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ORIGINAL ARTICLE

Typing keystroke duration changed after submaximal isometric finger exercises

Che-Hsu (Joe) Chang · Peter W. Johnson · Jeffrey N. Katz · Ellen A. Eisen · Jack T. Dennerlein

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Abstract A repeated-measures laboratory experiment tested whether keystroke duration during touch-typing changes after a finger performs submaximal isometric flexion exercises. Fourteen right-handed touch-typists used right ring finger to perform three 15-min exercise conditions, two isometric exercises and a no-force condition, each on a separate day. Before and after each exercise condition, typing keystroke duration and isometric force elicited by electrical stimulation were measured for right ring finger. Keystroke duration of right ring finger decreased by 5% (6 ms, $P < 0.05$) immediately after the exercises but not after the no-force condition. Peak isometric finger force elicited by electrical stimulation decreased by 17–26% ($P < 0.05$) for the flexor digitorum superficialis and decreased by 4–8% for the extensor digitorum communis after the isometric exercises. After the finger was exposed to isometric exercises, changes in typing keystroke duration coincided with changes in the physiological state of the finger flexor and extensor muscles.

Keywords Computer use · Muscle physiology · Fatigue · Musculoskeletal disorders · Exposure assessment

Introduction

Computer-related musculoskeletal disorders (MSDs) are of growing concern (Bergqvist et al. 1995; Eltayeb et al. 2007; Faucett and Rempel 1994; Matias et al. 1998), but the exposure–response relationship and injury mechanism are not yet well understood. Researchers have been studying the physiological changes in muscles in hope for understanding cumulative exposure and constructing the underlying exposure–response relationship. In previous studies, muscle fatigue is the most frequently discussed physiological change in that the factors associated with muscle fatigue are similar to those associated with injuries (Dennerlein et al. 2003). Laboratory and experimental evidence exists suggesting associations between muscle fatigue and injuries

C.-H. (Joe) Chang · J. N. Katz · E. A. Eisen · J. T. Dennerlein (✉)
Department of Environmental Health,
Harvard School of Public Health,
665 Huntington Avenue, Boston,
MA 02115, USA
e-mail: jax@hsph.harvard.edu

C.-H. (Joe) Chang
e-mail: chjchang@gmail.com

E. A. Eisen
e-mail: eeisen@hsph.harvard.edu

P. W. Johnson
Department of Environmental and Occupational Health Sciences,
School of Public Health and Community Medicine,
University of Washington, Box 357234, Seattle,
WA 98195-7234, USA
e-mail: petej@u.washington.edu

J. N. Katz
Department of Orthopedic Surgery and Division
of Rheumatolology, Immunology and Allergy,
Brigham and Women's Hospital, 75 Francis Street,
Boston, MA 02115, USA

J. N. Katz
Harvard Medical School, Harvard University,
Boston, MA, USA

J. N. Katz
Department of Epidemiology,
Harvard School of Public Health, Boston, USA
e-mail: jnkatz@partners.org

E. A. Eisen
Environmental Health Sciences, School of Public Health,
50 University Hall #7360, Berkeley, CA 94720, USA

(Mair et al. 1996; Taylor et al. 1993; Veiersted et al. 1993); however, field observations have not been completed due to the difficult nature of measuring muscle fatigue.

Integrative computer usage-monitors (usage-monitors) may be able to collect field data about muscle physiology. Usage-monitors have been used to measure computer use durations in longitudinal and cross-sectional field studies of computer-related MSDs (Chang et al. 2007; Lassen et al. 2005; Mikkelsen et al. 2007). They measure computer input device activities, including the calendar time and duration of each keystroke, button click and movement of the pointing device. These input device activities are repetitive tasks involving complicated motor control (Flanders and Soechting 1992) and therefore may contain valuable motor control information dependent on the physiological performance of muscles.

Keyboard typing is a complicated, hierarchal task consisting of repetitive finger movements. Typing performance may change when the performance of the associated muscles changes. During typing, the duration of each keystroke is determined by the motor control and performance of several muscles articulating the hands (Dennerlein et al. 1998; Rempel et al. 1994). Previous studies have reported that the motor control and performance of repetitive movements change after muscles are fatigued (Jaric et al. 1997; Johnston et al. 1998; Kruger et al. 2007; Lucidi and Lehman 1992). Therefore, keystroke duration might also change when the associated muscles are fatigued, and hence, we proposed the idea that changes in keystroke duration can be a surrogate for physical exposures that changes the physiological performance of muscles.

We conducted a laboratory experiment to test the hypotheses that typing performance as measured by keystroke duration, typing speed and typing accuracy changes after submaximal isometric finger exercises and that the physiological performance of forearm-finger muscles changes after the exercises. We measured the typing performance during typing tests and the physiological performance of muscles using neuromuscular electrical stimulation before and immediately after the exercises as well as during post-exercise recovery periods.

Materials and methods

Subjects

Fourteen right-handed participants (six males and eight females, 28.5 ± 6.7 years old) were recruited from the community through e-mail advertisement. All the subjects were touch-typists (typing speeds ranging from 37 to 80 words/min) and free of upper extremity musculoskeletal disorders and symptoms. Each participant provided consent to participate, and the experiment protocol was approved by the Human Subject Committee at the University of Washington and the Harvard School of Public Health. Participants were instructed to avoid lifting heavy objects and intensive upper extremity exercises within 24 h prior to any of the experimental days. For all protocols, subjects sat on an adjustable chair with an adjustable table such that their feet were flat on the floor, their thighs were horizontal and the work surface was at resting elbow height.

