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Differences in motor variability among individuals performing a standardized short-cycle manual task

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ABSTRACT

Motor variability (MV) has been suggested to be a determinant of the risk for developing musculoskeletal disorders in repetitive work. In this study we examined whether individuals consistently differed in the extent of motor variability when performing a standardized short-cycle manual task. On three separate days, arm kinematics was recorded in 14 healthy subjects performing a pipetting task, transferring liquid from a pick-up tube to eight target tubes with a cycle time of 2.8 s. Cycle-to-cycle standard deviations (SD) of a large selection of shoulder and elbow kinematic variables, were processed using principal component analysis (PCA). Thereafter, between-subjects and between-days (within-subject) variance components were calculated using a random effects model for each of four extracted principal components. The results showed that MV differed consistently between subjects (95% confidence intervals of the between-subjects variances did not include zero) and that subjects differed consistently in MV between days. Thus, our results support the notion that MV may be a consistent personal trait, even though further research is needed to verify whether individuals rank consistently in MV even across tasks. If so, MV may be a candidate determinant of the risk of developing fatigue and musculoskeletal disorders in repetitive occupational work.

1. Introduction

As pointed out by Bernstein 50 years ago (Bernstein, 1967), no particular movement is ever repeated with exactly the same movement trajectory, regardless of the extent of practice, experience, or skill of the subject performing the movement. This intra-individual motor variability (MV), defined as a spatiotemporal dispersion in joint movements, coordination and muscle activities between successive repeats of the same task, has traditionally been seen as undesirable performance inconsistencies or errors, reflecting immature or insufficient sensorimotor functioning. However, more recent research emphasizes positive functional aspects of MV, with respect to both long-term motor learning and short-term adaptations of movement strategies (e.g., Davids, Glazier, Araujo, & Bartlett, 2003; Latash, Scholz, Danion, & Schoner, 2002; Wu, Truglio, Zatsiorsky, & Latash, 2015). Thus, MV has been suggested to be essential for maintaining performance under

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changing environmental conditions, for adapting to changes in the musculoskeletal system during growth, and for permitting exploration of constraints in the task or environment, so that stable motor solutions can develop over time (e.g., Newell, Deutsch, Sosnoff, & Mayer-Kress, 2006; Newell & Vaillancourt, 2001; Riley & Turvey, 2002).

The functional role of MV has been emphasized also in occupational and clinical research (Srinivasan & Mathiassen, 2012). Repetitive work, where similar operations are repeated again and again (e.g., Kilbom & Persson, 1987), is a generally accepted risk factor for musculoskeletal disorders in the shoulders and upper extremities (Cote et al., 2008). Since increased posture and movement variability may potentially distribute stresses better between tissues, and thus reduce the cumulative load on specific tissues, MV could play a significant functional role in delaying or preventing acute fatigue and development of chronic musculoskeletal disorders (MSD; e.g., Mathiassen, 2006; Srinivasan & Mathiassen, 2012). Theories like the "Cinderella recruitment hypothesis" (Hägg, 1991), and the "Variability-overuse hypothesis" (reviewed in Bartlett, Wheat, & Robins, 2007), have further detailed why highly stereotyped motor behavior may increase the risk of developing MSDs. The Cinderella hypothesis states, on basis of Henneman's theory of a size-ordered recruitment of motor units with increasing contraction force (Henneman, Somjen, & Carpenter, 1965), that some low-threshold motor units will be activated as soon as the muscle contracts, and stay active during monotonous work until total rest, with increased risk for overuse of these, primarily, small sized (type I) muscle fibers. Thus, the Cinderella hypothesis implies that spatial and temporal variation in muscle recruitment is needed to alleviate risk. The variability-overuse hypothesis essentially conveys the same message, i.e. that lack of variation in postures and muscle recruitment can lead to overuse injuries.

