The combined influence of task accuracy and pace on motor variability in a standardised repetitive precision task

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Thirty-five healthy women, experienced in pipetting, each performed four pipetting sessions at different pace and accuracy levels relevant to occupational tasks. The size and structure of motor variability of shoulder and elbow joint angles were quantified using cycle-to-cycle standard deviations of several kinematics properties, and indices based on sample entropy and recurrence quantification analysis. Decreasing accuracy demands increased both the size and structure of motor variability. However, when simultaneously lowering the accuracy demand and increasing pace, motor variability decreased to values comparable to those found when pace alone was increased without changing accuracy. Thus, motor variability showed some speed-accuracy trade-off, but the pace effect dominated the accuracy effect. Hence, this trade-off was different from that described for end-point performance by Fitts’ law. The combined effect of accuracy and pace and the resultant decrease in motor variability are important to consider when designing sustainable work systems comprising repetitive precision tasks.

Practitioner summary: Variability in movements and/or muscle activities between repeats of the same repetitive task is associated with important occupational outcomes, including fatigue, discomfort and pain. This study showed that simultaneously decreasing accuracy and increasing pace in short-cycle repetitive work led to decreased motor variability in arm movements, indicating less favourable ergonomics conditions.

Keywords: cyclic movements; Fitts’ law; kinematics; linear and nonlinear variability; motor control; speed-accuracy trade-off

Introduction

Motor variability refers to the intrinsic variability naturally present in the motor control system. Occurring even in the simplest movements, it is usually manifested as a difference in joint movements, joint coordination and/or muscle activities between successive repeats of a task, which are intended to be identical in performance. In occupational life, examples include activities such as repetitive lifting tasks (Granata, Marras, and Davis 1999; van Dieen et al. 2001), carpentry work (Hammarskjöld, Harmsringdahl, and Ekholm 1990) and meat cutting (Madeleine, Voigt, and Mathiassen 2008). Motor variability has recently received increased attention from occupational biomechanics researchers due to its association with important variables in working life, such as pain, fatigue and skill acquisition (reviewed in Srinivasan and Mathiassen 2012). Furthermore, as ‘too little variation’ has been suggested to be an important cause of musculoskeletal disorders (MSD) in jobs consisting mainly of repetitive operations (Mathiassen 2006), some authors have suggested that individuals with a larger motor variability would be better protected against overuse injuries (Madeleine et al. 2003; Mathiassen, Moller, and Forsman 2003). This notion was formalised in a model describing changes in upper-extremity motor variability as a function of pain stages and experience (Madeleine 2010).

The recent review of motor variability in an occupational context by Srinivasan and Mathiassen (2012) concludes that one important area of research is to understand which factors in the design of work can be used to systematically manipulate motor variability. The review lists a set of factors such as pace, accuracy demands and workstation configuration, which can be expected to have an effect on motor variability, and thus be candidates for ergonomics interventions promoting variation in highly stereotyped, repetitive work. The present study explores the effects of changing both task accuracy demands and work pace on motor variability in a standardised repetitive task performed by the upper extremities.

The first question addressed by the present study concerns the effect of changing task accuracy demands on motor variability. In a study of 3D pointing movements, Tseng and colleagues found that the range of joint configurations used to control the hand’s movement path reduced when task accuracy was increased, and that the goal-equivalent variance

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decreased (Tseng et al. 2003). The authors suggest that this indicates a loss in the flexibility of the motor system when accuracy demands of a task are increased. Furthermore, their finding of reduced movement variability at the shoulder and elbow joints and in shoulder-elbow coordination with increase in accuracy demand was consistent with previous studies (Soechting 1984; Kudoh et al. 1997). Thus, we expected that decreased accuracy demands would increase motor variability, not just in discrete movements but also in cyclic tasks.

