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Review

Motor variability in occupational health and performance

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ABSTRACT

Several recent reviews have reported that 'repetitive movements' constitute a risk factor for occupational musculoskeletal disorders in the neck, shoulder and arm regions. More variation in biomechanical exposure is often suggested as an effective intervention in such settings. Since increasing variation using extrinsic methods like job rotation may not always be possible in an industrial context, the intrinsic variability of the motor system may offer an alternative opportunity to increase variation. Motor variability refers to the natural variation in postures, movements and muscle activity observed to different extents in all tasks. The current review discusses research appearing in motor control, sports sciences and occupational biomechanics literature to answer whether motor variability is important to consider in an occupational context, and if yes, whether it can be manipulated by training the worker or changing the working conditions so as to increase biomechanical variation without jeopardizing production. The review concludes that motor variability is, indeed, a relevant issue in occupational health and performance and suggests a number of key issues for further research.

1. Variation in repetitive work

In many jobs, often brought together under the term "repetitive work", a particular task is performed repeatedly for long periods of time, and often in a constrained posture (Kilbom, 1994a,b). Examples are short-cycle electronics assembly and meat-cutting. Musculoskeletal disorders (MSD) associated with repetitive work have consistently been identified as a significant problem, in particular with respect to the hand-arm, shoulder and low-back regions (Bernard, 1997; Buckle and Devereux, 2002; National Research Council, 2001; Sluiter et al., 2001; Winkel and Westgaard, 1992). Several current trends in occupational life, for instance outsourcing and standardization of task performance, may lead to an increased occurrence of repetitive work (Mathiassen, 2006), and hence it remains a critical and urgent issue to identify effective interventions in these settings.

The most frequently suggested intervention against MSD caused by repetitive work is to decrease its similarity, i.e. create more 'variation' in biomechanical exposure, in the sense that the exposure time-line shows more changes in the temporal domain (Mathiassen, 2006). This can be achieved by introducing additional tasks into the job of the operators that deviate from the repetitive tasks of concern, as in a job rotation scenario, and/or by breaking up work by periods of rest (Mathiassen, 2006). These methods can be described as 'extrinsic' since they focus on changing working conditions external to the individual.

The effectiveness of initiatives that introduce new tasks in the job, like job rotation, has not yet received firm empirical support, and evaluations have mainly been based on subjective psychophysical measures or expert judgment (Mathiassen, 2006). Similarly, field and semi-field studies of assembly work (Mathiassen and Winkel, 1996; Sundelin, 1993) and office tasks (Henning et al., 1997; McLean et al., 2001; Sundelin and Hagberg, 1989; van den Heuvel et al., 2003) could not conclusively show that interventions focusing on changing the duration or distribution of breaks in repetitive or static work had an effect on physiological outcomes of interest like fatigue or pain. Thus, extrinsic methods for increasing variation may not always be effective, and in several occupational settings, such as in standardised short-cycle industrial work, they may not even be feasible to the extent needed.

This opens the issue of whether another effective and viable alternative to obtain increased variation could be to employ 'intrinsic' sources of exposure variation, i.e. conduct interventions with the objective of changing the way the operator performs the task. A traditional ergonomics idea for increasing intrinsic variation is to encourage workers to voluntarily change their movement patterns and postures every once in a while, even while repeating the same task. But this idea sometimes conflicts with the notion of 'invariable task performance', as stipulated by standards of quality control, and hence, may not be possible to implement in many work situations, in particular in industry.

An emerging idea to increase variation even under such constraints focuses on 'motor variability', i.e. the intrinsic variability present in all actions controlled by the sensorimotor system, including repetitive occupational work (Madeleine, 2010; Mathiassen et al., 2003). Motor variability could manifest in both movements and postures, and several occupational studies have, indeed, shown that even highly controlled repetitive tasks are associated with considerable motor variability both in laboratory settings (e.g. (Granata et al., 1999; Hammarskjold et al.,

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1990; Jackson et al., 2009; Madeleine et al., 2008b; van Dieen et al., 2001)), and even more so in the field (e.g. (Christensen et al., 2000; Fethke et al., 2007; Moller et al., 2004)). Although motor variability has been an issue for decades in motor control research, possible applications of theories and findings in an occupational context have remained largely unattended to, let alone the issue of whether this intrinsic variability can be exploited as a source of biomechanical variation without compromising work performance.