While all individuals repeat a particular task with some MV, the extent of this variability appears to differ between individuals (e.g., Hammarskjold, Harms-Ringdahl, & Ekholm, 1990; Mathiassen, Moller, & Forsman, 2003; Srinivasan, Rudolfsson, & Mathiassen, 2015; van Dieen, Dekkers, Groen, Toussaint, & Meijer, 2001). In studies of work and sports, MV has been shown to be associated with the skill level of the individual (e.g., Madeleine & Madsen, 2009; Robins, Wheat, Irwin, & Bartlett, 2006), and it changes as a natural part of skill development (e.g., Gentile, 1972; Vereijken, Emmerik, Whiting, & Newell, 1992). Other individual factors known to influence MV are, for example; age (e.g., Kruger, Eggert, & Straube, 2013), gender (e.g., Svendsen & Madeleine, 2010), chronic pain (e.g., Madeleine, Mathiassen, & Arendt-Nielsen, 2008), and body composition (e.g., Chiari, Rocchi, & Cappello, 2002). Women typically exhibit lower MV than men, and older people lower MV than younger. Notably, Madeleine et al. (2008) found that acute experimental pain *increased* arm movement MV, presumably because subjects explored alternative motor solutions to reduce pain, while chronic pain was associated with *reduced* MV, interpreted to reflect an attempt to avoid painful movements and postures (Madeleine et al., 2008). However, consistent differences in MV between individuals are likely to occur even in populations that are rather homogeneous with respect to these factors. Motor behavior largely depends on anatomical and physiological constraints known to differ between individuals even if they have the same gender, age and health status, such as muscle strength, flexibility and sensory capacities. Also psychological traits and processes have a bearing on motor behavior. Recent MRI studies of the human brain suggest that individual differences in several basic and higher cognitive functions, including, for example; perception, motor control, memory, and the capacity for introspection can be predicted from the structural anatomy of the brain and so appearing to be stable individual attributes (reviewed in Kanai & Rees, 2011; MacDonald, Nyberg, & Backman, 2006). Hence, long-standing differences among individuals in physical and cognitive abilities, formed by genetics and lifetime experience, suggest consistent differences also in motor behavior, including motor variability. However, very few empirical studies, if any, have verified whether individuals in a homogeneous population with respect to gender, age and health do, indeed, differ consistently in MV, even after taking into consideration that any particular individual will vary in her motor patterns when performing a specific task several times within a day, as well as when performing on different days (Bernstein, 1967; Rabbitt, Osman, Moore, & Stollery, 2001). The issue of whether healthy subjects populating a particular job or enterprise differ consistently in MV is of high relevance in an occupational health context. Some evidence suggests that individuals with larger MV may be less prone to fatigue (Falla & Farina, 2007; van Dieen, Oude Vrielink, & Toussaint, 1993), and pain (Madeleine & Madsen, 2009), and that they may recover faster from injury (Moseley & Hodges, 2006). In extension, this could imply that individuals performing repetitive work with a larger MV would be less at risk of developing MSD than individuals performing the same tasks with less MV (Madeleine, 2010; Mathiassen, 2006).

Assessment of MV can be performed on different levels. Both higher level aspects of movement performance (kinematics, kinetics), and lower level aspects (muscle activation) provide unique perspectives, and they are usually modelled separately. Investigations of muscle activity are relevant in the context of musculoskeletal disorders, and some studies have, indeed, addressed both kinematics and muscle activity in occupationally relevant tasks (e.g., Bosch, Mathiassen, Visser, de Looze, & van Dieen, 2011; Madeleine, Mathiassen et al., 2008; Madeleine, Voigt, & Mathiassen, 2008). However, a challenge when investigating MV in complex multi-joint movements is the multitude of muscles involved, and the extensive redundancy both within and between muscles that needs to be identified and analyzed. Consequently, registrations of surface EMG are of limited use for more delicate studies of MV on a muscle activation level in dynamic movements like reaching. Most current models of motor control, however, assume encoding of high-level parameters of motor behavior such as velocity and position of the effector, rather than detailed specification of muscles (Shumway-Cook & Woollacott, 2012). A focus on kinematic aspects may therefore provide more realistic and applicable models of human movement behavior in dynamic multi-joint movements.

Kinematic analysis typically involve a large number of recordings and measurements such as displacements, velocities and acceleration of joints and segments. In previous work of the task addressed in the present paper we have reported day-to-day (within subject) and between-subjects variances for several metrics describing motor variability (Samani, Srinivasan, Mathiassen, & Madeleine, 2015; Srinivasan, Rudolfsson et al., 2015). While these MV metrics represent different movement aspects, the papers pointed out that they were likely highly correlated, suggesting that a multivariate analysis method should be adopted in future research for the purpose of extracting non-redundant main features of movement patterns.

Thus, in the present study, we apply a principal component analysis procedure in an attempt to answer the question: to which extent do young healthy females performing the same short-cycle manual task differ in the cycle-to-cycle variability of their kinematic movement patterns? As part of the analysis of differences between subjects, we also assessed the extent to which a particular individual shows the same motor variability on different days.

