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Differential effects of mental load on proximal and distal arm muscle activity

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Abstract Work-related upper extremity disorders (WRUEDs) that result from keyboarding tasks are prevalent and costly. Although the precise mechanisms causing the disorder are not yet fully understood, several risk factors have been proposed. These include the repetitive nature of the motor task and the associated sustained static working postures, but also more psychological factors such as mental load. Epidemiological surveys have shown that WRUEDs are more prone to develop in the postural muscles of the neck/shoulder area than in the executive muscles controlling the hand. The present study investigated whether the activation patterns of these two muscle types are differentially affected by an additional mental load during the performance of a repetitive tapping task. Participants tapped various keying patterns with their dominant index finger at two prescribed tempi. Mental load was manipulated by means of an auditory short-term memory task. We recorded the EMG activity of two neck/shoulder muscles (trapezius and deltoid), two upper arm muscles (biceps and triceps), and four forearm muscles (flexor digitorum superficialis, extensor digitorum, extensor carpi radialis longus and extensor carpi ulnaris) and analyzed the kinematics and impact forces of the index finger. The results confirmed that the upper limb has two functions. Specifically, activity of the executive distal musculature was increased during tapping at the higher pace, while the activity of the postural upper limb musculature was elevated due to the memory task. We argue that continuously increased muscular activity can lead to fatigue and thus eventually cause musculoskeletal complaints. The results are discussed with respect to biomechanical adaptation strategies that deal with the

consequences of increased noise in the neuromotor system due to enhanced mental processing.

Keywords Cognitive processing · Task performance and analysis · Computer work · Electromyography · Musculoskeletal disorders

Introduction

Keyboarding tasks are embedded in daily human functioning and their performance is thus continuously affected by other cognitive, psychosocial and physical demands. When typing a manuscript, for instance, an approaching deadline may induce stress in the author or he may be mentally preparing himself for tasks that will require his attention later that day. Furthermore, the keyboarder needs to cope with all kinds of sounds or noise emanating from the environment. These internal and external stressors may all strongly interfere with the precise keyboard movements the fingers, hands and arms need to make. From epidemiological studies (Bongers et al. 1993; Melin and Lundberg 1997; Haufler et al. 2000; Macfarlane et al. 2000; National Research Council, The Institute of Medicine 2001; Bongers et al. 2002) it has become clear that job demands and other physical and psychosocial stressors increase the likelihood of keyboarders developing musculoskeletal complaints of the upper limbs, also known as Work Related Upper Extremity Disorders¹. (WRUEDs). Why and how these complaints develop is still subject of debate

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¹Work related upper extremity disorder (WRUED) is one of the prevalent terms used to indicate this group of musculoskeletal disorders. Other more or less homonymous terms used are: Repetitive Strain Injury (RSI), Cumulative Trauma Disorder (CTD), Work Related Upper Limb Disorder (WRULD), Occupational Overuse Syndrome (OOS), Occupational Cervicobrachial Disorder (OCD), Upper Limb Disorder (ULD), and Workrelated Musculoskeletal Disorder (WMSD)

(see for a recent review Visser and Van Dieën 2005). However, there is a growing consensus that the repetitive nature of the motor task, resulting in local muscular overuse, together with sustained static working postures are among the main provoking factors of WRUED, and that these risk factors are strengthened by the above-mentioned psychosocial and mental stressors. Additionally, a personality trait like perfectionism could prevent people to quit typing as fatigue sets in (Van Eijsden-Besseling et al. 2004).

Recently, Van Gemmert and Van Galen (1997; see also Van Galen et al. 2000, 2002) provided a theoretical framework to explain why and how cognitive/psychological stressors may interfere with motor performance and eventually lead to WRUEDs. The theory emphasizes that producing movements efficiently requires the delicate control of intrinsically noisy muscle-recruitment signals. Besides neurophysiological and biomechanical sources of variability, neuromotor signals are, according to the theory, also contaminated by the variability originating from mental and psychological processes.

Recent physiological measurements support the notion that cognitive activity influences the variability of peripheral muscle-recruitment processes. Ribot-Ciscar et al. (2000), for instance, demonstrated enhanced muscle-spindle activity in subjects performing mental arithmetic, showing that cognitive processing may alter the muscles' sensitivity to length-change. We will expand on this issue in the discussion section.

As has been shown in many studies, mental and psychological stressors can influence motor performance in the sense the spatial accuracy or movement velocity alter. However, acceptable levels of performance can be maintained by resorting to adaptive movement strategies that either reduce the overall level of intrinsic neuromotor noise itself or minimize the detrimental effects of increased noise levels on performance. One such strategy is the control of velocity (Harris and Wolpert 1998). Moving at a lower velocity requires a less vigorous set of motor commands that exhibits less noise than the motor-command pattern associated with at higher speeds. Obviously, due to the work pressure common in real-life working conditions, this strategy is not always apposite.

An alternative strategy to increase the effectiveness of control signal is to low-pass filter the outgoing motor signals by setting a task-appropriate level of muscle and joint stiffness (Van Galen and Schomaker 1992; Franklin et al. 2003). Task-appropriate stiffness levels can be achieved by coactivating or cocontracting antagonist muscles of the relevant effector system. By changing the level of cocontraction, viscoelastic properties of the joint and muscles, and thus the whole limb-effector system alter (Hogan 1984; Milner 2004). Increased limb stiffness as a mechanism to adapt to changing physical and spatial task requirements has been demonstrated in e.g. graphical aiming (Van Gemmert and Van Galen 1997), writing (Meulenbroek et al. 2005), pointing (Laursen et al. 1998; Gribble et al. 2003), catching a ball (Lacquaniti and Maiolo 1987), pinching (Serrien et al. 1999;

Danion and Gallea 2004), and even after congenital brain damage (Van Roon et al., 2005). Besides the influence of spatial and physical demands, the dynamics of motor performance in fine motor tasks also changes by cognitive demands. Van Gemmert and Van Galen (1997), and Van Galen and Van Huygevoort (2000) showed increased pen pressure, which is an expression of increased limb stiffness (Wann and Nimmo-Smith 1991), in cognitively more demanding task conditions. Thus, stiffness regulation through cocontraction appears to be a strategy to deal with uncertainties in the motor signal in order to maintain performance at a satisfactory level. However, the strategy is metabolically costly and exposure studies have demonstrated that when muscles continuously work at a low intensity, signs of fatigue already become manifest after one hour (Fallentin et al. 1985; Sjogaard et al. 1986). In this sense, modulating muscular cocontraction is a risky and, in the long-term, a potentially harmful movement strategy. Indeed, we showed that WRUEDed patients displayed pen pressure increments that were a fourfold of that of the healthy controls (Bloemsaat et al. 2004).