A similar interest in the character, effects and prospects of motor variability has emerged recently in sports sciences, as discussed in a review by Bartlett et al. (2007). The authors argue that motor variability has important implications, for instance for skills achievement and susceptibility to injuries. Even clinicians have shown interest in motor variability, proposing that a larger variability leads to faster rehabilitation (Moseley and Hodges, 2006).

The present paper first summarizes basic concepts and notions regarding motor variability and how to measure it. It then continues by discussing why motor variability would be important in an occupational context. Studies are presented to show that motor variability differs between individuals, and that motor variability is related to important short-term outcomes of occupational relevance such as pain, fatigue and performance. Thereafter, the possibility of manipulating motor variability in occupational life is discussed, both in terms of individualized interventions such as training and skill development and in terms of changeable factors in the work environment and work organization that may have an effect on motor variability. The paper concludes with a general discussion, and identifies pertinent issues for further research. The focus of the paper is on motor variability in repeated, cyclic tasks, but studies of variability in non-cyclic work are also discussed if considered relevant in the context.

2. Motor variability: what is it and how can it be measured?

Motor variability addresses the variability observed at different levels of movement execution, especially across time within individuals. Motor variability can be assessed for several types of variables, including (a) performance measures like end-point precision of a pointing task, overall movement time or external force developed; (b) kinetic or kinematic components of the movement pattern like joint angles and velocities, joint torques etc.; (c) muscle activity and recruitment patterns of muscles within or outside the same synergy, of different regions within the same muscle, or among multiple motor units making up a muscle region; and, (d) 'coordinative' aspects like the relative angles or velocities of different link segments involved in a movement, or changes in the relative contribution of each muscle unit or joint towards achieving the final performance objective (Davids et al., 2006; Newell and Corcos, 1993; Stergiou, 2004).

Ideas of why motor variability occurs as an integral part of movements have changed in a historical perspective. Earlier, motor variability was often considered dysfunctional, and detrimental to task performance. Skill acquisition was then explained as a gradual development of 'optimal movement patterns' for performing a particular task. In recent years, research has shown that motor variability occurs at different control levels in movement execution, as explained below, and may play important functional roles. In parallel, different methods have also been developed in order to measure and interpret variability from these different perspectives.

2.1. Motor variability as sensorimotor noise

One idea about the nature of motor variability arises from the apparently stochastic behaviour of the sensorimotor control system; this is a 'classic' notion with a long history in motor control research. Attributed to 'noise' in the sensorimotor system (Newell and Slifkin, 1998), this interpretation of motor variability is usually quantified by a cycle-to-cycle statistic of any chosen kinetic or kinematic variable, such as its standard deviation, co-efficient of variation, inter-quartile range, or median absolute deviation. More advanced metrics include geometric curve-based techniques like the ellipse method or centroid calculation (Chau et al., 2005).

2.2. A dynamical systems approach to motor variability

Increased application of dynamical systems theories to movement control has led to the idea that motor variability is not just undesirable noise, but has a functional role in motor development and skill acquisition (Bartlett et al., 2007). In this paradigm, skill acquisition does not merely imply developing an adequate movement pattern, but also developing a certain optimal variability of that pattern. This motor variability, in turn, ensures that new motor solutions can be explored in response to changes in external environment or internal physiology (e.g. (Dingwell et al., 2001; Riley and Turvey, 2002)).

Optimal variability is said to lie between two limits (Stergiou et al., 2006): variability beyond the upper limit implies that the system is too unstable and sensitive to perturbations; variability below the lower limit indicates that the system is too stereotypical, less likely to exhibit exploratory behaviour, and thus less capable of adapting to perturbations. As an example, in young children each stride is close to being similar to preceeding strides, indicating little exploratory behaviour. Fluctuations in gait parameters increase in healthy adults, but even further for aging subjects and patients suffering from Huntington's disease, indicating that their movements are poorly controlled, as shown for instance by an increased fall frequency (Buzzi et al., 2003; Hausdorff et al., 1997). Functional, chaotic variability has been quantified using several nonlinear computational methods such as sample/approximate entropy and the Lyapunov exponent (Dingwell and Cusumano, 2000; Dingwell and Marin, 2006; Gates and Dingwell, 2010; Stergiou, 2004; Stergiou et al., 2004, 2006).