2. Methods

2.1. Participants and laboratory setup

Pipetting was used as a representation of repetitive manual work requiring low force but high precision (Park & Buchholz, 2013). The pipetting task was performed in a laboratory by 14 healthy female subjects, who repeated it on three different days under identical experimental conditions. Due to technical problems in the data, one subject was excluded from the study. The subjects were nurses or university students in nursing and health education programs. The subjects were aged, on average, 25 (SD 4.6) years, were 168.4 (SD 7.8) cm tall and weighed 62.1 (SD 6.8) kg. All participants were right-handed, free from any shoulder pain or injury at the time of the study, and had at least one year of experience in pipetting (on average 28 (SD 7) months). All subjects signed an informed consent prior to inclusion. The experiment was approved by the Ethical Review Board in Uppsala, Sweden (Dnr. 2012/344) and conducted in accordance with The Helsinki Declaration.

2.2. Workstation setup and task description

The standardized pipetting task setup is described in detail in recent publications investigating the reliability of MV variables in the task, as well as the dependence of MV on work pace and precision demands (Samani et al., 2015; Srinivasan, Mathiassen, Samani, & Madeleine, 2015; Srinivasan, Rudolfsson et al., 2015; Srinivasan et al., 2016). Briefly, the participants sat in a rigid chair, and their torsos were strapped to the back of the chair to restrain trunk movements and standardize the working posture. The fixture with target tubes for pipetting (see below) was placed on a height-adjustable table surface, which was positioned 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 to eight target tubes 20 times each, i.e. in total 160 cycles (8 tubes $\times$ 20 repeats), with a standardized work pace of 2.8 s/cycle. The pickup-tube was placed to the right and in front of the participant, and the target tubes were placed in a 10X10 array of identical tubes (Fig. 1). Light emitting diodes were mounted below the eight target tubes, and in each of the 160 cycles, the target tube to which liquid was to be transferred was indicated by that particular light coming on. The sequence and the pace at which lights were turned on and off (i.e., the sequence of target tubes and work pace) were controlled by a custom-made computer program, which acted as a metronome. Pilot tests were conducted to ensure that a complete pipetting session of 160 cycles, lasting 7–8 min, could be performed without any significant localized muscle fatigue in the arm.

Each subject performed the pipetting task under identical experimental conditions on three different days within a two-week period, with at least two days between each experiment.

Subjects were seated upright with no bending of the torso, and had on average a 41° upper arm elevation angle and a 67° elbow flexion angle (Hallman, Srinivasan, & Mathiassen, 2015). Surface electromyography recordings showed that, on average, subjects activated their right upper trapezius to 9% of the maximum voluntary capacity (MVC), and that the average forearm extensor activity corresponded to 10% of MVC (Hallman et al., 2015).

2.3. Measurements and data processing

Kinematic data were recorded and processed as described in a previous publication from the same research project (Srinivasan, Rudolfsson et al., 2015). Briefly, data were recorded by means of two synchronized electromagnetic tracking systems (Fastrak, Polhemus, USA), at a sampling rate of 30 Hz, filtered using a fourth order low-pass Butterworth filter with a cutoff 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, USA) mounted on the pipette's push button. The kinematic data were sampled continuously for each pipetting session, and then broken down into cycle-to-cycle data based on the pipette-tip velocity and thumb force signals. The starting point of a movement cycle was defined as the instant when the pipette tip was at the pickup-tube and its velocity was at a minimum. The end point was defined as the instant when the force on the pipette's push button was at its maximum (i.e. when liquid was dispelled into the target tube). Within each cycle, the instants when the velocity of the pipette-tip increased above and decreased below 5% of peak velocity were used as cut-off points to further trim each cycle. This procedure resulted in shoulder elevation and elbow flexion joint angle data for 20 repeats of the transfer phase of each pipetting cycle, i.e. the part of the cycle when liquid was transferred from the pick-up tube to the target-tubes; these data were used for further analyses.

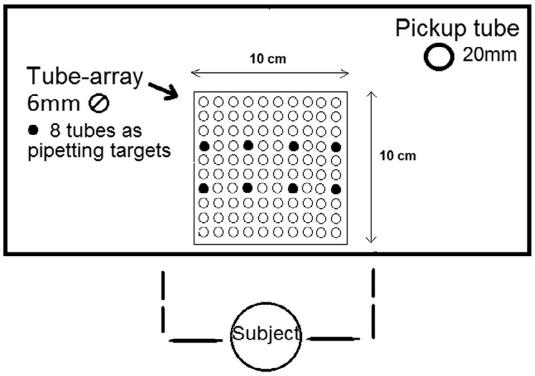

Fig. 1. Schematic of the work station setup.