Experiment protocol

In the repeated-measures laboratory experiment, participants completed three different 15-min submaximal isometric finger flexion exercises, one exercise per experimental day (3 days in total), with their right ring finger. Keystroke duration and the physiological performance of finger flexor and extensor muscles were measured pre- and post-exercise as well as at 30, 60 and 120 min into the recovery period after the end of each exercise. The ring finger was chosen due to the superficial location of its flexor digitorum superficialis (FDS) muscle and the ample number of keystrokes that could be measured from this finger.

The three exercise conditions included two isometric exercises, a fluctuating force exercise and a constant force exercise, and a no-force condition. The exercises were performed with participants seated and their forearm pronated and rested on the table. The fluctuating force exercise required the participants to press on a force transducer (Greenleaf Medical Pinch Meter, Palo Alto, CA, USA) fixed on the table with right ring fingertip force alternating between 200 ms of 0% finger flexion maximum voluntary contraction force (MVC) and 200 ms of 30% finger flexion MVC (i.e. 2.5 Hz with 50% duty cycle). The constant force exercise required the participants to press the force transducer with the constant force of 15% finger flexion MVC. The no-force condition required the participants to rest in the chair with their hands freely relaxed on the table. The order of the three exercise conditions received by each participant was randomized using a Latin square design.

The fluctuating force exercise was designed so that the finger flexor muscles repeatedly exerted a cyclical (transient) force profile, lasting approximately 200 ms, which was temporally similar to the force profile of actual keystrokes during typing. The constant force exercise was chosen, because it was known to cause muscle fatigue (Johnson 1998). In addition, we designed the two exercises to have same time-tension products (the product of the force, duty cycle and duration of the exercise), which were also expected to result in same average forces because the duration of the exercises was identical.

To control the force exertion during the exercises, participants viewed the force level digitally recorded from the force transducer at 10 samples/s and displayed in real time on a visual display (computer monitor). Participants were instructed to control the force level to match the target line displayed on the same visual display, and the shapes of the target line corresponded to the exercises. The average force levels recorded during the two isometric exercises were compared in a paired *t* test to ensure comparable exercise intensity.

Maximal voluntary contraction

Participants' maximum voluntary contraction force for finger flexion and extension were measured on a separate day prior to the actual experiment. For finger flexion, the participant pressed their right ring fingertip on a force transducer (Greenleaf Medical, Palo Alto, CA, USA) placed upward such that the right forearm was fully pronated. Participants were instructed to press as hard as possible for 5 s. Three exertions were completed with 2 min of rest between exertions. For finger extension MVC, the participant pressed on the transducer with the dorsal side of the distal end of the ring finger proximal phalanx such that the right forearm was fully supinated. The force signal was recorded at 1,000 samples/s with the highest 1-s interval representing the MVC for a given trial. The final MVC was the highest value among all trials.

Because of the anatomical difference between the FDS and EDC muscle, the relative mechanical contribution during the MVC tests might be different. Because this experiment was designed to evaluate each muscle in isolation under electrical stimulation, the difference in force contribution between muscles would not affect the statistical analysis or the interpretation of the results.

Measuring typing performance

Keystroke duration, typing speed and typing accuracy were measured during 5-min typing tests administered with a commercially available typing test software program (Typing tutor deluxe, COKeM International Ltd, Plymouth, MN, USA). The participants viewed the text from a window displayed on the visual display and typed the text into another window. They were instructed to type at the speed as they were working. The typing test software automatically calculated typing speed (words per minute), which only used the number of correctly typed words, and typing accuracy, which was the percentage of words correctly typed relative to the total number of words typed. The keystroke duration of each keystroke was recorded via custom designed usage-monitor software loaded on the same computer (Chang et al. 2004).

Measuring finger force response elicited by electrical stimulation

Immediately after each typing test, two types of muscle contractions, twitch and tetanic contraction, were elicited by electrical stimulation. The twitch contraction was elicited with electrical stimulation at 2 pulses per second (pps) for both the right ringer FDS and extensor digitorum communis (EDC). The tetanic contraction was elicited with 20 and 100 pps for only the FDS to keep the measurement protocol short enough and allow rest between measurements. The duration (0.1 ms) and the amplitude [set at the maximal tolerable level, six on a zero to ten pain scale (Hanchard et al. 1998)] of each pulse were controlled by a S48 stimulator, SIU5 stimulus isolation unit and constant current unit (Grass Instruments, W. Warwick, RI, USA) (Fig. 1).

On a separate day prior to the experiment, electrode placement was determined by repeatedly positioning the electrodes over the muscle until the force response of the muscle, based on visual observation, was maximal with minimal recruitment from the neighboring muscles. Once the optimal stimulation location was identified, two 12-mm disposable Ag/AgCl electrodes were placed with a 20-mm intercenter distance. The negative stimulating electrode was placed proximal to the positive electrode.

The FDS was measured before the EDC. For the FDS, three cycles of 1-s 100 pps stimulation and 1-s 20 pps stimulation were administered and followed by five trains of five-twitch 2 pps stimulations. The 100 and 20 pps stimulation potentiated the muscle prior to the 2 pps stimulations (Lin 2005). There were 30-s rests between cycles of 100 and 20 pps electrical stimulations, and 5-s rests between trains of 2 pps electrical stimulations. For the EDC, 90 s of continuous 2 pps stimulation were first administered to potentiate the muscle into a steady stimulation state, and then five trains of five-twitch 2 pps stimulation were administered (Johnson 1998; Lin 2005).