Movements generated with a writing stylus can be compared with those generated with a computer mouse since both tools afford fast and accurate movements on a flat surface. Results from experiments in which a ballpoint pen was used suggest that the activity of the entire arm musculature is augmented under increased processing demands. However, in a recently conducted, non-published [2003], key-tapping experiment we found effects of increased cognitive demands in the trapezius descendens muscle but not in the finger flexors. Given that epidemiological surveys show that in workers using visual-display terminals proximal (neck/shoulder) complaints are reported more frequently than distal (fore-arm/wrist/hand) complaints (Blatter et al. 2000; Palmer et al. 2001), we reasoned that cognitive load and spatial task demands might have differential effects on the contraction patterns of distal and proximal musculature. More specifically, we considered two possibilities: (1) that the activation of the proximal muscles of the upper-limb segments are more susceptible to cognitive task demands than activation of the muscles of the distal segments, the latter specifically highlighting spatio-temporal demands, or (2) that the muscles of the proximal and distal segments are equally reactive to increased mental and spatio-temporal processing. If the first option is true, then increased cognitive task demands should increase the activity of proximal muscles only. Conversely, if the second possibility holds, an overall increase of muscular activity should be found in the entire arm under increased mental and spatio-temporal load conditions. Finally, we expected a further increase of muscular activity when participants have to move at a higher pace during the concurrent mental processing task.

To test these hypotheses we conducted an experiment in which we asked participants to tap a repetitive pattern of predefined keystrokes with their dominant index fin-

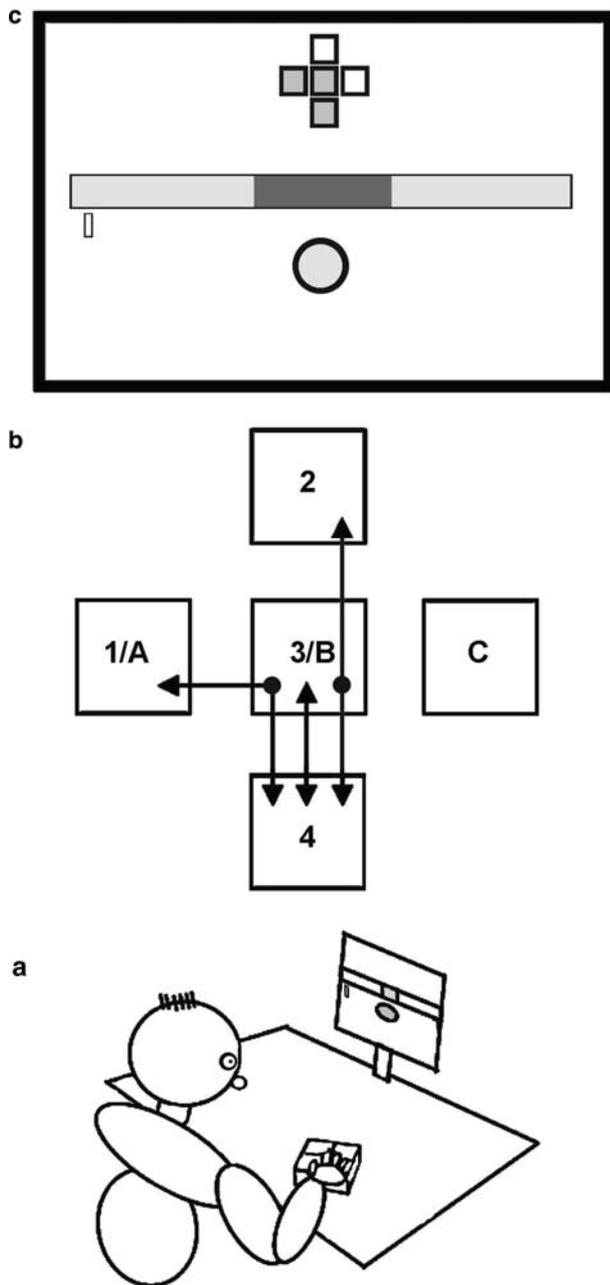


Fig. 1 Schematic representation of the experimental set-up. Panel a: View of participant; Panel b: Tablet configuration. Keys 1–4 were used in the tapping task. The arrows indicate the three cyclical tapping patterns. Subjects pressed keys A–C to give their motor judgment regarding the (dis)similarity of the presented auditory stimuli. Panel c: The stimulus screen

ger (for the patterns, see Fig. 1b). The task was to be performed at two different speeds. The secondary task used to manipulate mental load consisted of an auditory memory task. Participants listened to a 5-tone sequence that was presented prior to the tapping task and were instructed to memorize this tone sequence and compare it to a second 5-tone sequence that would be presented after they had completed the tapping task. Besides muscular activity, we analyzed the kinematics of the

movements generated by the index finger during the tapping task, as well as the impact forces the finger exerted on the keys.

Methods

Participants

Fourteen healthy, right-handed adult participants (5 men, 9 women) volunteered to take part in the experiment (mean age 26 years, SD 2 years, 8 months). All participants had sufficient experience (3 years or more) with the computer keyboard and had normal or corrected-to-normal vision. They received payment or course credits for their participation. The local ethics committee approved the experimental protocol and all subjects signed an informed consent form, as required by the 1964 Declaration of Helsinki.

Apparatus

Participants were seated in a height-adjustable chair at a height-adjustable table, 1 meter in front of a 19-inch computer screen. A force tablet (size 15×15 cm) consisting of five regular keyboard keys (distance between adjacent keys measured from centre to centre was 1.8 cm) was mounted on the table. Each subject sat in a relaxed posture with the right upper arm suspended alongside their trunk and the elbow flexed at 90°, the forearm stabilized on an armrest (for the subject's position and key configuration see Fig. 1, panels a and b). The tablet was positioned such that the stretched hand and index finger could easily press the top (farthest removed) key (2). Furthermore, the tablet was rotated such that the subject's forearm, hand and index finger were in line with the vertical row of keys (2–3–4), i.e. the wrist was positioned in a neutral posture.