The kinematic properties of shoulder elevation and elbow flexion movements were summarized using the metrics and procedures described in Srinivasan, Rudolfsson et al. (2015). The cycle to cycle standard deviation across all twenty repeated cycles of movement to each target were calculated for the following variables for both shoulder and elbow movements: range of motion, average angle, peak velocity, average velocity, time to peak velocity, area under the movement curve, and average phase (' ROM_{SD}', 'Avg $Angle_{SD}$', 'Peak Vel_{SD}', 'Avg Vel_{SD}', 'Time PV_{SD}', '$Area_{SD}$', 'Avg $Phase_{SD}$'). In addition to these variables, the standard deviation across all cycles of time-normalized angle and time-normalized phase (i.e. angle vs. angular velocity) were also computed as 'Time norm $Angle_{SD}$' and 'Time norm $Phase_{SD}$' (see Srinivasan, Rudolfsson et al. (2015) for details). These variables, describing kinematics of the shoulder and arm, are all standard in the motor control literature, and were selected for their potential relevance in the context of MSD in repetitive occupational work (Srinivasan & Mathiassen, 2012).

Since there were eight targets in total, the pooled cycle-to-cycle standard deviations across all the eight targets were calculated for each subject, on each test occasion, and these variables were used as descriptors of motor variability. This computation was repeated for each test occasion, and thus estimates of cycle-to-cycle standard deviations of shoulder and elbow MV variables were obtained for each subject on each of three days.

2.4. Data analysis

The between-days (within-subject) and between-subjects variance components of each of the MV variables were reported in Srinivasan et al. (2015). However, while representing different kinematic aspects the variables were correlated (r = 0.36–0.72), and may, to some extent, reflect similar underlying control properties, while still conveying independent information. Therefore, in the present study, multivariate analysis was conducted using principal component analysis (PCA) to reduce data dimensionality and aggregate variables into a few linearly uncorrelated principal components, while retaining the main part of the variance in the data. For each subject and MV variable, the root mean squared value across the three test occasions was calculated as an estimate of 'average' MV, and the PCA was performed on these estimated averages; one per MV variable and subject. The number of principal components was selected according to Kaiser's criterion of eigenvalues above 1 (Kaiser, 1960). Thereafter, each subject's results on the individual MV variables from days 1, 2 and 3 were multiplied by their respective PC score coefficient to give a score on each PC for each subject and day.

These individual PC scores were then checked for any systematic difference between measurement days, since the statistical model used below assumes that 'day' can be treated as a random source of variability. When no systematic effect of day was identified, the total variance in scores was partitioned for each of the PC components separately into its between-subjects and between-days (within-subject) components using a one-way random effects model:

$$p = \mu + \alpha_{sub} + \varepsilon_{day} \tag{1}$$

where P is the score of the analyzed PC for a particular subject on a particular day, μ is the grand group mean of that PC, α_{sub} is the subject effect and ε_{day} is the residual effect corresponding to the effect of day within subject.

This model was resolved using an one-way nested ANOVA in MATLAB to obtain the between-subjects variance component (S_{BS}^2) i.e. the variance of α_{sub} in the model, and the between-days within-subject variance component (S_{BD}^2), i.e. the variance of ε_{day}, along with their 95% confidence intervals.

The between-days variance component measures the consistency of individual MV patterns across the three days, while a consistent difference in MV between subjects will appear as a non-zero between-subjects variance. We also calculated intra-class correlation coefficients (ICC) of the component scores for each of the extracted PCs:

$$ICC = \frac{S_{BS}^2}{S_{BS}^2 + S_{BD}^2} \quad (2)$$

3. Results

The original 18 variables were reduced using the PCA to four PCs representing different dimensions of MV. Together, the PCs explained 87.6 percent of the total variance in data (Table 1). The correlation between the PCs and the original variables are represented by the variable loadings shown in Table 2.

The first component, PC1, primarily reflected the variability of average joint angles, range of motion and velocity, while PC2 was primarily composed of phase variability metrics. Together, PC1 and PC2 explained approximately 65% of the total variance in data (Table 1). PC3 and PC 4 together explained little more than 20% of the variance in the data; PC3 was dominated by the variability of the area under the movement curve, and PC4 was composed of high average velocities and opposing trends of% time to peak velocity of shoulder and elbow (i.e., a high positive loading of % time to peak *velocity* in the shoulder and a high negative loading of the same variable for the elbow, see Table 2).