The second question addressed by the present study is whether this expected effect of increased motor variability due to decreased accuracy demands would be modified by work pace in a ‘speed-accuracy trade-off’. In a previous study based on the same population, we have reported that increasing pace alone (without changing accuracy demands) led to a decreased motor variability in the shoulder and elbow joint movements when performing short-cycle precision work (Srinivasan et al. 2014). According to expectations from the classic Fitts’ law model of speed-accuracy trade-offs (Fitts 1954), a decrease in accuracy demands would have opposite effects on motor performance from those caused by an increased pace. Fitts’ law has been widely confirmed in both discrete and cyclic movements performed in a variety of conditions (reviewed in Plamondon and Alimi 1997; Schmidt and Lee 1999). Although different theories have been proposed, the neurophysiological and biomechanical properties of the motor system that form the basis of such speed-accuracy trade-offs, as well as the implications of these properties to motor control, are still not clearly understood (Smits-Engelsman, Van Galen, and Duysens 2002). In the present study, we investigated the hypothesis that the variability of joint kinematics in a short-cycle precision task would exhibit a speed-accuracy trade-off similar to that described by Fitts’ law, i.e., that less accuracy and faster pace have opposite effects on motor variability.

Thus, we hypothesised that when accuracy demands are decreased at a maintained work pace in a short-cycle precision task, motor variability increases, but if pace is then increased while keeping the decreased accuracy demands, motor variability is reduced again towards baseline levels, even if the extent of that reduction is difficult to predict. We have chosen baseline pace and accuracy demands in our task to simulate authentic conditions in real working life, and changed both factors within limits matching likely occupational demands. Motor variability can be described using both its size and structure. Both the size and structure of motor variability have been shown to convey complementary and important information about motor control (Sosnoff, Valantine, and Newell 2006). Furthermore, since both the size and structure of motor variability have been related separately to neck-shoulder pain and skills in repetitive work (Madeleine and Madsen 2009; Madeleine 2010), we investigated motor variability using metrics from both domains.

Methods

Pipetting was used as an ecologically valid model of short-cycle, repetitive precision work using the upper extremities (Park and Buchholz 2013). The pipetting task (see below) was performed in the laboratory by 35 right-handed female volunteers, who had at least 1-year experience in pipetting (mean 28 (SD 7) months), and were free from any shoulder pain or injury at the time of the study. Subjects were aged 25 (SD 5.8) years, had height of 164 (SD 8.8) cm and had body mass of 60.4 (SD 7.3) kg. All subjects signed an informed consent prior to inclusion. The experiment was approved by the Ethical Review Board in Uppsala, Sweden and conducted in accordance with The Helsinki Declaration. The present experiment was part of a larger study, from which other results have been reported elsewhere (Srinivasan et al. 2014).

Experimental setup

The pipetting task setup is described in detail in a recent publication investigating the effect of work pace on arm movement variability (Srinivasan et al. 2014). Briefly, the participants sat in a rigid chair, and their torsos were strapped to the back of the chair, to restrain trunk movements and thus standardise the working posture. The height-adjustable table surface was positioned to be at each participant’s elbow height when sitting in an upright position. One pipetting session consisted of transferring liquid repeatedly from a pickup-tube of diameter 20 mm, placed to the right and in front of the participant, to each of eight target tubes 20 times, i.e. in total 160 cycles (8 tubes × 20 repeats). The target tubes were placed in a 10 × 10 array of identical tubes to ensure a realistic task setup. In each of the 160 cycles, the target tube was indicated by a light mounted below that tube. The sequence of target tubes and the work pace were controlled by a computer program, which provided an auditory cue to signal pace, in addition to the shifting lights below the target tubes. The subjects were instructed that the primary requirement of the experimental task, i.e. successful performance, was to transfer liquid to the correct target tubes at the set pace.