Task and procedure

The participants were asked to perform visually guided, rapid tapping movements with their right, dominant index finger. The tapping rate was manipulated at 4 Hz [.25 s. inter-key interval] and 3 Hz [.33 s. inter-key interval]. Subjects tapped one of three possible repetitive key patterns presented on the computer screen: (1) a vertical two-key combination, (2) a vertical three-key combination, or (3) a three-key combination containing a 90° angle (Fig. 1b). Each pattern had to be tapped in a back and forward movement sequence. To manipulate the cognitive task demands, we made use of a short-term memory task that had already proven to be effective in previous pilot experiments [2003] in that the task had elicited errors and had thus necessitated the subjects to maintain certain levels of concentration. The task

required subjects to discriminate between two 5-tone sequences (produced by a mouth organ tuned in C), one presented at the beginning of each trial, i.e. before the actual tapping began, and one after the trial had been completed. In the memory-load condition the sequences were randomly comprised of three tones (tone duration .7 s, inter-tone interval .3 s, loudness 60 dB). The second sequence could differ from the first sequence on one or two tones. The subject judged the two sequences by pressing one of the keys that were assigned the letters A, B and C (see Fig. 1b): key A for equal sequences, and keys B or C for one or two differences, respectively. In the control condition (no memory load) all five tones were equal in both sequences and subjects always pressed key B. By pressing one of the keys (A, B or C) the trial ended.

After having given the participant written and verbal instructions, the experimenter prepared the EMG electrode locations by cleaning and rubbing the skin with alcohol and gel until skin resistance was below 10 k Ω , after which he placed the electrodes on the muscles under study (for more details, see section on data acquisition). Subsequently, one infrared marker was placed on the index finger's nail and one on the styloid process of the ulna. Signals were tested for quality and specification, i.e. whether cross-talk stemming from adjacent muscles appeared. EMG activity, kinematic and kinetic data needed for calibration and synchronizing purposes were collected both under conditions of rest and activity.

Figures 2 and 3 display a typical trial. At the beginning of each trial, the starting screen (as depicted in Figure 1, panel c) was activated showing a red dot, immediately followed by the presentation of the first series of five tones, after which a two-second visual presentation of the tapping pattern appeared. Following

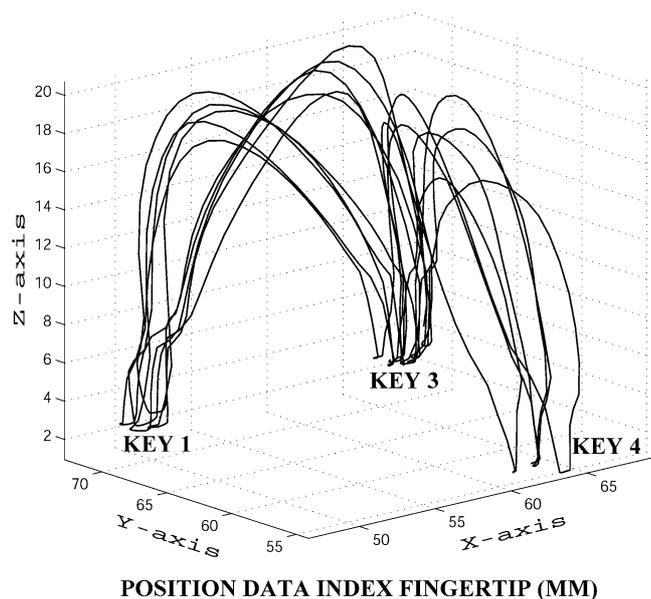


Fig. 2 Three-dimensional representation of a 90° tapping pattern embedded in a memory loaded trial

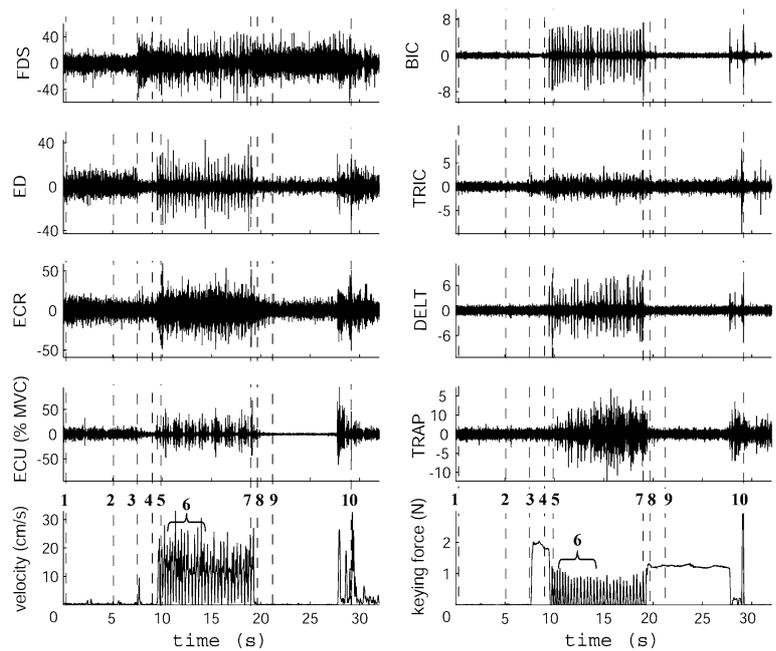
the pattern presentation, the colour of the dot changed from red to yellow. This indicated the subject to place and hold his/her index finger on the lower key until, after a random delay of 1.9 – 2.4 s, the colour of the dot turned to green signalling he/she should start tapping without delay. Simultaneously, a speed-feedback cursor appeared. Depending on the difference between the adopted keying speed and the required tempo, the cursor either moved into the red left-hand side of the bar when the tempo produced was too low or to the bar's red, right-hand side when the tempo was too high. The cursor moved into the central green area when subjects adhered to the correct tempo. Three seconds after the subjects had produced three consecutive back and forward repetitions of a tapping pattern in the correct tempo, the cursor disappeared, after which the green dot turned yellow, indicating that the index finger had to be placed back onto the lowest key of the tablet. One second later the second tone sequence sounded. Pending this presentation, the subjects again kept their right index finger on the lower key. After the last tone had sounded, the subjects pressed one of the response keys (A, B or C). One experimental trial lasted, on average, thirty seconds. After visual inspection and approval of the signals, the experimenter started the next trial. If subjects failed to produce the correct tempo within eight seconds after appearance of the green dot, the trial was repeated immediately.