2.3. Motor variability and coordination

The extent of variability in a single movement component from one body segment may not be sufficient to evaluate the entire information present in motor variability. Most routine movements are complex, involving coordinated movements of multiple muscles, joints and body parts, and interactions between different movement components are important, including how they are expressed in constituent motor variabilities. For example, in an investigation of the accuracy of pistol shooting (Arutyunyan et al., 1968), skilled marksmen were able to reduce errors in the final pointing position of the hand by employing compensatory, *more* variable movements of the arms, whereas novice marksmen were unable to produce such adjustments and therefore exhibited more variable end-point positions. Similarly, patients with back pain show increased sway in standing and sitting as compared to healthy subjects (Hodges et al., 2009; Mientjes and Frank, 1999; Mok et al., 2004) but hold their trunks very stiffly; the healthy subjects compensate the tendency to sway by coordinated adjustments of their trunk posture, i.e. an increased variability in this particular part of the overall motor pattern (Mok et al., 2007; van Dieen et al., 2003). Coordination variability can be assessed using techniques like vector coding, cross correlation of time series data and continuous relative phase analysis of angle-angle plots (techniques reviewed in (Davids et al., 2003)).

2.4. Motor variability arising from redundant degrees of freedom

Based on the notion that motor variability arises from redundant degrees of freedom available for performing multi-joint movements, concepts like the Uncontrolled Manifold Hypothesis (UCM) (Schoner, 1995) and Goal Equivalent Manifold Hypothesis (GEM) (Cusumano and Cesari, 2006) suggest to partition total motor variability into "good" and "bad" components. While the "bad" component causes a deviation from the final task goal or designated control variable, the "good" component will not have an effect on task performance but may be beneficial from a musculoskeletal health perspective since it promotes variation in the activity of muscles and/or muscle parts (Mathiassen, 2006). Specific algorithms have been developed to study variability separated into these components (e.g. (Domkin et al., 2002, 2005; Gates and Dingwell, 2008)).

These different views of motor variability, and the resulting wide array of methods for measuring it highlights the need for specifying which aspects of motor variability to address in any particular study and choose the metrics accordingly. Interpreting the information provided by a 'higher' or 'lower' motor variability is not a trivial issue, and results from different studies may be difficult to compare and compile.

3. Why is motor variability important in occupational work?

3.1. Motor variability and individual traits

The need for a more thorough understanding of motor control strategies, including their associations with physiological responses, has been emphasized in several reviews addressing work-related MSDs in the neck–shoulder region and upper extremities (Hagberg, 1992; Kilbom, 1994a,b; Westgaard and Winkel, 1996). The need to address differences between individuals has been particularly emphasized. The fact that individuals performing the same manual tasks differ significantly in their susceptibility to MSD has been attributed to differences in their motor patterns by a number of studies (Kilbom and Persson, 1987; Madeleine et al., 2003; Veiersted et al., 1993). This notion is encouraged by studies, summarized in Table 1, showing that individuals differ in motor variability when performing the same repeated or constrained task.

In a study of repeated short-cycle work of securing joints using hand-held nut runners (Mathiassen et al., 2003), significant inter-individual differences were observed in the variability of arm kinematics and trapezius electromyography (EMG) at any particular subtask, and subjects reacted differently in terms of motor variability to changed task conditions. These differences were interpreted as evidence for individualized motor control strategies. In the same study, the authors also suggest that the pooled within-subject (cycle-to-cycle) variability of selected postures, movements and muscle activity variables can be used as operational metrics in occupational studies to measure 'similarity' or 'repetitiveness' of a cyclic task, and thus as an indicator of whether the task allows individuals to utilize variable motor strategies. Evidence that individuals performing the same strictly controlled tasks differ considerably in muscle coordination patterns has also been found in EMG studies of non-cyclic work (Hammarskjold et al., 1990; Kilbom et al., 1986; Mathiassen and Winkel, 1996; Nieminen and Hameenoja, 1995; Westgaard et al., 1993).