Each participant performed pipetting in a reference condition at a standardised work pace of 2.8 s/cycle and with target tubes of diameter 6 mm, which is referred to as the ‘reference-accuracy-reference-pace’ condition (RARP). Another pipetting session was performed at the same work pace, but with target tubes of diameter 12 mm (low-accuracy-reference-pace condition, LARP), placed in a 4 × 4 array so that the eight target tubes were at the same distances from each other as
the target tubes in the reference condition, and at the same positions relative to the subject. In a third and fourth session, participants pipetted to the small and large target tubes, respectively, but at a faster pace, 2.4 s/cycle (reference-accuracy-high-pace and low-accuracy-high-pace conditions, i.e. RAHP and LAHP, respectively). Other than the work pace and size of target tubes, all other working conditions were maintained to be exactly the same for all four pipetting sessions. These paces and accuracy demands were chosen to simulate and be representative of realistic occupational demands when performing precision work. The paces roughly corresponded to 100 and 120 MTM (Methods-Time Measurement, a predetermined motion time system used in industrial settings to set the standard time for completion of a task, (Maynard, Stegemerten, and Schwab 1948)), and the target tubes were of sizes commonly used in pipetting in laboratories and hospitals. Each pipetting session of 160 cycles lasted 7–8 min, and the order of the different pipetting sessions was randomised, with 10 min of rest in between each successive session. Each pipetting session could be performed without any significant localised muscle fatigue in the arm, as confirmed by the stable amplitude and frequency content of electromyographic signals from the upper trapezius and forearm extensor muscles throughout each session (data not reported here). In order to get familiarised with the setup, all participants performed a practice session of 100 pipetting cycles in the reference-accuracy-reference-pace pipetting condition before actual data collection.

Data collection and processing

Kinematic data were recorded and processed as described previously (Srinivasan, Rudolfsson, and Mathiassen 2014; Srinivasan et al. 2014). Briefly, data were recorded by means of two synchronised electromagnetic tracking systems (Fastrak, Polhemus, USA), at a sampling rate of 30 Hz, filtered using a fourth order low-pass Butterworth filter with a cut-off frequency of 3 Hz, and used for estimating shoulder, elbow and wrist joint angles as defined by the ISB conventions (Wu et al. 2005). Thumb forces exerted on the pipette were recorded using a thin-film finger-tip force sensor (A201, Tekscan, Inc., Boston, USA) mounted on the pipette’s push button. In addition, electromyography recordings were collected from shoulder and arm muscles but only the kinematics data will be presented in this paper. The kinematic data were sampled continuously for each pipetting session, but then broken down into cycle-to-cycle data based on the pipette-tip velocity and thumb force signals. Cycles of shoulder elevation (i.e. the conical angle between the upper arm and axis of gravity) and elbow flexion (i.e. the angle between the upper arm and fore arm segments) associated with pipetting movements to each target were used for all further analyses.

In each pipetting cycle, the following variables were computed for shoulder elevation and elbow flexion: range of motion (ROM), peak velocity (Peak Vel), average velocity (Avg Vel), time to peak velocity (Time PV), and area under the movement curve (Area). The cycle-to-cycle standard deviation of each variable was first computed across 20 repetitions to each target, and the median value across all eight targets was then used as an estimate of pooled cycle-to-cycle standard deviation. These pooled cycle-to-cycle standard deviations (‘ROMSD’, ‘Peak VelSD’, ‘Avg VelSD’, ‘Time PVSD’, ‘AreaSD’) were used as metrics describing the size of motor variability of shoulder elevation and elbow flexion movements (Madeleine, Mathiassen, and Arendt-Nielsen 2008; Madeleine, Voigt, and Mathiassen 2008).

In addition to these variables, time-normalised angles were calculated for each cycle by expressing angle recordings in terms of 11 equidistant samples, such that each normalised data point represented ~10% movement time (cf. Chau, Young, and Redekop 2005). Similarly, time-normalised phase was calculated and expressed in terms of 11 samples/cycle, where phase at any time instant was defined according to (Hamill et al. 1999):

$$\phi = \tan^{-1} \frac{\dot{\theta}_{\text{norm}}}{\omega_{\text{norm}}}$$

where $\theta_{\text{norm}}$ is the joint angle normalised to maximum joint angle in the cycle and $\omega_{\text{norm}}$ is the joint velocity normalised to maximum velocity in the cycle.

The standard deviations across all cycles of time-normalised angle and phase were calculated for each target, and their median values across all eight targets were termed ‘Time norm AngleSD’ and ‘Time norm PhaseSD’.