Prior to the experimental trials the subjects performed a series of 13 practice trials allowing them to master the task at hand. The experiment proper consisted of a total of 72 trials divided into 4 blocks of 18 trials. Within each block, memory load was held constant (A-memory load, B-no memory load) and counterbalanced according to an ABBA or BAAB design. Participants were aware when they had to memorize the tone sequence by an indication of the experimenter. Each of the four blocks was subsequently divided into two smaller blocks of nine trials each. Within these smaller blocks, tempo (either 3 Hz or 4 Hz) was held constant. The tapping pattern varied quasi-randomly from trial to trial. After every 18th trial, subjects were given a 1-minute break to avoid fatigue.

Data acquisition

The tablet was mounted via a custom-made construction (Instrumentation Service, Radboud University, Nijmegen) on a single load cell (DS EUROPE, BC302 miniaturized compression load cell, range 0–6 kg, sensitivity 5.5 gram/milliVolt), which in turn was connected to a custom-made amplifier (Electronic Research Group, NICI, Radboud University, Nijmegen). We recorded position data of the index finger and the forearm using an Optotrak 3020 3D motion-tracking device (Northern Digital), sampling 5×5 mm infrared markers (IREDs) at 200 Hz. Raw EMG activity was sampled at 2 kHz using the Fysioflex (CMRR 90 dB,

Fig. 3 Velocity, force and EMG functions of a typical trial. Numbers 1–10 represent successive events: (1) presentation of first 5-tone sequence, (2) presentation of tapping pattern, (3) placement of the index-finger on key no 4, (4) appearance of cursor, (5) start of tapping, (6) three cycles used for the analysis, (7) end of tapping, (8) placement of the index-finger on key no 4, (9) presentation of second 5-tone sequence, (10) key press of memory task marking the end of the trial



high-pass 20 Hz, low-pass 500 Hz), an EMG-interface module consisting of a custom-made, front-end physiological amplifier (Medical Instrumentation Service, Radboud University, Nijmegen). Adhesive, disposable pre-gelled Ag/AgCl surface EMG disc electrodes (diameter 9 mm, inter-electrode center-to-center distance 2 cm) were placed in a bi-polar derivation, parallel to the fibres at the bellies of the muscles under study, with the reference electrode placed on the spinous process of the seventh cervical vertebra. We measured muscles primarily involved in movements of the hand/wrist (Flexor Digitorum Superficialis, FDS; Extensor Digitorum, ED; Extensor Carpi Radialis Longus, ECR; Extensor Carpi Ulnaris, ECU), of the elbow (lateral aspect of the Biceps Brachii Long Head (Ter Haar Romeny et al. 1984), BIC; Triceps Brachii Lateral Head, TRIC) and of the shoulder/neck (Anterior Deltoid, DELT; Trapezius Descendens, TRAP). An ODAU-II system (Northern Digital, Waterloo, Canada), facilitating 16-bit synchronized collection of analogue and digital data with the Optotrak IRED-displacement data, digitally converted the raw EMG signals and the signals from the strain gauges to 1000 Hz. All data were stored on a computer and the data obtained from the load cell provided the subjects with real-time visual feedback of their tapping rate via a 19-inch stimulus presentation screen.

Data preparation and data analysis

Kinematics and force production

Position data from the Optotrak were converted to 3D position data in a Cartesian coordinate system and subsequently low-pass filtered at 20 Hz using a 2nd order zero phase-lag elliptic filter (MATLAB 5.3,

Mathworks). Fingertip-position data combined with the filtered pressure data from the load cell (low-pass filtered at 20 Hz with 3rd order zero phase-lag elliptic filter), allowed us to determine which key was tapped and the moment at which it was pressed.

EMG

The raw EMG signals were digitally band-pass filtered from 20–400 Hz by means of a fifth-order elliptic filter. Pre-processing of the raw EMG data consisted of applying a Root Mean Square (RMS) filter with a time constant of .02 s, resulting in a rectified, filtered surface-EMG signal (hereafter EMG) for each of the investigated muscles. These signals were expressed as a percentage of a reference Maximum Voluntary Contraction (%MVC).

Due to the elastic properties of the musculotendinous unit, a time discrepancy exists between the recorded EMG signal and the detectable motor response. This delay is termed the electromechanical delay (EMD). EMD has to be accounted for when relating EMG signals to kinematic and/or kinetic data, especially when the investigated time window is of such a short duration as was the case in our experiment. To this end, we determined the EMDs for each subject separately. The EMG data were subsequently time-shifted by the associated delay in order to synchronize them with the kinematic and kinetic data. We did not test the EMDs of the m. trapezius and the m. deltoid because we did not expect the activity of these muscles to be time critical during the experimental task. The EMDs for these muscles were the same as we assigned for the m. biceps brachii. Means and standard deviations in milliseconds of the EMDs for the muscles of the forearm and upper arm were: ED [55/11], ECR [53/9], ECU [50/9], FDS [93/18], BIC [51/8], & TRIC [45/11].

Muscular contraction patterns

The EMG pattern of the primary muscles in keyboarding tasks is characterized by biphasic contractions (Dennerlein et al. 1998). Simply put, in keyboarding the extensor lifts the finger from the key and the flexor moves it down towards the key. The extensor does not need to arrest the downward movement because of the stiff resistance at the end of the key press. Burst and tonic EMG activity distinguishes the reciprocal contractions of the forearm flexor and extensors.

Various procedures are used to represent cocontraction. For example, Winter (1990) expressed it as a ratio between agonist and antagonist activity, while Thoroughman and Shadmehr (1999) introduced the concept of 'wasted contraction', i.e. the amount of muscle activity cancelled out by the opposing muscle(s). These representations, as applies for any other measure that expresses time-varying cocontraction as a kind of ratio or difference between an agonist-antagonist muscle pair, should take into account factors like continuously changing muscle moment arms, differences in force-generating capability for the muscles under study, changing EMG activity under muscle-length or velocity change, and synergistic muscles contributing to the finger and wrist movements.

In our study we did not measure the kinematics of the finger-and wrist joints nor did we record EMG activity from all muscles contributing to the finger and wrist movements. Consequently, estimation of time-varying cocontraction based on a ratio of agonist and antagonist muscle activity seemed inappropriate to us. However, an alternative way to define cocontraction is to determine the amount of antagonist muscle activity (Gribble et al. 2003) after movement ending. We reasoned that this method might also be applicable to movements if, despite increased cognitive processing, no change would appear in the kinematics of the movement, i.e. no net torque changes. Otherwise the results would be confounded, because cocontraction alters when kinematics change (Suzuki et al. 2001). As will be described in the results section, the external visual pacing controlled the participants' performance speed during the entire experiment and we therefore considered it was justified to use antagonist muscle activity as a measure of cocontraction.