An association between the motor adaptation strategy adopted by an individual and the resulting physiological responses was suggested in a study on arm elevation in which female subjects were required to maintain an isometric and isoelectric contraction for 15 min (Mathiassen and Aminoff, 1997). Individuals differed markedly in response and the authors attributed this to individuals differing in neuromuscular adaptation strategies to the required low-level contraction. Other studies confirm that fatigue during isometric exercise develops slower in subjects with more variable muscle activation strategies (van Dieen et al., 1993). Thus, as a reasonable hypothesis, personal traits in motor variability may explain the common observation of why individuals differ in

Table 1
Motor variability vs. individual traits: design and results of selected key studies.

Study	Task	Subjects	Study design	Motor variable(s)[a]	Motor variability metric(s)	Results
(Barrett et al., 2008)	Treadmill locomotion	18 + 15 healthy M & F	3 min of treadmill locomotion at speeds of 5.5 km/h (walking) and 8,10, 12 km/h (running); 30 s of gait data recorded	Gait parameters such as stride length & stride time; 3D rotations of hip, knee and ankle joints	CV for stride length and stride time; coefficient of multiple determination (CMD) for joint rotations	No gender differences in variability of gait parameters; transverse plane rotations of the hip, knee and ankle joints less variable for F than M at the fastest speed (12 km/h)
(Falla et al., 2008)	Isometric 90° shoulder abduction	9 + 9 healthy M & F	60 s contractions before and after injection of hypertonic saline in the upper trapezius	Surface EMG from 13 × 5 electrode grid on the upper trapezius	2D centroid position of EMG amplitude map in the medio-lateral and cranial–caudal directions	Without pain: progressive increase in EMG amplitude, more in the cranial than the caudal region for both M and F; with pain: similar response in M, but no caudal to cranial shift in activity with time in F
(Mathiassen et al., 2003)	Simulated automotive assembly	5 + 2 healthy experienced M & F	Secured threaded fasteners using pneumatic nut runners at three locations on a rack, using 2 different kinds of tools; 20 repeats, each lasting 20 s, of each combination of location and tool.	Bilateral EMG from upper trapezius and lower arm extensors; Inclinations of the head and right and left upper arm	Cycle-to-cycle SD and CV of mean exposure.	Individuals differed systematically in the size of MV, and they responded to different extents, in terms of MV, to changes in tool and location.
(Svendsen and Madeleine, 2010)	Isometric elbow flexions	10 + 10 healthy M & F	(i) 5 s contractions at 10 to 90% MVC (10% increments with 30 s pauses) (ii) Ramp contractions from 5 to 50% MVC; 30 s duration in total (iii) contraction at 20% MVC until exhaustion	Exerted force in 3D: elbow flexion and two tangential forces	Amount of variability: SD and CV across time; structure of variability: sample entropy (SaEn)	SD increased and CV decreased with increasingforce in all three directions; Larger SD and smaller CV for M than F; SaEn showed an inverted U shape with increasing force; complexity higher in males than females;

M – male subjects, F – female subjects, MVC – maximum voluntary contraction, SD – standard deviation, CV – coefficient of variation, MV – motor variability.

[a] Only those variables that are used in subsequent variability analyses are reported here.

physiological responses even when performing the same standardized repetitive tasks (e.g. (Christensen, 1986; de Looze et al., 2009; Habes et al., 1985; Mathiassen and Winkel, 1996)).

Gender and age have been suggested to be determinants of motor variability. In a study of isotonic elbow flexion endurance (Svendsen and Madeleine, 2010), the produced force varied less around the target force in women than in men. This was attributed to gender differences in control and compensatory mechanisms. In a study on experimental shoulder pain (Falla et al., 2008), females were not able to redistribute their shoulder muscle activity as much as males, and eventually, women also reported higher perceived pain than men. In another study of treadmill locomotion at 4 different speeds (Barrett et al., 2008), women were found to exhibit lower variabilities of hip, knee and ankle joint rotations than men when running at the fastest speed in the experiment (12 km/h). Age-related differences in motor variability have been reported in gait (Hollman et al., 2007; Menz et al., 2003) and in postural stability (Huxhold et al., 2006; Maylor and Wing, 1996).