Complementary to the size of motor variability, structural variability was quantified using sample entropy and recurrence map analysis. All pipetting cycles to each target were divided into three sets each containing an approximately equal number of concatenated cycles. Each set was offset-corrected by subtracting its mean value, and normalised to its own standard deviation. Sample entropy (SaEn) (Richman and Moorman 2000), percentage of determinism in the recurrence map (DET) and Shannon entropy of the sequential recurrent map (RMEn) (Webber and Zbilut 1994; Webber Jr and Zbilut 2005) were calculated for each set and target, and afterwards averaged across the three sets for each target. Median values of these averages across all eight targets were computed and used as metrics describing the structure of motor variability in shoulder elevation and elbow flexion movements.
In addition to these motor variability metrics, liquid transfer times, i.e. the time between picking up liquid from the pickup tube and delivering it into the designated target tube, were computed as a measure of temporal motor behaviour. Liquid-transfer-time variability (cycle-to-cycle standard deviations of transfer-time) and task performance were also computed, using procedures described in (Srinivasan et al. 2014).

Statistical analysis
The size and structure variability metrics were tested for the effects of change in task accuracy only, as well as simultaneous change in pace and accuracy demands by pairwise comparisons of the LARP and LAHP sessions, respectively, with the RARP session. The effect of changing pace alone, without changing the demands on accuracy, was investigated in a previous publication comparing the RAHP with the RARP session (Srinivasan et al. 2014).

Since the 10 dependent variables (motor variability metrics) showed low to moderate pairwise correlations, and since none of these metrics was expected to be normally distributed, we compared pipetting conditions in this study using multivariate spatial signed-rank tests, separately for shoulder elevation and elbow flexion (Möttönen and Oja 1995; Oja and Randles 2004; Möttönen, Oja, and Serfling 2005).

Post-hoc analysis was performed for each of the 10 variables using univariate Wilcoxon signed-rank tests, with Holm’s sequentially rejective procedure to adjust for multiple tests (Holm 1979). Holm’s adjustment implies that the result for any particular variable is considered significant only if the corresponding p-value is less than $p/n$, where $p$ is the univariate test result and $n$ is the rank of that particular test among all univariate tests according to its p value. For instance, the variable with the smallest $p$ value of all 10 tested variables needs to have a $p < 0.05/10 = 0.005$ to be considered statistically significant.

Effect sizes were calculated using the procedure described in a previous paper (Srinivasan et al. 2014): i.e. as the difference in median values between conditions divided by the inter-quartile range among subjects in the reference condition. Similar to categories used in parametric statistics (Cohen 2013), effect sizes were described as being either small (effect size $\sim 0.2$), moderate (effect size $\sim 0.5$) or large (effect size $\sim 0.8$).

Univariate Wilcoxon signed-rank tests were run separately on liquid-transfer-time variability and task performance, to test for the effect of low accuracy and the combination of high pacing and low accuracy on these variables ($p$-values less than 0.05 were considered statistically significant).

All statistical analyses were performed in MATLAB® (release 2012b, The MathWorks, Inc., Natick, MA, USA).

Results
Averaged over all cycles, targets and subjects, the group mean liquid-transfer-time (grand SD across all cycles) was 1.17 (0.21) s in the RARP condition, 1.31 (0.22) s in the LARP condition and 1.08 (0.18) s in the LAHP condition. Liquid-transfer-time variabilities, expressed as median (inter-quartile range across all cycles) were 0.24 (0.08) in the RARP condition, 0.26 (0.1) in the LARP condition and 0.18 (0.08) in the LAHP condition. Liquid-transfer-time variability increased when accuracy was lowered (LARP vs. RARP conditions: $z = -2.96, p = 0.003$), with a small effect size of 0.25, whereas cycle-time variability decreased with increased pace and lowered accuracy (LAHP vs. RARP: $z = 9.73, p < 0.001$, with a large effect size of 0.75).

Performance results showed that the median number of mistakes made by any particular participant when performing the 160 operations in a pipetting session (i.e. the number of times liquid was pipetted to wrong target tubes) did not differ across conditions; it was 0 (inter-quartile range 1) in both the RARP and LARP conditions, and 0 (2) in the LAHP condition.