A force transducer (Greenleaf Medical, Palo Alto, CA, USA) measured the isometric force elicited by the electrical

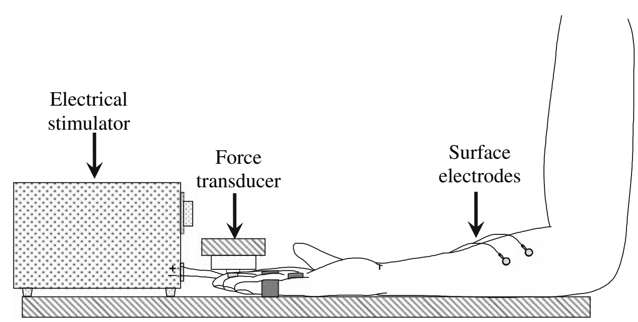

Fig. 1 The schematic of the experimental setup for electrical stimulation of the FDS muscle. For the EDC muscle, the posture remained the same, the electrodes were placed over the EDC muscle and the force transducer was located underneath the ring finger

stimulation (Fig. 2). For the FDS, the transducer was placed at the ventral side of fingertip with the hand and forearm fully supinated (Fig. 1). For the EDC, the transducer was placed at the dorsal side over the end of the proximal phalanx of the right ring finger. The adjacent fingers were restrained with straps.

Data processing

Keystroke durations were allocated to each finger based on touch-typing rules (e.g. durations of the L and O keys were allocated to the right ring finger) and were averaged across each keystroke within each finger for each 5-min typing test. During each 5-min typing test, the participant's right ring finger typed on average 120 keystrokes. This number was similar across all typing tests performed during the experiment. Keystrokes longer than 250 ms were excluded from data analysis, because under our default computer setting, the automatic repeat function was activated for keystrokes longer than 250 ms.

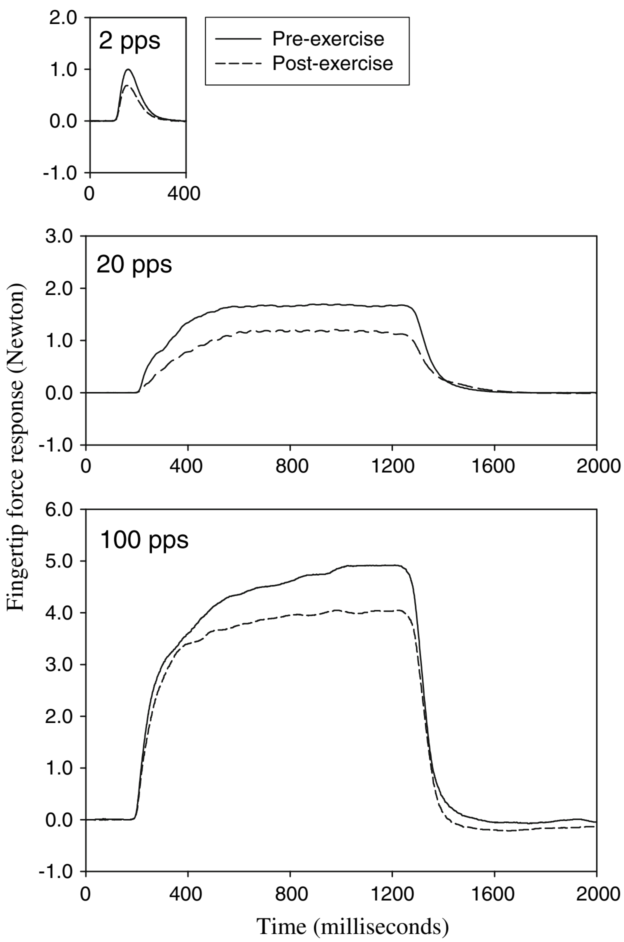

Fig. 2 The trace of fingertip force responses to electrical stimulation. The plots are based on data collected from a single participant at a pre-exercise measurement and a post-exercise measurement. The two finger exercises in the experiment were associated with similar changes in the force response profile

From the force of the muscle twitches elicited by 2 pps electrical stimulation of the FDS and the EDC muscles, the peak twitch force, contraction time and one-half relaxation time were calculated. The peak twitch force was the difference between the force at the twitch peak and the baseline force level 10 ms before the twitch onset; the contraction time was the duration between the twitch onset and twitch peak; the one-half relaxation time was the time it took for twitch force to drop from the twitch peak to one half of the peak twitch force. Decreases in the force response indicate muscle fatigue.

From the force of the tetanic muscle contraction elicited by 100 and 20 pps electrical stimulation of the FDS, the peak force was calculated by averaging the highest force within the 250-ms window during the last one-third of the 1-s stimulation. The first cycle of 100 and 20 pps stimulation within each instance of electrical stimulation measurement was not included, because the participants often moved during the first cycle, and the measured force might contain unwanted voluntary forces.

To allow for comparisons across exercise conditions, all the aforementioned parameters measured during each typing test and electrical stimulation measurement were normalized to the value of the pre-exercise measurement within the same exercise condition.

Data analysis

To test the hypothesis that keystroke duration changes after the exercises, we fitted mixed analysis of variance (ANOVA) models (PROC MIXED, SAS 9.1, SAS Institute Inc., Cary, NC, USA) to keystroke duration as a function of the measurement time and exercise condition. Keystroke durations of different fingers were tested in separate models. The predictor variables included the fixed effects of exercise conditions (categorical) and measurement times (categorical), the random effect of participant (categorical) and all associated two-way interactions. The covariance structure of the mixed model was set to be first-order autoregressive. Based on the result of the mixed model, we then completed post-hoc pair-wise comparisons (Dunnett's tests) between the pre-exercise measurement and each of the post-exercise measurements. The pair-wise comparisons were presented as our primary results. Two additional mixed models were used to examine if typing speed and typing accuracy changed across typing tests.