Thus, individuals differ in motor strategies while performing repetitive tasks. These differences are also expressed in the extent of motor variability, and some evidence suggests that motor variability has a bearing on acute physiological responses. While a core question is whether these inter-individual differences in motor variability could prospectively explain why some people are more susceptible to MSDs caused by occupational repetitive tasks than others (Mathiassen et al., 2003), a more answerable question is whether motor variability shows any association with occupationally relevant short-term variables describing pain, fatigue and performance.

3.2. Motor variability and pain

The following section reviews evidence for an association between motor variability and pain. While the possible role of motor variability as a determinant of the occurrence, recurrence and chronicity of pain may be of particular interest in a preventive occupational context, the reversed relationship – pain influencing motor variability – may be of interest in the context of proper task performance.

Studies of motor variability and pain are summarized in Table 2. In a simulated cutting task (Madeleine et al., 2008a), acute experimental pain increased arm movement variability, allegedly because alternative motor solutions were explored to reduce pain, while chronic pain was associated with reduced motor variability, suggested to reflect an attempt to avoid painful movements and postures. In a companion study of the effects of experience on motor variability among butchers (Madeleine et al., 2008b), motor variability increased during the first six months of employment. Kinematic motor variability was also higher among experienced butchers in a no-pain group than in a group of experienced butchers with pain. 'More variable motor strategies' were proposed as a protective factor against the development of work-related MSDs.

In a subsequent field study of butchers (Madeleine and Madsen, 2009), motor variability during a deboning process was found to vary with neck–shoulder discomfort as well as experience. More work experience was associated with less variability but increased complexity of the head-shoulder displacement pattern, while neck–shoulder discomfort was associated with less motor variability using both linear and non-linear estimation methods.

The notion of long-term pain conditions being associated with less motor variability has been supported by a number of clinical studies. In subjects with unilateral knee injury (Georgoulis et al., 2006), the injured knee exhibited less motor variability during gait than the non-injured knee of the same subject. Similar results of reduced variability in an injured limb when compared to the non-injured limb were reported in another study of subjects with unilateral patellofemoral pain (Heiderscheit et al., 2002), and in children with spastic hemiplegic cerebral palsy (Jeng et al., 1996). In a recent study on trunk kinematics in gait (van den Hoorn et al., 2012), people with low back pain exhibited reduced trunk movement variability during gait in comparison to a control group with no pain. Subjects with patellofemoral pain showed less less variability in lower-extremity coordination than matched controls (Hamill et al., 1999), and in a sitting postural control study (Sondergaard et al., 2010), the magnitude of variabilities in centre-of-pressure (COP) displacement and lumbar curvatures were found to increase with increasing discomfort, while the structure of the variabilities changed: discomfort led to larger but more regular deviations from the mean sitting posture.

In studies of repetitive reaching performed until exhaustion by subjects with and without chronic neck–shoulder pain (Lomond and Cote, 2010, 2011), both subject groups exhibited a decrease in relative arm movement variability during continued performance of the task. But the pain group also exhibited a decrease in the shoulder range of motion, and hence an increase in 'relative variability' (variability normalized by the range of motion) about the shoulder joint. Thus, the pain group, which had some difficulty in controlling shoulder movements (authors' interpretation from observations of larger relative variability) and also showed shorter endurance times than the no-pain group, seemed to accomplish the task with a larger contribution of movements in non-painful joints (e.g. trunk movements), allegedly in an attempt to minimize pain.

While these studies can not, due to their cross-sectional design, explain whether decreased variability was a cause or an effect of pain or injury, a study by Heiderscheit (2000) lends support to the hypothesis that decreased variability is a *result* of subjects in pain constraining their movements within tighter boundaries so that pain can be reduced; in that study gait variability in a pain group increased to almost that of a healthy group when pain was temporarily reduced by the application of patella taping. Supporting this notion, (Gallagher et al., 2011) concluded that changes in COP displacement variability observed in chronic low-back pain patients were the result of an adaptive response to pain, rather than being a factor causing pain. They based their case on the observation that there was no difference in postural control strategy (in terms of shifts in COP location) between individuals that eventually developed transient low back pain during 2 h of prolonged standing and individuals who did not develop any pain.

While pain-protective adaptations may be useful in the short term, they often persist when pain has disappeared (Sterling et al., 2001), thus indicating an inability of the motor system to recapture its flexibility (Lomond and Cote, 2010). In line with this notion of a negative effect of too little motor variability, Moseley and Hodges showed that subjects with more motor variability recovered more effectively from experimental low back pain than those with less variability (Moseley and Hodges, 2006).