For all variance components except the between-subjects variance of PC3, the 95% confidence intervals did not include zero (Table 3), indicating that subjects differed consistently in "average" MV, and that days differed consistently in MV

Table 1
Eigenvalues of and variance explained by the four principal components extracted in the PCA of kinematic motor variability metrics (cycle-to-cycle SDs) averaged over three days.

Principal component	Eigenvalue	Explained variance (%)	Cumulative variance (%)
PC1	7.5	41.5	41.5
PC2	4.3	23.7	65.2
PC3	2.4	13.2	78.4
PC4	1.7	9.2	87.6

Table 2
Loading matrix of the four principal components. Loading values exceeding 0.32 are marked in bold indicating non-trivial relationships (Tabachnick & Fidell, 2013).

Kinematic variable	Principal component			
Shoulder	1	2	3	4
SD ROM (°)	**0.869**	−**0.440**	−0.041	0.132
SD average angle (°)	**0.895**	−0.106	−0.243	−0.271
SD peak velocity (°/s)	**0.905**	−0.288	−0.220	0.157
SD average velocity (°/s)	**0.831**	0.243	−0.199	**0.389**
SD time-to-peak velocity (%)	0.194	**0.397**	0.199	**0.445**
SD area under the movement curve (°s)	−0.154	−**0.607**	**0.733**	0.136
SD average phase (°)	0.254	**0.865**	0.115	0.221
SD time-normalized angle (°)	**0.933**	−0.002	−0.219	−0.247
SD time-normalized phase (°)	**0.338**	**0.864**	−0.048	−0.192
Elbow				
SD ROM	**0.888**	−**0.336**	−0.060	0.091
SD average angle (°)	**0.866**	−0.121	0.158	−0.178
SD peak velocity (°/s)	**0.601**	−**0.571**	0.180	0.272
SD average velocity (°/s)	**0.379**	**0.417**	0.243	**0.720**
SD time-to-peak velocity (%)	**0.392**	−0.252	**0.643**	−**0.436**
SD area under the movement curve (°s)	−0.127	−0.099	**0.873**	0.112
SD average phase (°)	0.275	**0.889**	0.262	−0.137
SD time-normalized angle (°)	**0.913**	0.027	0.242	−0.157
SD time-normalized phase (°)	**0.408**	**0.637**	**0.405**	−**0.392**

Table 3
Variance components and intra-class correlations (ICC) for the four principal components.

Principal component	Between-subjects variance of cycle-to-cycle SD S_{BS}^2 (95% CI)	Between-day (within-subject) variance of cycle-to-cycle SD S_{BD}^2 (95% CI)	ICC
PC1	2.65 (0.32–8.80)	2.19 (1.35–4.17)	0.55
PC2	2.95 (1.11–8.66)	0.86 (0.53–1.63)	0.78
PC3	3.63 (0–12.80)	4.02 (2.47–7.66)	0.48
PC4	3.40 (0.77–10.77)	2.07 (1.27–3.94)	0.62

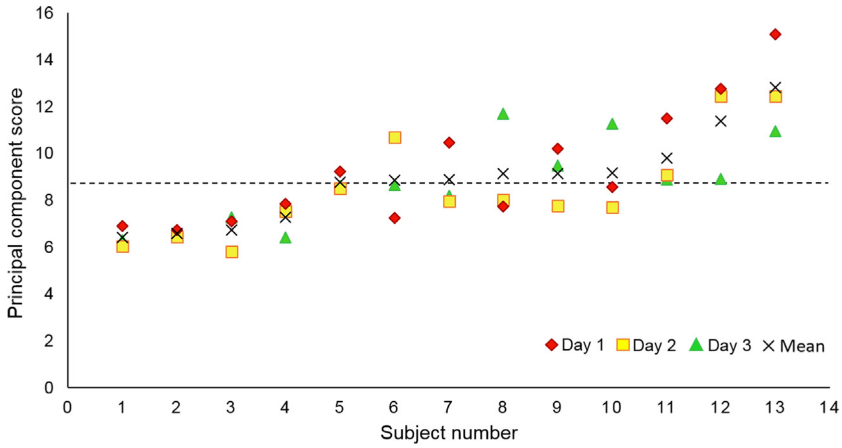

Fig. 2. PC1 scores for each subject on each of the three measurement days, ordered according to the (increasing) value of individual average scores. The dashed line shows the group mean.

within a subject. Also, for all principal components except for PC3, the between-days (within-subject) variance component was smaller than the between-subjects variance (Table 3). Relative consistency of the MV between days for the included subjects, as measured by the intra-class correlation coefficient, ranged between 0.48 and 0.78 (Table 3).