To test the hypothesis that the physiological performance of the forearm-finger muscles changes after the exercises, similar mixed models were fitted with respective outcome variables including the peak force elicited by 2, 20 and 100 pps electrical stimulation, twitch contraction time and twitch one-half relaxation time.

Results

The average finger flexion force applied on the force transducer during the fluctuating force exercises was slightly lower than the force during the constant force exercise (3.46 vs. 3.68 N, $P = 0.07$ by paired Student's t test). When these average forces were normalized by individual MVC force, the two exercises exhibited similar level of muscle exertion, 13.4 and 14.0% ring finger flexion MVC for the fluctuating force exercise and constant force exercise, respectively ($P = 0.12$ by paired Student's t test).

Keystroke duration

Keystroke duration of the right ring finger, as measured from the "L" and "O" keys during typing tests, decreased at the post-exercise measurement after the participants performed the two isometric finger exercises (Figs. 3, 4). Compared with the pre-exercise value, post-exercise keystroke duration decreased by 5% (from 119 to 113 ms, $P = 0.047$) after the fluctuating force exercise and decreased by 5% (from 118 to 112 ms, $P = 0.02$) after the constant force exercise. For the no-force condition, the post-exercise keystroke duration was relatively unchanged (from 120 to 122 ms, $P = 0.88$). The post-exercise changes in keystroke duration for the fluctuating and constant force exercise conditions were larger than that for the no-force condition ($P = 0.07$ and $P = 0.09$, respectively), and post-hoc analysis suggested that the power for these two statistical comparisons were 0.37 and 0.92, respectively.

During the recovery period, keystroke duration returned to the same level as the pre-exercise value at 30 and 60 min after the fluctuating and constant force exercises, respectively (Figs. 3, 4). The keystroke duration for the no-force condition remained unchanged during the recovery period.

The keystroke duration of all the other fingers, the typing speed and the typing accuracy, which were based on all fingers, remained relatively unchanged throughout the experiment for all exercise conditions (Table 1).

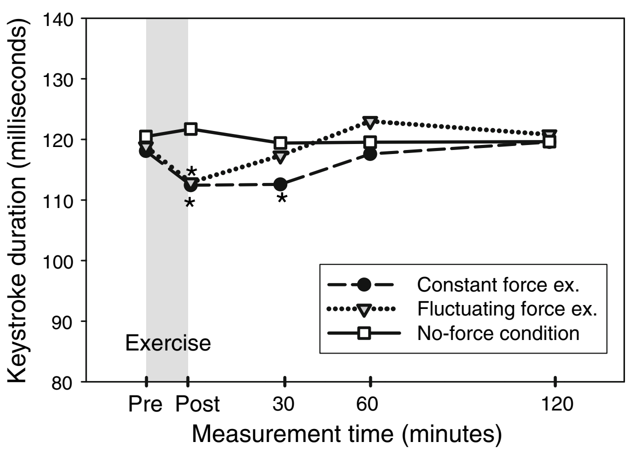

Fig. 3 The original values of the keystroke duration measured during each typing test. *Asterisk* denotes statistical significant difference ($P < 0.05$) when compared with the pre-exercise measurement within the same condition. Standard error bars were omitted for clarity

Muscle force response of the FDS

For the FDS, the peak finger force elicited by electrical stimulation decreased at the post-exercise measurement after the two isometric exercises. For the 2 pps stimulation, peak force (4.6 ± 2.0% MVC as measured pre-exercise) decreased by 26 and 17% after the fluctuating and constant force exercises, respectively (both $P < 0.01$ when the values were compared with the pre-exercise values) (Fig. 4). The 20 pps stimulation peak force (10.0 ± 4.5% MVC as measured pre exercise) decreased by 17 and 11% after the fluctuating ($P = 0.01$) and constant ($P = 0.16$) force exercises, respectively. For the 100 pps stimulation, peak force (17.3 ± 8.3% MVC as measured pre-exercise) slightly decreased by 9 and 5% ($P = 0.7$ and $P = 0.3$) post-exercise after the fluctuating and constant force exercises, respectively (Fig. 5). Peak finger force also decreased, albeit smaller, for the no-force condition (10% for 2 pps,

Fig. 4 The normalized values of keystroke duration and peak force measured during 2 pps electrical stimulations. Values were normalized to the pre-exercise measurement. *Asterisk* denotes statistical significant difference ($P < 0.05$) when compared with the pre-exercise measurement within the same condition. Standard error bars were omitted for clarity