Whereas the distal upper-limb segments executed the movements on the keyboard, the elbow and shoulder remained in an externally supported position. In principle, this should require little extra effort from the muscles spanning the elbow and shoulder. As the shoulder and elbow remain in a stable position, there is not a clear state of agonistic or antagonistic muscle functioning. Further, the muscles we tested in the shoulder do not function as opposites. Therefore, the use of the term cocontraction or coactivation is avoided. Instead, we may conclude in the case of globally increasing proximal muscle activity that contact areas of the joints come closer to each other, which lead to increased joint stiffness (Bosga et al. 2003).

Statistics

We analyzed the trace of the tapping trajectory that was identical for all three keying patterns, i.e. the movements between the lowest key (4) and the centre key (3). Both the movement from key 3 to 4 and the reverse movement between key 4 and 3 were included in the data analyses and the combination of these two movements was treated as a single cycle. The starting movements (the first two key presses) were omitted from the time-series analysis due to high variability both between and within subjects. Additionally, to control for possible abating effects of memory load over time, we restricted the analysis of the tapping movements to the first four cycles following the eliminated starting movements only. Obviously, the time needed to make four repetitions of the two-key pattern was shorter than the time needed to generate the four repetitions of the three-key patterns.

The EMG data during tapping were time-normalized to a hundred data points per cycle comprising the back-and-forth movements between keys 4 and 3. Per trial, the averaged four cycles provided a mean pattern of muscle activation. Single data points were created for keying force, reaction and movement times, accuracy measures, and for muscle activity during the stationary phases of each trial. All data points served as entries for a within-subject MANOVA (TEMPO [2] * MEMORY LOAD [2]). The results of the time-normalized EMG data were considered statistically significant if three consecutive bins were significant². Data analysis was carried out with SPSS 11.5.

Results

In the next paragraphs the results will be described for the various measures separately. In Figure 4, the panels a-d, f-i display the time-normalized, averaged muscular activity of the eight muscles under investigation and the panels $e_{1&2}$ and $j_{1&2}$ show the average tangential velocities and the vertical index finger lift respectively for the experimental variables *memory load* and *tempo* separately.

Performance changes over the course of the experiment

We assessed possible performance changes due to learning or fatigue by comparing memory task errors, reaction time, and the time subjects needed to produce three consecutive tapping cycles of forward and backward movements in the correct tempo during the first and the second half of the experiment.

²Assuming an alpha of 0.05, the odds that three consecutive bins hold a type I error is $0.05 * 0.05 * 0.05 = 0.000125$ or 1 in 8000 cases. We tested 100 bins, the chance of a Type I error being $100 * 0.000125 = 0.0125$, which is well below the initial alpha level of 0.05 (see also Van Schie et al. 2003).