Even though the focus of this study is on kinematic motor variability, the mean values of kinematic parameters are shown in Figure 1 for descriptive purposes. The mean values for shoulder joint angles in Figure 1(a) show that when accuracy demands were lowered, the average velocity and time to peak velocity decreased, and the area under movement curve increased significantly. Only a decrease in the time to peak velocity was observed when comparing the LAHP with the RARP condition. The elbow angles in Figure 1(b) show that peak velocity, average velocity and time to peak velocity were lower, whereas the area under movement curve was higher in the LARP than the RARP condition. Significant increases in the peak and average velocities and a drop in time to peak velocity was observed in the LAHP compared to the RARP condition.

Effect of a change in only accuracy demands (comparison of LARP with RARP)
Box plots of all motor variability metrics in the RARP and LARP conditions are shown in Figures 2 (shoulder) and 3 (elbow). The general trend is that for shoulder elevation movements, all metrics of motor variability increased when accuracy was lowered, except for SaEn, which decreased in the LARP condition, when compared to the RARP condition. The multivariate signed-rank test showed a significant difference in shoulder motor variability between LARP and RARP conditions ($p = 0.0047$). Subsequent univariate Wilcoxon signed-rank tests indicated that this increase was significant only
for ‘Area SD’ ($z = -2.74, p = 0.006$) and ‘DET’ ($z = -2.64, p = 0.008$), but not for any of the eight other variables. Effect sizes were 0.41 for the increase in ‘Area SD’ and 0.14 for the increase in ‘DET’. The same trend of most metrics of motor variability increasing when accuracy was lowered, except for SaEn, was also found for elbow flexion movements (Figure 3). The multivariate signed-rank test indicated that there was a significant difference in elbow motor variability between LARP and RARP conditions ($p = 0.0016$). However, subsequent univariate Wilcoxon signed-rank tests indicated that only the decrease in SaEn from RARP to LARP was significant ($z = 4.38, p < 0.001$), with an effect size of 0.50.

**Effect of a change in both accuracy demands and pace (comparison of LAHP with RARP)**

Box plots of all motor variability metrics in the RARP and LAHP conditions are shown in Figures 2 (shoulder) and 3 (elbow). For shoulder elevation movements, all metrics of motor variability were lower in the LAHP than the RARP conditions.
The multivariate signed-rank test indicated that there was a significant difference in shoulder motor variability between the LAHP and RARP conditions ($p = 0.0006$). Results of the subsequent univariate Wilcoxon signed-rank tests are presented in Table 1, showing the decrease in motor variability to be significant for 6 of the 10 metrics. Furthermore, the effect sizes for a simultaneous change in accuracy and pace were small for ‘$\text{Area}_{SD}$’ and ‘Time-norm Phase $\text{SD}$’ and moderate-large for all other variables.

The general trend of a decrease in motor variability in LAHP when compared to the RARP condition was also found for elbow flexion movements, for all metrics except peak velocity (Figure 3). The multivariate signed-rank test showed that there was a significant difference in elbow motor variability between the LAHP and RARP conditions ($p = 0.0001$). Subsequent univariate Wilcoxon signed-rank test results shown in Table 1 showed that the decrease in motor variability was significant in 6 of the 10 metrics. Effect sizes for the simultaneous change in accuracy and pace were small for ‘Time-norm Phase $\text{SD}$’ and moderate-large for all other significantly different metrics.
Table 1. Median values, M, with Inter-Quartile Range, IQR, of dependent shoulder and elbow variables in the reference-accuracy-reference-pace (RARP) and low-accuracy-high-pace (LAHP) pipetting conditions; results of Wilcoxon signed-rank tests of the difference between conditions (z statistic and p-values); and effects sizes for significant effects, as marked by boldface p-values.