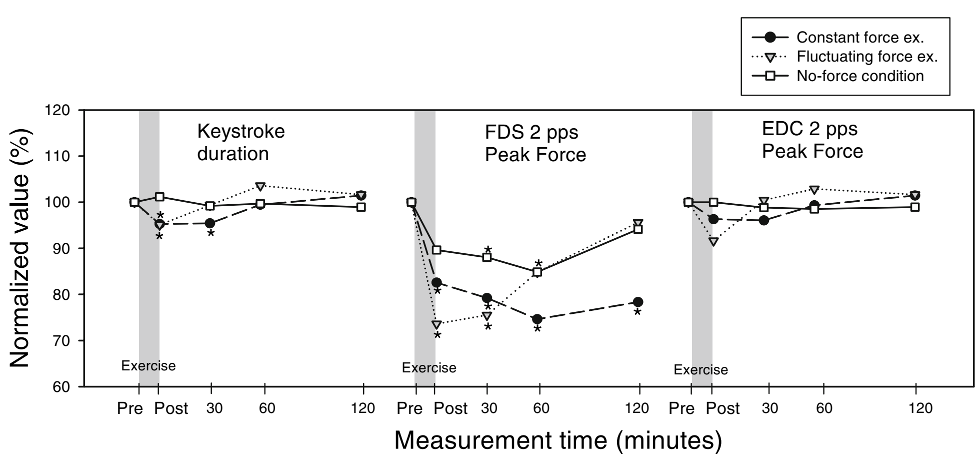

Table 1 Typing speed and typing accuracy measured during the typing tests

	Typing speed (words per minute)			Typing accuracy (%)		
	No-force	Fluct.	Const.	No-force	Fluct.	Const.
Pre-	53.1 ± 3.3	51.1 ± 2.9	51.6 ± 3.4	95.1 ± 0.7	93.9 ± 1.5	94.6 ± 0.9
Post-	52.6 ± 3.4	52.2 ± 3.0	53.3 ± 3.1	93.4 ± 0.9	93.1 ± 1.4	93.5 ± 0.8
Post-30	53.1 ± 2.9	53.1 ± 3.7	50.2 ± 3.5	93.6 ± 0.8	93.1 ± 0.9	92.4 ± 1.1
Post-60	54.3 ± 3.5	54.4 ± 3.0	52.7 ± 3.4	94.2 ± 1.0	93.7 ± 0.9	93.6 ± 0.9
Post-120	53.8 ± 3.3	52.5 ± 3.3	52.4 ± 2.9	94.1 ± 0.8	93.3 ± 1.2	93.4 ± 0.8

No statistical significance was found when comparing any post-exercise measurement with the pre-exercise measurement

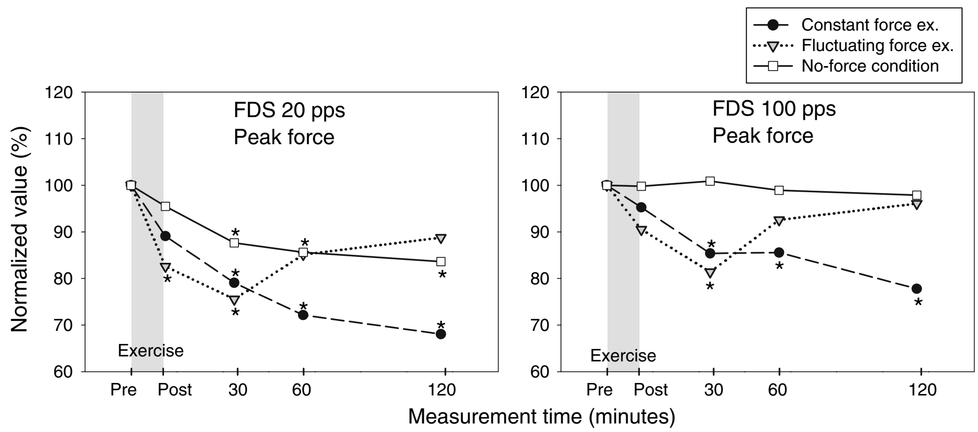

Fig. 5 The normalized values of the peak force measured during FDS 20 pps and 100 pps electrical stimulation. Values were normalized to the pre-exercise measurement. *Asterisk* denotes statistical significance ($P < 0.05$) when compared with the pre-exercise measurement. Standard error bars were omitted for clarity

$P = 0.06$, 5% for 20 pps, $P = 0.66$ and <1% for 100 pps, $P > 0.99$).

During the recovery period, the peak FDS finger force elicited by electrical stimulation returned to the pre-exercise level for the fluctuating force exercise condition, but not for the constant force exercise condition. For the no-force condition, a decreasing trend was observed for the peak FDS finger force elicited by the 2 and the 20 pps electrical stimulation, but recovery was then observed for the 2 pps electrical stimulation at the end of the recovery period (Figs. 4, 5).

The twitch contraction time (58.8 ± 7.7 ms as measured pre-exercise) and one-half relaxation time (57.7 ± 15.1 ms as measured pre-exercise) of the FDS 2 pps electrical stimulations decreased by 5–7 ms (−8 to −12%) at the post-exercise measurement after the fluctuating and constant force exercise ($P < 0.05$ when compared with the pre-exercise value) and returned to the same level as the pre-exercise value by the end of the recovery period (Fig. 6).

Muscle force response of the EDC

For the EDC, at the post-exercise measurement, the peak isometric finger force elicited by 2 pps electrical stimulation (4.6 ± 2.0% MVC as measured pre-exercise) slightly decreased by 8 and 4% ($P = 0.48$ and $P = 0.14$) after the fluctuating force exercise and constant force exercise, respectively, and remaining relatively unchanged (0% change) after the no-force condition (Fig. 4). The peak force then returned to baseline quickly during the recovery period. The contraction time and one-half relaxation time of the EDC twitches elicited by 2 pps electrical stimulation did not exhibit any trend of statistical significance (Fig. 6). Among all the parameters measured during electrical stimulation, the changing patterns of the peak force of the EDC emulated the changing patterns of keystroke duration.

Discussion

The goals of this experimental study were to test the hypotheses that the typing performance during touch-typing changes after submaximal isometric finger exercises, and that the physiological performance of the forearm-finger muscles also changes after the exercises. We observed decreases in keystroke duration and decreases in finger force response, indicating muscle fatigue, after the exercises. While the responses of these parameters to the exercises varied, the results supported both hypotheses, and therefore, keystroke duration is found to provide information about the status of submaximal isometric finger exercises changing the physiological performance of forearm-finger muscles.