Thus, both experimental pain and short-term discomfort developing during the performance of a specific task seem to be associated with an increase in motor variability, probably to find motor solutions that can reduce pain. On the other hand, persisting pain seems to be associated with diminished motor variability, probably because subjects have learned to avoid painful motor solutions or because it becomes more difficult to control painful joints. More stereotypical motor solutions may be preferred in chronic pain over other possible alternatives of performing the same task, even if they imply a less optimal performance (Cote et al., 2005).

While, thus, pain has an effect on motor variability, evidence also suggests that the size of motor variability in a healthy subject has a bearing on the prognosis for contracting pain. This is expressed in the 'variability-overuse hypothesis' proposed by sports biomechanists (reviewed in (Bartlett et al., 2007)), and feeds the notion in occupational health that biomechanical variation decreases the risk of developing MSDs. If movements are repeated more identically, it would be more likely that the same soft tissues receive large doses of exposure. Increased movement and posture variability would therefore modify tissue loads from repetition to repetition, distribute stresses more equally among tissues, and thus reduce the cumulative load on any particular tissue. The idea that a "large" motor variability may be a protective factor

Table 2
Motor variability vs. pain: design and results of selected key studies.

Study	Task	Subjects	Study design	Motor variable(s)[a]	Motor variability metric(s)	Results
(Georgoulis et al., 2006)	Walking on treadmill	10 subjects with complete unilateral rupture of the anterior cruciate ligament in the knee	2 min walks at 120% and 80% of comfortable speed; ~80 strides collected at each speed	Flexion/extension (sagittal) knee angular displacements	Approximate entropy (ApEn)	Injured knee showed significantly smaller ApEn values than normal knee at both speeds
(Hamill et al., 1999)	Running on treadmill	Subjects with patello-femoral pain and controls	10 runs on a force platform at 3 different running speeds: 2.5 m/s, 3 m/s and 3.5 m/s;	Thigh, leg and foot kinematics	Trial-to-trial SD of continuous relative phase (CRP) between segments calculated from phase plots of joint angles	Variability of CRP coupling in pain group was decreased compared to control group at all running speeds, both in the swing and stance stride phases
(Heiderscheit et al., 2002)	Running on treadmill	8 healthy F and 8 Fsubjects with unilateral patello-femoral pain (PFP)	20 s running at a fixed (2.68 m/s) and preferred speeds	Stride length and duration; 3D bilateral thigh, leg and foot kinematics;	SD of stride length and stride duration for first 15 strides at each speed; coordination variability of inter-segment coupling measured through vector coding	PFP patients showed higher stride length variability than controls, and a thigh-leg rotation variability at heel-strike which was lower in the injured limb and higher in the uninjured limb than among controls
(Lomond and Cote, 2010, 2011)	Repetitive reaching in standing	16 chronic neck–shoulder pain patients, and 16 control subjects	Horizontal reaching at shoulder height at 1 Hz until exhaustion	Whole body centre of mass (COM); RMS EMG of shoulder muscles; Arm movement kinematics	Cycle-to-cycle SD relative to average range of motion (RoM) for each kinematic variable; and relative to average RMS EMG	Arm RoM increased and arm variability decreased with fatigue in the control group. In the pain group COM movement increased and shoulder movement decreased; arm motor variability increased while COM variability decreased. Pain group showed decreased EMG variability compared to control group
(Madeleine and Madsen, 2009)	Deboning task conducted in a slaughter-house	18 M subjects in groups with high/low experience and with/without neck–shoulder pain	Six normal 35–50 s work cycles recorded	Head-shoulder, shoulder-hip and elbow-hip displacements	Amount of variability: cycle-to-cycle SD & CV Complexity: sample entropy & approximate entropy	With experience, variability decreased but complexity increased; with pain, variability and complexity of head-shoulder decreased but variability and complexity of elbow-hip displacement increased
(Madeleine et al., 2008b)	Simulated meat cutting	Group 1: 12 F with less than 1 month experience Group 2: 20 M with no experience & 6 M experienced butchers	Group 1: 3 bouts of 3 min work with 5 min rest in between, recorded during the 1st and 6th month of employment in fish/poultry industry Group 2: one 3 min work session	Cycle time; EMG amplitude ratio of active vs. inactive periods for 4 shoulder muscles; Trunk and arm kinematics	Cycle-to-cycle SD	Group 1: cycle-time variability decreased, posture & movement variability increased with experience; 6 subjects developed pain and 6 did not, in 6 months; pain caused increase in variability of initial arm position but decreased trunk movement variability Group 2: experienced workers showed higher kinematic variability than novices, but smaller EMG ratio variability
(Madeleine et al., 2008a)	Simulated meat cutting	Group 1: 20 healthy subjects Group 2: 12 butchers with chronic neck–shoulder pain and 6 controls (butchers with no pain)	Group 1: 3 min of work followed by experimental pain induction and 3 min of work in painful condition Group 2: 3 bouts of 3 min work with 5 min rest in between	Cycle time; EMG amplitude ratio of active vs. inactive periods for 4 shoulder muscles; Trunk and arm kinematics	Cycle-to-cycle SD	Cycle time variability increased with both chronic and experimental pain; kinematic variability increased with experimental pain but was decreased in chronic pain patients
(Moseley and Hodges, 2006)	Arm flexion/ extension, seated	7 + 9 healthy M & F	Control: 40 movements; experiment: 70 movements while a painful stimulus was delivered to the abdominal muscles; followed by 70 pain-free movement	EMG from right shoulder (anterior and posterior deltoids) and abdominal muscles (right obliquus externus)	Timing SD of the onset of activity in the abdominal muscles relative to shoulder muscles	13 ”resolvers” showed an increased variability at start of pain condition relative to the control condition, which then decreased with time, recovering to control level at the start of the no-pain condition; for 3 ”non-resolvers, variability at start of pain condition increased relative to control, but then