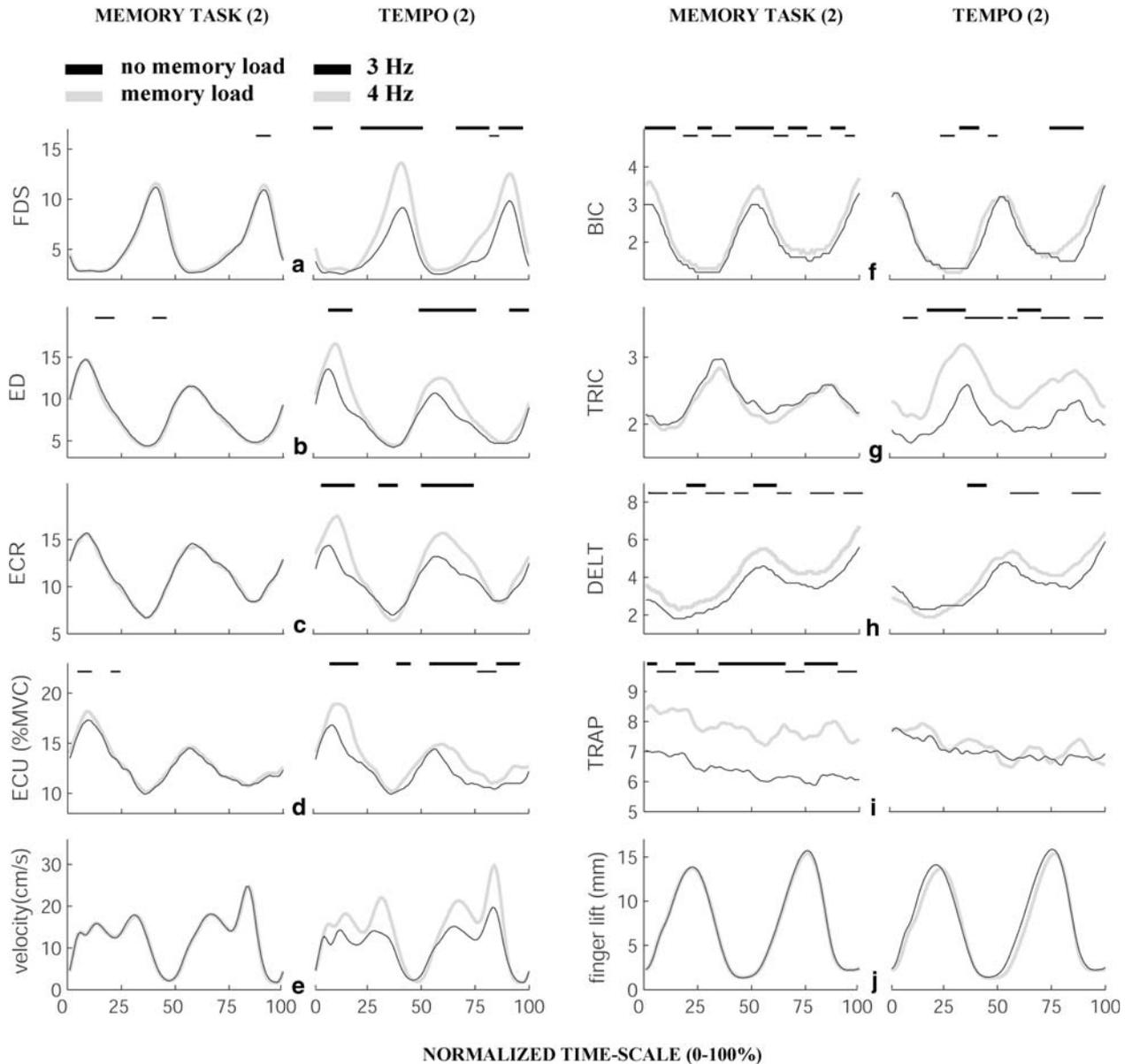


Fig. 4 The panels (a-d, f-i) display the mean traces of muscle activity (% MVC) for the muscles under study presented on a time-normalized scale. The left-hand side of the panels represent the reactions on the short-term memory task (1), the right-hand side the reactions on the speed of tapping (2). Significance levels per bin are indicated by *thick bar* for $P < .05$ and by *thin bar* for $P < 0.1$. The averaged velocity traces are depicted in panel e and the vertical lift of the index finger tip in panel j

The short-term memory task appeared to be quite difficult. On average, the subjects misidentified 27% of the tone sequences in the memory-loaded trials. There were no significant differences between the first and second part of the experiment, nor was the error rate significantly influenced by tapping tempo. The results further showed that subjects tended to react faster in the second half of the experiment (268 ms versus 245 ms, $F_{(1,13)} = 3.97$, $P = .068$). This proved to be an overall, consistent trend because there were no significant

interactions with memory load or with the required tapping tempo. Furthermore, the time subjects needed to attain the correct tempo was not significantly different (on average 5.19 s, $F_{(1,13)} = 1.5$, ns) between the halves.

Motor performance

Next, we will describe whether and how the kinematics, the temporal -and spatial accuracy, and the keying force changed during the first four cycles in the tapping sequence as a function of memory load and tempo.

Contrary to our hypotheses of a mutual influence of memory load and tempo on the measured variables, the results revealed no significant interaction on any of the variables. Since this was true for all the dependent measures that were assessed, we will not mention this again in our discussion of the various findings below.

Kinematics

The panels e_1 and e_2 of Fig. 4 show the velocity profiles of the index finger. As expected, typing at a higher tempo led to higher velocity. As can be seen in the figure, increased memory processing did not lead to changed velocity profiles of the index finger.

Spatial accuracy

The area of key impact along the Y-axis (the axis in line with the forearm, hand and index finger) became slightly smaller for the memory loaded condition as compared to the non-loaded condition (1.2 mm vs. 1.4 mm, $F_{(1,13)} = 13.2$, $P = .003$). As a result of this decrease, the overall spread was reduced for the memory-loaded condition (from 1.5 mm to 1.4 mm, $F_{(1,13)} = 10.4$, $P = .007$). Movement speed did not influence spatial accuracy.

Temporal accuracy

In the memory-load condition, on average, the participants deviated more from the imposed tempo (16 ms) than they did in the control condition (13 ms), $F_{(1,13)} = 5.3$, $P = .038$, i.e. in the loaded condition participants were less consistent in their tapping rate. Further, tapping in the 4 Hz tempo led to a small but significant augmented tempo deflection compared to the 3 Hz tempo (16 ms vs. 13 ms, $F_{(1,13)} = 5.0$, $P = .044$).

Keying force

During the two stationary phases of the experimental trials, isometric keying force on the bottom key (4) changed under memory demands. Participants pressed harder in the memory-loaded conditions of both stationary phases 1.99 N versus 1.78 N during the pre-tapping period ($F_{(1,13)} = 7.4$, $P = .018$) and 1.91 N versus 1.78 N during the post-tapping period ($F_{(1,13)} = 5.7$, $P = .033$). However, during tapping no difference in keying force was observed as a result of memory load ($F_{(1,13)} < 1$, ns). For tempo, the situation was reversed: isometric key pressure in the stationary phases was unchanged, while key pressure during tapping increased from 1.6 N to 1.75 N for the faster tempo ($F_{(1,13)} = 29.3$, $P < .001$).

EMG activity of the proximal and distal arm musculature

Pre-trial stationary measurements

After the auditory presentation of the first series of tones and the visual presentation of the typing pattern,

participants placed and held their right index finger on the lower key (4). Memory load led to higher average EMG activity in three of the eight muscles. Mean ECU activity was raised from 8.8% MVC to 9.8% MVC ($F_{(1,13)} = 11.2$, $P = .005$) and FDS from 6.9% MVC to 8.0% MVC ($F_{(1,13)} = 3.3$, $P = .09$). Trapezius descendens increased from 6.8% MVC to 8.5% MVC ($F_{(1,13)} = 5.3$, $P = .04$). The pre-imposed tempo did not significantly affect the pre-tapping EMG activity in any of the measured muscles.

First four cycles of tapping

As memory load did not alter tapping velocity, the changes in EMG due to the memory load were not contaminated by changed kinematic profiles.

Memory load (Fig. 4, left panels grey thick line), operationalized by having the participants remember a 5-tone sequence, elicited small, local effects in the prime movers. FDS and EDC phasic peak activity increased significantly (the mean difference both being .7% MVC; see Fig. 4, panels a_1 and b_1). During the remaining course of the movement, however, no further changes were observed. In contrast, overall consistent reactions were found in three of the four postural upper limb muscles. Biceps activity increased slightly but significantly in the memory-load condition. On average, EMG activity was raised from 2.0% MVC to 2.3% MVC. DELT activity displayed a trend of increased activity ($P < .1$) over most of the movement trajectory. Mean DELT EMG activity increased with .7% MVC (3.3% MVC to 4.1% MVC). Finally, TRAP activity showed the largest and most distinct effect under the influence of memory load, its activity rising from 6.4% MVC to 7.8% MVC.

Tempo (Fig. 4, right panels) significantly affected the prime movers of the hand and fingers. Tapping at the faster rate of 4 Hz produced higher EMG activity in all four forearm muscles measured. As can be seen in panels a_2 - d_2 of Fig. 4, the increase in activity was mainly significant during those parts of the movement where the involved muscle had a phasic function, i.e. where the muscle acted as an agonist. When the muscle functioned as the antagonist, no significant differences occurred. Of the proximal muscles (Fig. 4, panels f-i), only TRIC activity was enhanced when a faster typing rate was used (mean difference .5% MVC), while BIC and DELT were activated more immediately before the middle key was pressed (3). TRAP activity remained the same in both speed conditions.