While we observed changes in keystroke duration after the submaximal isometric exercises, other studies have observed mixed results of changed and unchanged movement performance after exercises. The flexion and extension durations of rapid finger repetitive movement have

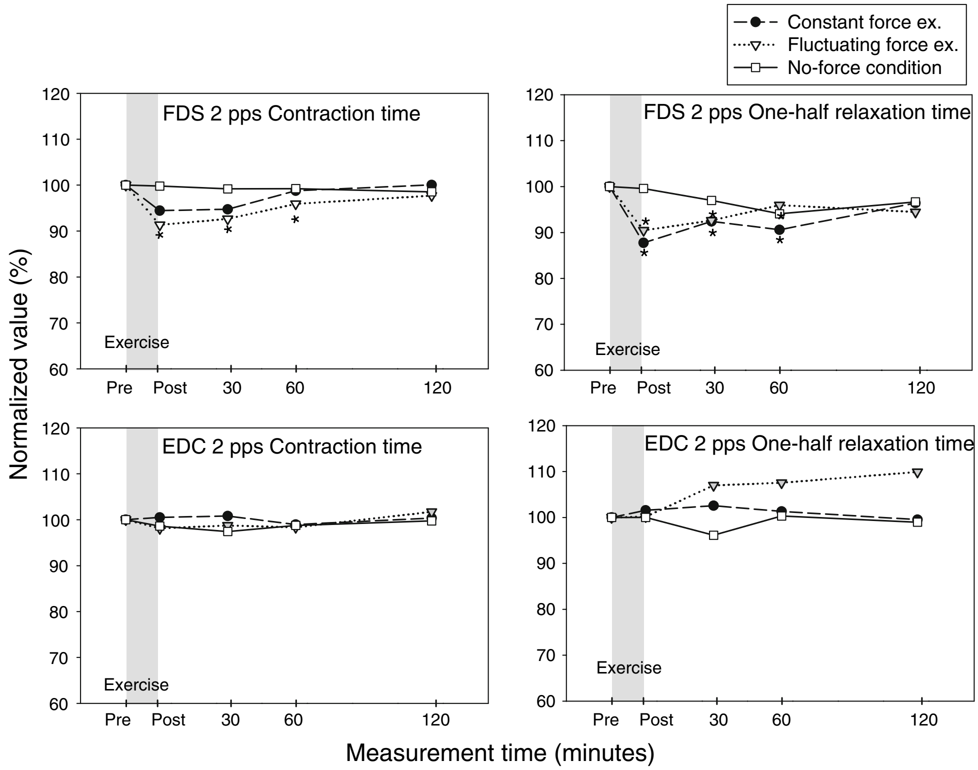

Fig. 6 The normalized values of the contraction time and one-half relaxation time measured during 2 pps electrical stimulation. Values were normalized to the pre-exercise measurement. *Asterisk* denotes statistical significance ($P < 0.05$) when compared with the pre-exercise measurement. Standard error bars were omitted for clarity

been found to remain invariant after the forearm muscles are fatigued by exercises (Heuer et al. 2002). In contrast, the peak velocity, acceleration and deceleration of rapid elbow flexion/extension movements have been observed to decrease when upper arm muscles are fatigued (Jaric et al. 1997). The relationship between physiological changes and the movement performance of muscles is complex and not yet well understood. The mixed findings in the literature suggest that the physiological changes in muscles could either change the movement performance or be compensated by motor control to maintain the same performance. Other unmeasured central mechanisms, motor control and physiological changes might also contribute to the underlying association.

In the experiment, we only measured peripheral muscle fatigue with involuntary electrical stimulation, while the voluntary performance measure (keystroke duration) could have been affected by both peripheral and central mechanisms. It has been demonstrated that muscle activity patterns can adapt to maintain the kinematic and force aspect of movement performance when peripheral muscle fatigue is present (Lucidi and Lehman 1992). Here, however, we did observe changes in the performance of repetitive movements (i.e., keystroke duration).

Compared with the repetitive movement tasks performed in previous studies investigating movement performance, keyboard touch-typing is a much more complicated task, because it involves more components, such as cognitive processing (Gordon et al. 1994) and integration of tactile feedback (Rabin and Gordon 2004). It is reasonable to assume that there are many determinants for the changes in keystroke duration. Further studying the central components (e.g. cognitive processing, central fatigue, etc.) and peripheral components (e.g. muscle fatigue, sensory input, etc.) of keyboard typing will also provide more information to help understand how physiological changes in muscles influence motor control and movement performance.

While the two finger exercises in the experiment both decreased the force response to electrical stimulation of the FDS, the recovery patterns were different. The force response recovered to the pre-exercise level by the end of the experiment for the fluctuating force exercise condition, but not the constant force exercise. A possible explanation is that the sustained muscle contraction during the constant force exercise might have limited the blood supply to the muscle (Sadamoto et al. 1983), thereby prolonging and delaying the recovery of the muscle. In addition, the force exerted during the constant force exercise was slightly higher than that for the fluctuating force exercise, which might also contribute to the delayed recovery following the constant force exercise.

In our results, changes in the twitch force of the EDC were different from the changes in the twitch force of the FDS (as shown in Fig. 4), although the changing pattern and magnitude in the twitch force of the EDC were similar to the changes in keystroke duration of the right ring finger (of the order of 4–8%). The changes in the FDS force response were much larger (of the order of 17–26%). In the experiment, finger flexion exercises were administered, because we originally suspected the FDS to be a strong determinant for keystroke duration. However, keystroke duration, as measured by usage-monitors, could be a function of both the finger flexor and extensor muscles, because it is determined by the timing of both the beginning and the end of a keystroke signal. A keystroke signal begins when the key cap reaches the end of the key travel. In terms of motor control, this time point is determined by the timing of turning off of the extensor muscles and the timing of the flexor muscle onset. The onset of the extensor muscles activity then occurs at the end of the key travel (Dennerlein et al. 1998; Kuo et al. 2006), and a keystroke signal ends when the force of the finger extensors becomes large enough to overcome the flexion and gravity force to lift the finger from the end of the key travel (Dennerlein et al. 1999). Both the finger flexor and the extensor muscles could be important to determine the keystroke duration. While our study focused on creating FDS muscle fatigue, an alternative experiment design focusing on the EDC fatigue will help further understand the underlying interaction between the two muscle groups as well as injury mechanisms.