<table>
<thead>
<tr>
<th>Shoulder elevation</th>
<th>Elbow flexion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M (IQR): RARP</td>
</tr>
<tr>
<td>ROM&lt;sub&gt;SD&lt;/sub&gt; (%)</td>
<td>4.1 (2.4)</td>
</tr>
<tr>
<td>Peak Vel&lt;sub&gt;SD&lt;/sub&gt; (%)</td>
<td>13.3 (5.5)</td>
</tr>
<tr>
<td>Avg Vel&lt;sub&gt;SD&lt;/sub&gt; (%)</td>
<td>6.4 (2.6)</td>
</tr>
<tr>
<td>Time PV&lt;sub&gt;SD&lt;/sub&gt; (%)</td>
<td>11.2 (2.7)</td>
</tr>
<tr>
<td>Area&lt;sub&gt;SD&lt;/sub&gt; (%)</td>
<td>7.5 (3.7)</td>
</tr>
<tr>
<td>Time norm Angle&lt;sub&gt;SD&lt;/sub&gt; (%)</td>
<td>5.1 (1.4)</td>
</tr>
<tr>
<td>Time norm Phase&lt;sub&gt;SD&lt;/sub&gt; (%)</td>
<td>13.1 (3.8)</td>
</tr>
<tr>
<td>SaEn</td>
<td>0.2 (0.1)</td>
</tr>
<tr>
<td>DET</td>
<td>97.6 (0.7)</td>
</tr>
<tr>
<td>RmEn</td>
<td>3.4 (0.2)</td>
</tr>
</tbody>
</table>

<sup>a</sup>Difference in median values between conditions divided by the inter-quartile range among subjects in the reference condition

Discussion

Motor variability has recently emerged as an issue of interest in occupational studies. Changes in the size and structure of motor variability without any decrease in performance can occur due to the availability of redundant degrees of freedom to perform multi-jointed movements, illustrating the flexibility in motor control (Bernstein 1967; Dingwell and Marin 2006). Changes in structural metrics of variability have been interpreted as showing that the time line of a process changes (Stergiou, Harbourne, and Cavanaugh 2006), by identifying the dynamics of movement control systems (Slifkin and Newell 1999). Moreover, changes in the size and structure of motor variability have been shown to be associated with important outcomes in occupational life such as pain, fatigue and performance (Madeleine 2010; Srinivasan and Mathiassen 2012).

The present study investigated the changes in size and structure of motor variability caused by manipulating the pace and accuracy demands of a standardised short-cycle repetitive precision task. We used pipetting as an experimental model, to not just investigate the kinematics of that task per se, but also to obtain data that would be representative of short-cycle repetitive work occurring in many different occupational settings, such as industrial assembly and food processing (Ohlsson et al. 1994; Fallentin et al. 2001; Juul-Kristensen et al. 2002; Hansson et al. 2006; Nordander et al. 2008).

All subjects participating in this study had at least 1-year experience in pipetting, and were also subjected to a practice session of 100 trials before data collection, to ensure that the effects found in this study were not confounded by gradual learning. Proficiency was confirmed by the fact that the median number of mistakes in a single pipetting session was zero (out of 160 cycles) in all three investigated conditions.

Motor variability was studied using seven metrics describing its size and three metrics reflecting its structure in the present study. Previous reports of motor variability in occupational literature have considered one or more of these metrics, but not all the ones reported here (e.g. Côte et al. 2005; Madeleine, Mathiassen, and Arendt-Nielsen 2008; Madeleine, Voigt, and Mathiassen 2008; Madeleine and Madsen 2009; Lomond and Cote 2010; Bosch et al. 2011). Since different studies have reported on different metrics, it is difficult to compare results across studies, and also to get a comprehensive picture about motor variability and its interpretation (since the same factor can increase the variability in some metrics, and decrease that of others). It is also still not clear from the literature as to which of these metrics are the most relevant for assessment of performance or risks in occupational work (reviewed in Srinivasan and Mathiassen 2012). Hence, we have studied the effects of pace and accuracy on several of the most commonly reported metrics, as a follow-up of our earlier studies on the reliability of these metrics in pipetting work (Srinivasan et al. 2014; Samani et al. 2015).