Post-trial stationary measurements

Memory load caused significant reactions in two muscles, one muscle showed a trend. Trapezius descendens ($F_{(1,13)} = 5.0$, $P = .043$) and ECU ($F_{(1,13)} = 4.7$, $P = .05$) increased activity from 6.9% MVC to 8.4% MVC, and from 9.3% MVC to 9.9% MVC respectively. Biceps

activity ($F_{(1,13)}=3.9$, $P=.07$) rose from 1.1 to 1.3% MVC. Again, we did not find an effect of TEMPO on EMG activity in any muscle.

Discussion

We investigated potential effects of mental processing on the muscular activation patterns of the upper limb system during tapping activity of the dominant index finger. For this purpose, we designed a keying task and analyzed the muscle activation, kinematics, and kinetics at three different points in time: pre-movement, during movement and post-movement. The keys were mounted on a force tablet and participants had to press various repetitive key combinations in a prescribed, on-line visual-feedback maintained tempo (3 Hz or 4 Hz). We introduced additional mental processing in the form of a concurrent short-term memory task. The subjects had to memorize a 5-tone sequence presented before the actual tapping task, which they had to compare with a second 5-tone sequence after they had completed the tapping task.

The main finding of this study points to a functional separation between primarily executive and primarily supportive musculature of the upper limb segments in reaction to cognitive stress. While the prime movers of the index finger and wrist (EDC, ECR, ECU and FDS) showed little to no change in reaction to increased memory demands, the supportive musculature displayed consistent effects. In three of the four upper limb/shoulder muscles measured (BIC, DELT, and TRAP) EMG activity was elevated, with the increase present in respectively eleven, ten, and twelve out of the fourteen participants tested. On the kinematic level we found no alterations in velocity due to increased memory processing. During tapping in the memory-loaded trials, participants showed reduced spatial variation but increased temporal variability of their tapping movements. Although a trade-off between these two variables seemed likely, no significant correlation was found. The effects of tapping tempo mainly manifested itself in the prime movers of the hand and the wrist. The faster tempo led to increased muscular activity, particularly during the movement phases when the muscle had an agonistic, phasic function.

Differential effects of cognitive processing on upper-limb muscle activity

The results of our study suggest different functions for the executive distal upper-limb musculature and the proximal supporting upper-limb musculature. Thus, our first proposal that the muscles of proximal upper-limb segments are more susceptible to cognitive task demands than muscles from the distal segments seems to be confirmed.

The majority of studies examining the influence of mental stressors on muscle activity in visual display terminal (VDT) tasks, focussed on the trapezius as the muscle of interest. This is a logical choice since most complaints are reported from that area. A general conclusion from those experiments is that mental load increases the activity in the trapezius muscle (e.g. Lundberg et al. 1994; McNulty et al. 1994; Bansevicius and Sjaastad 1996; Lundberg et al 2002). Fewer studies take the forearm muscles into account (e.g. Finsen et al 2001; Van Galen et al. 2002; Wahlstrom et al. 2002). To our knowledge only one study by Waersted and Westgaard (1996) also analysed the contribution of upper arm muscles in a cognitive loaded task. In that study, subjects performed a complex two-choice reaction-time task with the fingers of the right hand, and cognitive processing was manipulated by motivational stimuli (money incentives or continuous feedback on performance). While they recorded EMG signals stemming from muscles of the arm, shoulder, face, spine, trunk and calves, EMG from the primary executing muscles of the right forearm we not measured. Furthermore, the movements of the right fingers were not recorded. However, the general conclusion from the Waersted and Westgaard study (1996) is in agreement with the outcome of our experiment, i.e. that muscle activity tended to decrease in caudal direction in reaction to a psychological stressor. Furthermore, as participants did not display altered kinematic and kinetic profiles during the memorizing of the tone sequences, the increment of EMG activity can be assigned to the cognitive loaded condition solely. Latter is a strength of our experimental setup, because interpretation of other experimental data is often complicated by changing motor performance, e.g. muscular activity increases as a result of increased time pressure, but at the same time the motor output is being enhanced by the higher demands (Birch et al. 2000).

In a previous experiment (Bloemsaat et al. 2004) involving a graphical aiming task, we reported increased pen pressure as a function of mental processing and regarded that as a sign of increased limb stiffness. Stiffness regulation can be exploited to optimize motor performance as has been demonstrated in various settings (see Introduction). However, we showed in the present experiment, that no sign of cocontraction following increased cognitive processing appeared in the distal parts of the arm. This finding suggests that a possible filtering strategy does not by definition occur in the total limb. In the next paragraphs we introduce a number of possibilities that could provide explanatory grounds for our findings.

Intuitively, it makes sense to resist against a perturbation, whether it is of internal or external origin, with the aid of larger and stronger muscles than with the aid of smaller and weaker muscles. Hamilton et al. (2004) recently presented experimental evidence for this notion. Using a torque-matching task, they demonstrated that the motor output from the stronger, more proximal

joints in the human arm showed less variability than the output from the weaker, more distal joints. They further showed an inverse relationship between the level of noise found in the upper-limb muscles and the number of motor units within that muscle, i.e. the muscles with smaller numbers of motor units displayed higher levels of motor noise. Based on their findings, it is plausible that the larger muscles positioned around the shoulder and neck are better suited to deal with the increased neuromotor noise following increased mental processing than the smaller muscles of the forearm and hand.

An alternative explanation of the presently observed increased proximal muscle activity under memory-loaded conditions is that the enhanced neuromotor noise required adjustments of the available biomechanical degrees of freedom (DOF) in the motor system in order to optimize performance. This notion fits in with the theoretical view advocated by Bernstein (1967), which is best illustrated by the ranking of the top 10 athletes in the "Men 50 m Rifle 3 Positions" at the 2004 Olympic Games in Athens. These athletes showed the highest accuracy when they fired their shots from a prone position, followed by kneeling down with the supporting elbow placed on the knee. The 'poorest' performance occurred while shooting from an upright stance, where practically all joints in the body can attribute to the variability. Soechting (1984) also provided experimental evidence supporting a DOF reduction in order to increase accuracy. He showed that the coupling between the elbow and shoulder joints became tighter when subjects reached towards a smaller target. DOF adaptation also plays a role in coping with increased psychological processing. Van Loon et al. (2001) demonstrated that in a combined weight-lifting and arithmetic task the elbows were positioned closer to the body in a mental-stress condition than in a control condition. Higuchi et al. (2002) reported that more spatially constrained movement paths were generated when participants had to hit a target under conditions of increased accuracy demands. In their experiment the targets did not vary in size but light electrical shocks served as a psychological motivator to elicit accurate movements.