Other studies have found that the extensor muscles play a distinct role during computer use and keyboard typing. The EDC has been observed to be more susceptible to muscle fatigue than the FDS during keyboard typing (Lin et al. 2004), which might be associated with the wrist and finger extensor tendonitis observed among computer users (Gerr et al. 2002). A laboratory study has also found that faster keyboard typists exhibit less finger extensor muscle activity during typing than slower typists, but the levels of finger flexor muscle activity are the same (Gerard et al. 2002). Studying extensor muscle may be crucial, since they are weaker muscles and more often a site of injury. Ultimately, the complex interaction will be best understood by studying both muscles together.

This study supported our hypothesis that there are changes in keystroke duration as the forearm-finger muscles go through fatigue and recovery. The results are the first step toward verifying and developing keystroke duration as a new dimension in the exposure assessment of studying MSDs. Although prolonged computer use duration has been related to increased risk of MSDs in epidemiologic studies, the effect of other possible covariates is not yet well understood (Chang et al. 2007; Gerr et al. 2006). For example, it is still unclear how muscle physiology and cumulative exposures to computer use are related to the development of MSDs. Because both keystroke duration and computer use duration can be measured by usage-monitors inexpensively and non-invasively, field studies will be promising to determine if keystroke duration and computer use duration can be used together to identify increased risk of MSDs.

The first limitation of our study was that it is unclear if our exercises changed the muscle physiology in the same way as actual computer use. The muscle exertion during exercises were relatively large compared to the actual forces and force patterns encountered during keyboard use, and therefore, it is uncertain whether the same changes in keystroke duration and muscle physiology will occur during actual keyboard use. We designed the isometric exercises to induce finger flexor muscle fatigue in a relatively short period of time, and we observed decreases in finger force response of both the FDS and the EDC. The observed small EDC muscle fatigue could result from cocontraction during the exercises (Calder and Gabriel 2007). The decrease of the FDS finger force elicited by both 20 and 100 pps electrical stimulation also suggested that the muscle might have experienced both low- and high-frequency fatigue after the finger exercises (Bystrom and Kilbom 1991). Data collected during actual computer use are needed to determine how keystroke duration is related to the physiological changes resulting from computer use.

The second limitation was that the typing tests and electrical stimulation could have caused muscle fatigue. As shown in the no-force condition, the force response of the FDS declined relative to pre-exercise measurement, indicating that there was fatigue induced by either or both measurements. While randomizing the order between typing test and electrical stimulation might override the interaction between the fatigue caused the two measurements, we always administered typing test first to measure keystroke duration without the discomfort and possible physiological changes immediately following electrical stimulation. In addition, the decrease of finger force associated with the measurement protocol was smaller than the decrease associated with the submaximal isometric finger exercises. Because keystroke duration remained unchanged throughout the no-force condition, the changes in keystroke duration after the two finger exercises were unlikely to be related to the measurement protocol.

In conclusion, we observed that keystroke duration decreased immediately after submaximal isometric finger exercises of the order of 5%. Similar temporal changes in muscle fatigue and the physiological performance of the FDS and EDC muscles were also observed after the exercises, with the response of the FDS being much larger (of the order of 17–26%). Keystroke duration provided information about the status of finger exercises associated with muscle fatigue and therefore has the potential to serve as an objective measure of the physiological changes in forearm-finger muscles. This pilot study provides a basis to future studies examining how keystrokes can be used to study the exposure–response relationships of MSDs in laboratory and field settings.

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Reference

Bergqvist U, Wolgast E, Nilsson B, Voss M (1995) The influence of VDT work on musculoskeletal disorders. Ergonomics 38:754–762. doi:10.1080/00140139508925147

Bystrom S, Kilbom A (1991) Electrical stimulation of human forearm extensor muscles as an indicator of handgrip fatigue and recovery. Eur J Appl Physiol Occup Physiol 62:363–368. doi:10.1007/BF00634974

Calder KM, Gabriel DA (2007) Adaptations during familiarization to resistive exercise. J Electromyogr Kinesiol 17:328–335. doi:10.1016/j.jelekin.2006.02.006

Chang CH, Wang JD, Luh JJ, Hwang YH (2004) Development of a monitoring system for keyboard users performance. Ergonomics 47(14):1571–1581

Chang CH, Amick BC 3rd, Menendez CC, Katz JN, Johnson PW, Robertson M et al (2007) Daily computer usage correlated with undergraduate students' musculoskeletal symptoms. Am J Ind Med 50:481–488. doi:10.1002/ajim.20461

Dennerlein JT, Mote CD Jr, Rempel DM (1998) Control strategies for finger movement during touch-typing. The role of the extrinsic muscles during a keystroke. Exp Brain Res 121:1–6. doi:10.1007/s002210050430

Dennerlein JT, Diao E, Mote CD Jr, Rempel DM (1999) In vivo finger flexor tendon force while tapping on a keyswitch. J Orthop Res 17:178–184. doi:10.1002/jor.1100170205

Dennerlein JT, Ciriello VM, Kerin KJ, Johnson PW (2003) Fatigue in the forearm resulting from low-level repetitive ulnar deviation. AIHA J (Fairfax, Va) 64:799–805

