$)							($n = 20$)			
	50th$^{\%tile}$ posture (°)	3 (13)	5 (18)	5 (18)	4 (18)	6 (18)	5 (18)	0.07	11 (8)	11 (9)	11 (9)	11 (8)	10 (10)	11 (9)	0.78
	Range of motion (°)	39 (15)	42 (14)	39 (19)	42 (18)	40 (9)	42 (15)	0.51	25 (5)	26 (6)	25 (7)	25 (6)	26 (5)	25 (6)	0.89
	RMS acceleration (°/sec^2)	236 (176)	228 (164)	228 (166)	263 (192)	244 (138)	248 (128)	0.40	185 (67)	181 (79)	191 (84)	207 (120)	192 (74)	206 (71)	0.71

Note: *p*-values determined from *F*-distribution tables. Bold values indicate a significant effect ($p < 0.05$) associated with hour of measurement.

Discussion

In this study, we aimed to determine if a single hour of continuous measures was sufficient to obtain a representative estimate of an individuals typing force and wrist kinematics exposure magnitude during computer use. We collected measurements in the field as workers completed actual work activities for six continuous hours a day on three separate days (not necessarily consecutive). Consistent with our first hypothesis, variance in measurements across subjects was significantly greater than variance in measurements across days and hours within subjects. Therefore, for epidemiologic studies which aim to evaluate the relationship between biomechanical exposure magnitude and musculoskeletal injuries, a single hour of measurement, collected on any day, at any time of the day, is sufficient to characterise differences in typing force and wrist kinematics between individuals.

With respect to our second hypothesis, for the most part, exposure magnitude measurements of typing force and wrist kinematics did not vary across day or hour of the day. One of 38 summary measures was found to differ across HOURS (right wrist extension during mousing), and 4 of 38 summary measures were found to differ across DAYS (left wrist extension during mouse activity, left wrist extension during idle tasks, right wrist ulnar range of motion during mouse activities, and peak force during typing). There did not appear to be a consistent order effect associated with day of measurement for the measures in which an effect of day was observed. A potential order effect associated with hour of measurement was observed in right wrist extension joint angle during mousing; extension joint angles were smaller during the earlier hours (hours 1–3) compared to the later hours (hours 4–6).

Overall these results indicate that when comparing exposure magnitude measurements of typing force and wrist kinematics during computer activities between subjects, a single hour of measurement is sufficient and that the day or hour of measurement are not significant factors. However, when comparing exposures magnitudes within a subject (as is typically done for repeated measures studies), for the few measures in which an effect of day or hour was observed, the day and hour of measurement may have to be taken into account.

The results of this study must be evaluated in the context of the study design. Recruited participants completed computer work on average, 50% of each hour with an average of 5, 15 and 10 minutes of keyboard, mouse and idle computer activities, respectively. This distribution of activities is consistent with previous studies which evaluated typical computer users (Chang *et al*. 2008, Jacobs *et al*. 2008, Richter *et al*., 2008, Ijmker *et al*. 2011). For workers who spend significantly less time using computers (e.g. nurses), or have a significantly different distribution of computer activities (e.g. data entry workers who almost exclusively use the keyboard), an alternative sampling strategy may be required. In addition, all participants in this study used standard workstations with a traditional keyboard and mouse combination. Variance in exposure magnitudes may be different for workers who use laptop computers or non-traditional input devices.

Finally, this study focused on developing sampling strategies for collecting direct measures of typing force and wrist kinematics during computer use. In addition to computer use, office workers may perform a wide variety of other activities including desk work, telephone use and filing. Investigators evaluating an office workers complete exposure profile would need to account for exposures during these activities as well which can pose a challenge as self-contained ambulatory instrumentation would have to be developed and used.