(continued on next page)

Table 2 (*continued*)

Study	Task	Subjects	Study design	Motor variable(s)[a]	Motor variability metric(s)	Results
						decreased to below control by the end of the pain; variability did not recover during the following pain-free condition
(Sondergaard et al., 2010)	Prolonged sitting	9 healthy M	~90 min sitting; divided in18 equidistant intervals for analysis	body centre of pressure (COP); lumbar curvature	SD and sample entropy of COP displacements and lumbar curvature in each 5 min analysis interval	SD (but not mean) of COP and lumbar curvature correlated positively with discomfort ratings; COP and lumbar curvature sample entropies of both correlated negatively with discomfort
(van den Hoorn et al., 2012)	Treadmill walking	12 healthy & 13 chronic low-back pain subjects	3 min treadmill walking at 12 speeds, from 0.5 to 1.72 m/s, at increments of 0.11 m/s.	Gait parameters such as stride length & stride time; joint rotations of pelvis, thorax and trunk	Stride-to-stride variability of the trunk, pelvis and thorax rotations computed as the median of deviations from the mean; relationships between pelvis and thorax variability assessed by Pearson correlations	Gait parameters did not vary between groups; pain group had smaller stride-to-stride variability in trunk rotation, and more correlation between pelvis and thorax rotation variabilities than the no-pain group

M – male subjects, F – female subjects, MVC – maximum voluntary contraction, SD – standard deviation, CV – coefficient of variation, MV – motor variability, RMS – root mean square.

[a] Only those variables that are used in subsequent variability analyses are reported here.

in preventing chronic MSDs has been proposed in (Mathiassen et al., 2003), and supported in (Cote, 2012; Madeleine et al., 2008a,b).

3.3. Motor variability and fatigue

Similar to pain, fatigue is an undesirable short-term outcome in occupational settings. Besides being of interest in its own right, muscle fatigue is cited as an adverse physiological response that could be a precursor to chronic MSD (Rempel et al., 1992). As discussed below, more motor variability may imply a slower development of fatigue, and/or reflect adaptation strategies that can relieve the load on fatiguing tissues (studies summarized in Table 3). Thus, as with motor variability and pain, an association between motor variability and fatigue is probably bi-directional.