Fig. 2 illustrates scores on PC1 for each participant. In addition to the obvious difference between subjects in average score, the figure shows that individuals appear to differ in their between-days variability in PC1 component scores: those with a small average variability also have smaller between-days variability. Thus, subjects with a relatively low MV behave more consistently on different days.

4. Discussion

In a healthy population of young females, proficient in the studied repetitive pipetting task, MV patterns differed consistently between individuals. This was inferred from between-subjects variance components for all principal components describing MV being significantly different from zero, even after adjusting for variability between days within subject. Notably, we found these significant differences in MV between subjects in a study population which was small and homogeneous with respect to several factors that could lead to MV differences between subjects, including age (Kruger et al., 2013; MacDonald et al., 2006), gender (Svendsen & Madeleine, 2010; Vafadar, Cote, & Archambault, 2015), body composition (Chiari et al., 2002), work experience (Madeleine & Madsen, 2009; Madeleine, Voigt et al., 2008), and pain status (Madeleine, Mathiassen et al., 2008; Sandlund, Röijezon, Björklund, & Djupsjöbacka, 2008). Thus, the results lend support to the notion that some individuals show a more stereotypical movement behavior than others, as a personal trait that may be associated with factors that probably did differ within our population, even if it was homogeneous in other important aspects.

While research on motor variability has evolved rapidly during the recent decade, few studies have investigated the consistency of motor variability for a particular individual. The potential contradiction that can be perceived in the idea of "stable variability", following from a traditional theoretical view of MV as random phenomena ("motor noise"), has likely discouraged research on this subject, as has the norm of modern science to emphasize group average data on the expense of interest in inter-individual differences in normal populations (Kanai & Rees, 2011; Kostrubiec, Zanone, Fuchs, & Kelso, 2012; MacDonald et al., 2006). However, an exception is research in the field of gait and walking stability where recent studies have provided evidence of consistent individual MV levels across walking sessions (Hollman et al., 2010; König, Singh, von Beckerath, Janke, & Taylor, 2014; Reynard & Terrier, 2014; Toebes, Hoozemans, Mathiassen, Dekker, & van Dieen, 2016; van Schooten, Rispens, Pijnappels, Daffertshofer, & van Dieen, 2013). For example, König et al. (2014)) demonstrated high test-retest reliability of kinematic MV parameters sampled during overground "figure-8" walking. Although clearly a different class of movement, our findings parallel their results as individual MV shows relatively low variability across days. The fact that König and co-workers analyzed the consistency of single MV variables across two repeats of a task interspersed by, on average, three days, while we studied aggregated measures of MV based on 18 variables from three experiments within two weeks, might partly explain weaker ICC coefficients of the present study. A fine motor skill like pipetting may also be less automatized and involve more possible movement solutions than a gross motor function like gait (England & Granata, 2007), which would imply an inherently more variable motor performance. The, on average, slightly smaller ICCs in our study than those reported by König and co-workers may be due to differences in both within-subject and between-subject variance since the ICC coefficient is a ratio including both of these variance components (cf. Eq. (2)). To this end, in being a variance ratio, the ICC does not convey information about the extent to which subjects differ consistently in MV; this will be contained specifically in the between-subject variance component. Therefore, comparison of studies reporting ICCs without informing about the specific variance components is problematic.

Both internal and external factors influence control of movements and thus MV. In the present study, we strictly controlled the task and the conditions for performing it, leaving individual factors as the major source of possible MV differences between subjects. The subjects were all young, healthy women of similar age and pipetting experience, and they differed little in body constitution. Therefore, our finding of consistent differences between subjects in MV cannot likely be attributed to major differences in biomechanical or physiological properties, or task proficiency.