Eltayeb S, Staal JB, Kennes J, Lamberts PH, de Bie RA (2007) Prevalence of complaints of arm, neck and shoulder among computer office workers and psychometric evaluation of a risk factor questionnaire. BMC Musculoskelet Disord 8:68. doi:10.1186/1471-2474-8-68

Faucett J, Rempel D (1994) VDT-related musculoskeletal symptoms: interactions between work posture and psychosocial work factors. Am J Ind Med 26:597–612. doi:10.1002/ajim.4700260503

Flanders M, Soechting JF (1992) Kinematics of typing: parallel control of the two hands. J Neurophysiol 67:1264–1274

Gerard MJ, Armstrong TJ, Martin BJ, Rampel DA (2002) The effects of work pace on within-participant and between-participant keying force, electromyography, and fatigue. Hum Factors 44:51–61. doi:10.1518/0018720024494757

Gerr F, Marcus M, Ensor C, Kleinbaum D, Cohen S, Edwards A et al (2002) A prospective study of computer users: I. Study design and incidence of musculoskeletal symptoms and disorders. Am J Ind Med 41:221–235. doi:10.1002/ajim.10066

Gerr F, Monteilh CP, Marcus M (2006) Keyboard use and musculoskeletal outcomes among computer users. J Occup Rehabil 16:265–277. doi:10.1007/s10926-006-9037-0

Gordon AM, Casabona A, Soechting JF (1994) The learning of novel finger movement sequences. J Neurophysiol 72:1596–1610

Hanchard NC, Williamson M, Caley RW, Cooper RG (1998) Electrical stimulation of human tibialis anterior: (A) contractile properties are stable over a range of submaximal voltages; (B) high- and low-frequency fatigue are inducible and reliably assessable at submaximal voltages. Clin Rehabil 12:413–427. doi:10.1191/026921598671467836

Heuer H, Schulna R, Luttmann A (2002) The effects of muscle fatigue on rapid finger oscillations. Exp Brain Res 147:124–134. doi:10.1007/s00221-002-1230-6

Jaric S, Radovanovic S, Milanovic S, Ljubisavljevic M, Anastasijevic R (1997) A comparison of the effects of agonist and antagonist muscle fatigue on performance of rapid movements. Eur J Appl Physiol Occup Physiol 76:41–47. doi:10.1007/s004210050210

Johnson PW (1998) The development, characterization and implementation of a technique to measure muscle fatigue during computer use. Doctoral Thesis, University of California

Johnston RB 3rd, Howard ME, Cawley PW, Losse GM (1998) Effect of lower extremity muscular fatigue on motor control performance. Med Sci Sports Exerc 30:1703–1707. doi:10.1097/00005768-199812000-00008

Kruger ES, Hoopes JA, Cordial RJ, Li S (2007) Error compensation during finger force production after one- and four-finger voluntarily fatiguing exercise. Exp Brain Res 181:461–468. doi:10.1007/s00221-007-0942-z

Kuo PL, Lee DL, Jindrich DL, Dennerlein JT (2006) Finger joint coordination during tapping. J Biomech 39:2934–2942. doi:10.1016/j.jbiomech.2005.10.028

Lassen CF, Mikkelsen S, Kryger AI, Andersen JH (2005) Risk factors for persistent elbow, forearm and hand pain among computer workers. Scand J Work Environ Health 31:122–131

Lin Y-N (2005) The effects of high frequency stimulation on fatigue and twitch potentiation. Master Thesis, University of Washington

Lin MI, Liang HW, Lin KH, Hwang YH (2004) Electromyographical assessment on muscular fatigue—an elaboration upon repetitive typing activity. J Electromyogr Kinesiol 14:661–669. doi:10.1016/j.jelekin.2004.03.004

Lucidi CA, Lehman SL (1992) Adaptation to fatigue of long duration in human wrist movements. J Appl Physiol 73:2596–2603

Mair SD, Seaber AV, Glisson RR, Garrett WE Jr (1996) The role of fatigue in susceptibility to acute muscle strain injury. Am J Sports Med 24:137–143. doi:10.1177/036354659602400203

Matias AC, Salvendy G, Kuczek T (1998) Predictive models of carpal tunnel syndrome causation among VDT operators. Ergonomics 41:213–226. doi:10.1080/001401398187260

Mikkelsen S, Vilstrup I, Lassen CF, Kryger AI, Thomsen JF, Andersen JH (2007) Validity of questionnaire self-reports on computer, mouse and keyboard usage during a four-week period. Occup Environ Med 64:541–547. doi:10.1136/oem.2005.026351

Rabin E, Gordon AM (2004) Tactile feedback contributes to consistency of finger movements during typing. Exp Brain Res 155:362–369. doi:10.1007/s00221-003-1736-6

Rempel D, Dennerlein J, Mote CD Jr, Armstrong T (1994) A method of measuring fingertip loading during keyboard use. J Biomech 27:1101–1104. doi:10.1016/0021-9290(94)90227-5

Sadamoto T, Bonde-Petersen F, Suzuki Y (1983) Skeletal muscle tension, flow, pressure, and EMG during sustained isometric contractions in humans. Eur J Appl Physiol Occup Physiol 51:395–408. doi:10.1007/BF00429076

Taylor DC, Dalton JD Jr, Seaber AV, Garrett WE Jr (1993) Experimental muscle strain injury. Early functional and structural deficits and the increased risk for reinjury. Am J Sports Med 21:190–194. doi:10.1177/036354659302100205

Veiersted KB, Westgaard RH, Andersen P (1993) Electromyographic evaluation of muscular work pattern as a predictor of trapezius myalgia. Scand J Work Environ Health 19:284–290