Our findings are similar to those reported by other studies which evaluated variance in biomechanical exposure magnitude measures among computer workers. Ortiz *et al*. (1997) collected postural measures using manual goniometers to determine the magnitude of variability between subjects and within subjects. They reported that variability across subjects was significantly greater than variability across days and times of day as well as across raters and therefore a single measurement of joint angle was sufficient to distinguish an individual subjects' joint angle from another. Their study however was limited to static joint angles measured only once, whereas we explored summary measures from continuously recorded electrogoniometric data recorded six hours a day over three different days. In a study evaluating mouse grip and click forces, Johnson *et al*. (2000) collected continuous measures across multiple hours and multiple days. Similar to our findings, they reported a 42 minute window was sufficient to accurately capture a subject's mechanical exposure to forces applied to the mouse.

Median wrist extension angles during keying (35°) and mousing (37°) reported in this study are larger than those reported in the literature which ranged between 13° and 23° for keyboard tasks (Simoneau *et al*. 1999, Dennerlein and Johnson 2006, Rempel *et al*. 2007) and 20° to 28° for mouse tasks (Burgess-Limerick *et al*. 1999, Dennerlein and Johnson 2006). Median wrist ulnar deviation postures (16° and 11° for keying and mousing, respectively) were similar to previously reported values, 10° to 15° for keying (Simoneau *et al*. 1999, Dennerlein and Johnson 2006, Rempel *et al*. 2007), 5° to 11° for mousing (Burgess-Limerick *et al*. 1999, Dennerlein and Johnson 2006). Median key strike forces measured in our study (1.2N) were similar to those previously reported (Bufton *et al*. 2006, Dennerlein and Johnson 2006). Peak key-strike forces (3.2N), however, were greater. Bufton *et al*. (2006) reported

50th and 90th percentile keyboard reaction forces of 1.3N and 2.8N, respectively; Dennerlein and Johnson (2006) reported 50th and 90th percentile forces of 1.2N and 2.3N, respectively.

The discrepancies in median wrist extension joint angle and typing forces may be due to differences in key switch design parameters (e.g. make force, key-travel, etc.), workstation configurations (our study allowed users to configure their workstation per their preference, while previous studies configured the workstation per HFES recommendations) and/or tasks (our study measured typing forces during actual work tasks while previous studies had participants complete simulated tasks).

Consistent with the findings in the laboratory study by Dennerlein and Johnson (2006), significant differences between keyboard, mouse and idle computer activities were observed in all measures of wrist kinematics, except for median extension joint angles of the right wrist. These results highlight the importance of assessing biomechanical exposures individually for each of these tasks as their distribution during an assessment period can have a significant impact on exposure.

This study identified a continuous one hour sampling period as an adequate time window for estimating an individual's typing force and wrist kinematics exposure magnitudes associated with each computer activity (keyboard, mouse and idle activities). Magnitude is one component of exposure, with duration and frequency comprising the other two. For computer workers, quantifying the duration and frequency of exposure to keyboard, mouse and idle computer activities can be automated and implemented on a large scale with relatively minimal effort through computer interaction monitoring software (Chang *et al*. 2008, Richter *et al*. 2008). This lends a particular advantage to activity-based assessments for quantifying exposure to biomechanical risk factors among computer workers.

The value of activity-based exposure methods however, has been questioned. In a study of physical exposure in monotonous repetitive work Fallentin *et al*. (2001) concluded that variance within groups was larger than the variance across groups for their exposure metrics, leading to methodological problems associated with grouped exposure assessment. Seixas *et al*. (2003) observed that their estimates of exposure included a substantial degree of error when there is larger inter-individual variability for a given activity. Mathiassen (2005) concluded effective implementation of activity-based exposure methods in epidemiological studies is difficult if large between-subject variability exists in the exposure magnitude measures of each activity.

Estimates of an individual's total exposure may be better represented, if the between-subject variability can be estimated through an exposure magnitude calibration process and incorporated into the activity-based exposure model. Our findings indicate a one hour window of measurement would be sufficient to estimate the between-subject variability in exposure magnitude measures during computer activities. Future studies however would have to validate whether this method does in fact improve estimates of an individual's total exposure.

Ultimately, the aim of this study was to identify an effective and efficient sampling strategy for estimating biomechanical exposure magnitudes associated with computer work. Our results indicate continuous measures collected over an one-hour period, are sufficient to characterise an individual's typing force and wrist kinematics exposure magnitudes for the three major types of computer activities (keyboarding, mousing and idle).

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