Individual MV patterns likely represent individualized priorities and, hence, individualized solutions at several levels in the central nervous system, which will vary even among "typical" subjects (Latash, 2008). This would include differences between subjects in the way that the sensorimotor system discriminates, decodes and transforms visual, proprioceptive and other inputs into neural activity, and subsequently interpret them into motor actions. The procedures used by the CNS to prioritize among different inputs are largely unknown, but have been suggested to relate to certain cost functions of the movement, such as demands for precision, jerkiness, effort, joint torque or end-state comfort (Latash, 2008; Todorov & Jordan, 2002). While the exact cost functions are currently unknown, it is possible that skilled performance may be achieved, not by exactly reaching the optimal limit of potential cost functions, but by reaching a "good enough" state, and different individuals may exercise different tradeoffs for how much is good enough. Such differences may lead to subject-specific patterns of MV also in subjects sharing many personal characteristics, such as those included in our study. It may be that the subjects showing the lowest levels of MV exert "over-control" or co-contraction of muscles, which would influence joint stiffness and, thus, kinematic patterns and MV; however, we could not verify this hypothesis on basis of the available data. As a reasonable assumption, individualized motor control priorities are also modulated by higher cognitive functions, affordances, mood, or perceived biomechanical constraints. As an example, the intensity and direction of attentional focus has been shown to be associated with kinematic MV in goal-directed movements (Carson, Collins, & Richards, 2014). Circumstantial evidence of a relationship between MV and personality factors may also be found. For example, van Eijsden-Besseling, Peeters, Reijnen, and de Bie (2004) were able to show an association between perfectionism and work related upper limb disorders, and explained it to be mediated by "inadequate movement strategies" (van Eijsden-Besseling et al., 2004),

The relevance of MV in the context of performance and health is emphasized by several studies (Berardelli et al., 1996; Cirstea & Levin, 2000; Latash & Anson, 2006; Latash, Scholz, & Schoner, 2007). Very low MV appear to characterize overly rigid biological systems less prone to exploration while excessive MV levels signify "noisy" systems. Both situations may lead to problems to adapt to perturbations. Consequently, it has been suggested that there may be an optimal level of MV operating between "too much" and "too little" (e.g., Stergiou, Harbourne, & Cavanaugh, 2006). While, thus, some MV may be essential to movement adaptation and learning, and beneficial in the context of fatigue and chronic pain, a too high MV may be negative to optimal performance and "production" in work and other situations. Some studies suggest that under challenging task constraints, variability may, however, be selectively directed into task-irrelevant degrees of freedom (e.g., Domkin, Laczko, Jaric, Johansson, & Latash, 2002; Scholz, Reisman, & Schoner, 2001; Todorov & Jordan, 2002; Tseng, Scholz, & Schoner, 2002). Notably, in our study all participants performed the pipetting task with close to perfect goal performance (Srinivasan, Rudolfsson et al., 2015), showing that the level of MV when performing this specific task did not lead to critical variability in the task space.

Our measurements do not allow any allocation of the participants on a scale from "too little" to "too large" MV, in the sense discussed above. However, our findings do suggest that some individuals can be described as "repeaters" in the sense that they perform a task with a very consistent motor solution, whereas others are "replacers" who utilize, to a greater extent, the available options for performing the task with varying motor solutions (Madeleine, 2010; Mathiassen, 2006; Mathiassen et al., 2003). In the present study, we could show that one necessary condition for this suggestion to be valid was satisfied, i.e., that individuals differ consistently in MV when performing one particular task. As illustrated in Fig. 2, it even appeared that subjects with a small average MV behaved more consistently on different days. Thus, we found indications that subjects who are "repeaters" on a narrow time scale, i.e. cycles within a day, are also "repeaters" over longer time periods, i.e., from day to day. A challenging question, however, is whether individuals consistently show a low (repeater) or high (replacer) MV, even across different conditions when performing a particular task and across different tasks. Consistency of an individual's MV across tasks (or rather, the ranking of MV relative to that of other individuals) would be required for MV to be considered a genuine personal trait. Studies of individual consistency in MV are rare, and findings are ambiguous. Rabbitt et al. (2001) concluded that timing variability is a stable individual characteristic, based on a study of reaction time in various letter categorization tasks (Rabbitt et al., 2001). In contrast, Zelaznik and coworkers demonstrated, in a series of studies of finger tapping and circle drawing, that timing variability correlated weekly between tasks, thus disputing that timing would be a personal trait (e.g., Zelaznik, Spencer, & Doffin, 2000). However, so far no study has to our knowledge addressed whether an individual's size or ranking of kinematic MV relative to other individuals is consistent across conditions and tasks.

We emphasize that we have no intentions of defining any explicit criterion or discrete cutoff value for when a certain subject would be labeled a "repeater" or a "replacer"; the terms are intended as an illustrative description of two extremes on a continuum of motor variability, much like labelling people as "short" or "long". If future studies confirm that some individuals do, indeed, show a consistently lower MV than others when performing repetitive occupational work, this may reflect an individual trait with a bearing on the risk of contracting work-related MSD (Srinivasan & Mathiassen, 2012). Without explicitly addressing motor variability, a handful of studies have proposed differences in motor behavior to be an explanation of why workers performing similar repetitive manual tasks differ in their susceptibility to MSD (Kilbom & Persson, 1987; Madeleine, Lundager, Voigt, & Arendt-Nielsen, 2003; Veiersted, Westgaard, & Andersen, 1993). The current study does not allow any interpretation of the MV of individuals in terms of MSD risk, but we encourage further research examining the predictive association of MV with disorders.