As accuracy demands were lowered without changing the pace (LARP vs. RARP), liquid-transfer-time variability increased significantly, even though the effect size was small (0.1). Shoulder and elbow kinematic variabilities increased in general when accuracy demands were lowered, in line with our hypothesis, but the changes were not statistically significant in most of the metrics (c.f. Figures 2 and 3). The direction of changes in the size of motor variability with accuracy is in line with previous results reported in studies of pointing tasks (Soechting 1984; Tseng et al. 2003). The moderate effects in our study could possibly be explained by pointing tasks requiring exact precision with no tolerance, whereas realistic precision work, as in our task, does allow a certain tolerance at the target since the task is successfully performed whenever the pipette tip arrives at the target tube (target tube diameters were 6 and 12 mm in the RARP and LARP conditions, respectively). SaEn decreased in both the shoulder and elbow movements, and this decrease was statistically significant with a large effect.
size for elbow flexion angles, indicating a decrease in complexity. Such a decrease in entropy has been previously associated with discomfort and pain in other studies (Madeleine and Madsen 2009; Madeleine 2010). To the best of our knowledge, changes in the structure of kinematic motor variability with changing task accuracy demands have not been reported before in the literature. Further research including longitudinal studies is necessary to answer whether this decrease in movement complexity in presence of lower accuracy demands leads to detrimental physiologic effects.

When simultaneously increasing pace by 15% and lowering the accuracy demand by doubling the diameter of the target tube, motor variability systematically decreased in 6/10 metrics for both shoulder and elbow movements (c.f. Figures 2 and 3, and Table 1 comparing LAHP with RARP). Although the variability in range of motion and peak velocity did not change, the other variables, i.e. average velocity, time to peak velocity, area under the movement curve, time-normalised angle and phase, showed less variability in the in the LAHP condition with increased pace and less accuracy demands than in the reference RARP condition. This systematic decrease in the size of motor variability was similar to that previously reported when pace was increased by 15% without changing the demands on accuracy (Table 1 in Srinivasan et al. 2014). The result that variabilities in the range of motion and peak velocity did not differ between the conditions, while the average velocity and time to peak velocity did, may indicate that temporal aspects of the size of variability are more susceptible to change while variability in movement amplitude is less sensitive to changes in pace and accuracy. Among the metrics reflecting the structure of motor variability, only RmEn decreased significantly in both the shoulder and elbow movements, indicating a decrease in movement complexity, in line with findings from (Dingwell and Marin 2006). Thus, when both accuracy and pace were changed simultaneously, we did find, as hypothesised, that increased pace and decreased accuracy had opposite effects on motor variability. Furthermore, the pace effect seemed to be equally strong irrespective of accuracy demands; i.e. the pace effect masked the effect of accuracy, at least at the levels of pace and accuracy investigated in our study.

In an occupational context, the trade-off between accuracy and pace is of particular interest in precision work like pipetting, where workers may not have the opportunity to relax on accuracy to the extent allowed in other short-cycle repetitive tasks, such as letter sorting into pigeon holes. Furthermore, pace within limits relevant in, e.g. industrial tasks, had effects on motor variability that dominated over those resulting from relevant changes in demands for accuracy. According to Fitts’ law (Fitts 1954), performance can be maintained at an increased work pace if accuracy is relaxed accordingly, but our study suggests that the speed-accuracy trade-off is different for motor variability and dominated by pace effects.

Thus, in addition to the extensive literature available on risks associated with exposure levels of, for instance, muscle loads and postures, our study documents for the first time that changes in pace and accuracy demands in short-cycle repetitive tasks can lead to changes in motor variability. The decrease in the flexibility of motor control following from pace and task accuracy changes may, in the long run, lead to undesirable outcomes such as muscle fatigue (Srinivasan and Mathiassen 2012). The idea, that a limited motor variability may also be a risk factor for musculoskeletal disorders (MSD) in repetitive work, has been proposed and discussed in several previous studies (e.g. Mathiassen, Moller, and Forsman 2003; Mathiassen 2006; Madeleine, Mathiassen, and Arendt-Nielsen 2008; Madeleine, Voigt, and Mathiassen 2008; Madeleine 2010; Côté 2012). Thus, our results can be of importance when designing work systems comprising repetitive precision tasks, even though the interpretation of different metrics for motor variability in a context of occupational health, well-being and performance is, so far, not developed to any major extent.

Further research is necessary to verify whether the effects of pace and accuracy found in this study of pipetting as a model of repetitive work are also generalisable to more complex tasks occurring in working life. Also, the effects of pace and accuracy demands on motor variability might be different for other occupationally relevant levels of pace and accuracy than those tested in this study.

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