Although the presence of a mechanism controlling the available biomechanical DOFs might be a different theoretical approach to explain how humans deal with the problem of increased cognitive processing, there undoubtedly is overlap with the neuromotor noise theory of motor control. In the latter theory, a control mechanism, i.e. muscular cocontraction, filters the noisy motor signal by adjusting muscle stiffness. At the same time, however, the contact surfaces of the joints' constituent bones are brought closer together by the increased cocontraction of the surrounding musculature, thus tightening the joint (cf. Bosga et al. 2003) and reducing the various DOFs.

We expected an additive effect of memory load on EMG activity in the speeded tapping condition. However, we found that muscle activity increased similarly in

both tempo conditions. Again, the reason for this phenomenon may be that the larger muscles are the ones that primarily (have to) deal with the consequences of increased neuromotor noise. Apparently, muscular activation patterns as studied in the present experiment may differ fundamentally from the patterns observed in experiments using the pen as the device of input. In our task, the armrest divided the participant's arm in two separate functional units: executive (wrist/hand) versus postural (elbow/shoulder). Conversely, writing and drawing tasks imply that the segments of the arm function as tightly coupled units (Wann and Nimmo-Smith 1991). The existence of two separate functional arm units in our tapping task may thus explain why memory load did not interact with tempo. As was shown in the results section, tapping speed did not alter the activity of the majority of the proximal musculature. Therefore, an interaction between tempo and memory load was less likely to occur.

Effects of continuously enhanced muscular activity

One could cast doubts on the overall small effects of the mental load in our experiment and its relevance regarding the development of WRUED. Nonetheless, the effects in the postural musculature were continuously present over the entire range of the analyzed movement segments and several researchers have found adverse effects of such continuous low-level muscular activity. Fallentin et al. (1985) and Sjogaard et al. (1986) showed that continuous low-muscle activity, i.e. less than 10% of the MVC, in time does lead to muscle fatigue. Furthermore, Kim et al. (1999) reported increased blood-flow under such conditions, which is a sign that, due to the accumulation of metabolites, hypoxia already occurs after a 30-s low-intensity (5% MVC) isometric contraction. An additional contribution of 1.5% MVC due to increased mental processing then could become a significant risk factor for developing complaints.

Capitalizing on the effects of continuous muscular activity, Johansson and Sojka (1991) formulated a pathophysiological mechanism to explain the genesis and spread of muscular tension in WRUED. In short, they propose that when chemosensitive group-III and group-IV slow-conducting muscle afferents are activated, for example by fatigue, the γ -fusimotor system is triggered. The latter system allows state-dependent adjustments of length and velocity feedback. Increased γ -motoneuron activity influences the discharge of both types Ia and II muscle-spindle afferents. These muscle spindles respond to increasing length and length-change by increasing their firing frequency, thereby exciting the α -motoneurons of the muscle containing the spindles and enhancing the reflex-mediated component of the muscle stiffness (intrinsic muscle stiffness is dependent on the viscoelastic properties of the muscle and the existing actin-myosin cross bridges). Furthermore, the CNS can alter the muscle spindles' sensitivity via activity

in the γ -fusimotor system. Increased activity in the fusimotor system will, in turn, lead to a further increase of muscle stiffness.

Furthermore, it is suggested that the fusimotor system, rather than being automatically triggered to compensate for muscle shortening, can be activated independently from the α -motoneuronal system (Ribot-Ciscar et al. 2000). The possibility of independent activation is interesting in the light of the assumption that the γ -fusimotor system may play a role in human cognitive processes. Ribot-Ciscar et al. (2000), Rossi-Durand (2002), and Nafati et al. (2004) have recently investigated this view. In a series of experiments they mechanically or electrically stimulated nerves or had participants make passive joint movements and recorded the activity of muscle spindle afferents. Increased activity would indicate that the γ -fusimotor system sensitizes the muscle spindle. Indeed, under the influence of cognitive load, muscle-spindle discharge increased. The implication here is that in humans, similar to what has been shown in non-human mammals (see review by Prochazka 1989), the fusimotor system adapts to arousal and expectancy to perform the ongoing motor task and regulates the reflex-mediated component of the muscle stiffness. Such state-dependent stiffness regulation fits in with the notion that optimal signal-to-noise ratios in motor output can be achieved by adjusting limb stiffness (Van Galen and Van Huygevoort 2000).

Some final comments have to be made with regard to the results of our experiment. Of the four measured proximal muscles, only triceps activity did not increase following amplified memory processing. A possible clarification might lie in the anatomical and functional proximity of the biceps to the shoulder compared to the triceps lateral head. Whereas the latter is a monoarticular muscle head solely spanning and controlling the elbow joint, the long head of the biceps brachii, besides the elbow, also spans and controls the shoulder. Yamazaki et al. (2003) showed that coactivation in muscles that share the primarily moving or focal joint is greater than in muscles that do not share that joint. Assuming that the focus of the adaptation to increased neuromotor noise is situated in the shoulder area, that area then could be considered as the focal joint. While the biceps span the focal joint, the triceps lateral head does not, and therefore did not cocontract in our experiment.

A second comment concerns the salience of the cognitive stimuli. Even if the cognitive stimuli we used only affected the proximal musculature, it is likely that mental processing could have affected the forearm muscles had the presented stimuli been stronger. Other experiments already showed that stronger stimuli do change motor behaviour. However, stimuli like the STROOP colour-word test (used in Laursen et al. 2002), tap attentional resources to such a high degree that they cannot be considered as ecological equivalents of activities normally present in dual task performance; they rather represent the extremes on a continuous scale.

Future research could test whether a systematic relationship exists between the intensity of cognitive processing and the consequences on a muscular and performance level.

Finally, we already suggested that typing with the arm supported might separate the upper limb into two functional units, viz. an executive and postural unit. It would be of interest to investigate whether the effects of cognitive processing would be changed with different arm configurations, i.e. whether we would observe a shift towards an entire upper-limb activity increase in situations where memory demands are higher and the limb configuration more tightly coupled. This would help clarify whether the use of armrests in an office environment could be beneficial to employees and also what parts of the body should certainly be targeted in remedial therapy when complaints of WRUED have developed.

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