The approach of using PCA to analyze biomechanical data has previously been advocated (Daffertshofer, Lamoth, Meijer, & Beek, 2004), and it is well motivated in the present study as it permits detection of general tendencies in MV on the basis of a large selection of variables. The need to include multiple variables in a study of MV is, in turn, apparent from the complex nature of this phenomenon. In the present study, we selected variables of spatiotemporal dispersion, which we judged to be frequently used in motor control research, and relevant both for the control of this motor task and in the context of occupational repetitive work (Srinivasan & Mathiassen, 2012). Recent advances in techniques and equipment for data acquisition and processing have led to a dramatic increase in the number of variables that are accessible, while, to some extent, overlapping in informational content (Samani et al., 2015; Srinivasan, Rudolfsson et al., 2015). PCA provides an effective method of data reduction that can detect more general patterns in such multidimensional spaces.

PC 1, which accounted for nearly 42 percent of the total variance, and so is therefore the major base of our interpretations, was composed almost entirely of positive loadings of variables describing movement velocity, range of movement and joint angle rotation of both the shoulder and elbow. In representing the majority of the shared variance of all the MV variables, PC1 reflects the features of spatiotemporal MV with most potential to impact biomechanical stresses and tissue loadings. The uniform pattern of positive loadings indicates that an increase in PC1 score can be interpreted as an increase in variability of the above included variables. The other three PCs were composed of a mixture of positive and negative variable loadings, and did not allow a straight-forward interpretation in terms of whether a particular score would identify if an individual would have a high or low motor variability.

A strength of the present study is its focus on examining MV in a work task that does, in fact, occur in real occupational settings; this increases the relevance of the study in an occupational health context. Most previous studies of MV have been devoted either to gait or to very stereotyped and simple movements of the arm(s) like reaching. Another strength of our study is the use of a homogeneous population, implying that the differences we found between individuals are likely not due to extrinsic factors like sex, stature, age, or pipetting experience, but, arguably, related to inherent differences in motor control mechanisms (Latash, 2008; Missitzi et al., 2013). Moreover, the multivariate PCA approach for retrieving information on superior dimensions of MV allowed a comprehensive overview of MV that did not capitalize on scattered effects observed for individual variables.

However, the study also has some limitations. Subjects in the study were strapped to the back of a chair when performing the pipetting task. While this helps standardizing the working posture, it also implies that ecological validity may be compromised. The subjects were also required to perform the task at a standardized pace, in terms of a controlled total cycle time. While this may also represent a somewhat more strict constraint than what occurs in repetitive occupational work, the subjects were still allowed to modify the temporal structure of the different parts of the pipetting operation. We cannot exclude that the working technique of the subjects, including MV, was influenced by these constraints, and, thus, that our results may, to some extent, be specific to the investigated combination of spatial and temporal task demands.

We therefore emphasize that our results cannot readily be generalized to other repetitive tasks performed under different conditions in terms of, e.g. pace, movement directions and cognitive demands, which likely influence MV (Srinivasan & Mathiassen, 2012). Our study supports the notion that MV could be a consistent personal trait, but in order for this hypothesis to be confirmed, individual consistency would need to be verified in studies spanning even longer time periods, and studies investigating individual MV across different tasks. Intriguing avenues for continued research would also include studies of underlying mediators of MV, including a plausible association to personality traits such as perfectionism and adaptability (Hamtiaux & Houssemand, 2012; Magnusson, Nias, & White, 1996; van Eijsden-Besseling et al., 2004).

In conclusion, the present study supports the notion that MV may be a consistent personal trait, which can be identified in the spatiotemporal characteristics of repetitive movements performed across several days. Our results encourage further research into individual movement patterns in occupationally relevant repetitive tasks, and the possible importance of inter-individual differences in movement variability to occupationally relevant outcomes, including performance, fatigue and work-related pain. To this end, studies need verify whether the MV properties of an individual in one particular task persist to other tasks and settings, that is, whether some individuals are consistent 'repeaters' with a low MV, while others are 'replacers' with a larger MV.

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