Some studies claim that a re-organization of motor strategies during a fatiguing task occurs for the purpose of preserving performance. For instance, in a study of repetitive load lifting (Sparto et al., 1997), decreased range of motion at distal joints such as the knee and hip was compensated by increased trunk motion, in order to preserve lifting performance. Similarly, in another study of repetitive reaching, subjects were observed to evolve compensatory strategies to reduce load on the fatigued shoulder, such as decreasing shoulder abduction angles, and shifting the centre of gravity of the body laterally towards the non-reaching arm, such that task performance was still maintained (Fuller et al., 2009). In a repetitive reaching study (Fuller et al., 2011), cycle-to-cycle variability of the shoulder and elbow joints and the centre of mass (COM) average position increased with fatigue, but such that the increased variabilities were not associated with any deterioration in performance. Even in cross-country skiing (Cignetti et al., 2009) a positive linear correlation has been found between the extent of fatigue and movement variability.

(Fuller et al., 2011) proposed that in the presence of fatigue, similar to the effects of acute pain, there is a rapid search for a new movement solution so that task performance can be preserved and that this is evidenced by increased variabilities, both at the local site of fatigue as well as for the whole body. Evidence suggesting that changes in motor patterns may help in preserving performance during a fatiguing task has also been reported in repetitive throwing (Forestier and Nougier, 1998; Huffenus et al., 2006), hammering tasks (Cote et al., 2005, 2008), and repeated elbow flexion/extension for tracking a target (Selen et al., 2007).

In contrast to the above studies, a decrease in tracking performance with fatigue was reported in another study of a similar task (Huysmans et al., 2008), and negative effects of fatigue has been documented even on the precision on target of repetitive pointing movements (Missenard et al., 2008). The conflicting results in different studies regarding the effect of fatigue on task performance may be explained by those effects being task specific, and/or by differences in individual capacity to alter movement patterns in response to fatigue (discussed in (Bosch et al., 2011)). Skill may be one personal factor influencing the ability of the motor system to adjust to fatigue; with fatigue, expert table tennis players were found to maintain performance during fatigue by using compensatory adjustments to movement patterns whereas recreational players were unable to do so (Aune et al., 2008).

As with pain, the temporal relationship between development of fatigue and changed motor variability is an issue of debate. A study of repeated knee extentions (Skurvydas et al., 2010) suggests that motor variability in the non-fatigued state may predict the ability to perform prolonged work: a larger torque variability at baseline was associated with slower development of muscle fatigue. A complementary line of studies support this ‘protective’ role of motor variability in showing that the muscular system has the capability to produce sustained force in an isometric and isotonic contractions by using variable spatio-temporal muscle recruitment patterns, and that recruitment variability has a bearing on endurance times during both sustained and intermittent isometric contractions of the corresponding muscles. This has been observed in both trunk (van Dieen et al., 1993, 2009) and shoulder muscles (Falla and Farina, 2007; Farina et al., 2008; Palmerud et al., 1998).

3.4. Motor variability and performance

The relationship between performance and movement variability has been particularly addressed in sports sciences, including studies devoted to basketball, dart throwing and pistol shooting (reviewed in (Bartlett et al., 2007)). Studies focussing on associations between motor variability and performance are summarized in Table 4.

In a study of an aiming task (Balasubramaniam et al., 2000), participants were equipped with a hand-held laser pointer to point at a target, but the hand was made immobile and subjects had to stay aligned with the target by controlling their trunk posture to stand still for prolonged periods of time. Posture variations in the task-relevant direction were selectively inhibited, while posture variability in other directions increased. The authors suggested that a certain minimum amount of posture variability was required to maintain balance, and that the subjects chose a structure of this variability that did not compromise performance. That some postural variability is necessary to maintain balance in quiet standing has been confirmed in studies of both healthy subjects and Parkinson patients (Riccio, 1993; Schieppati et al., 1994). In a study of repetitive lifting (Mirka and Marras, 1993), muscle activity levels of the right and left erector spinae varied significantly between repeated lifts, but the changes were coordinated so that the external torque produced by the

Table 3
Motor variability vs. fatigue: design and results of selected key studies.

Study	Task	Subjects	Study design	Motor variable(s)[a]	Motor variability metric(s)	Results
(Cignetti et al., 2009)	Cross-country skiing on treadmill	4 + 4 healthy M & F	Skied till exhaustion at a constant speed and slope corresponding to 90% maximal oxygen uptake	Kinematics of knee, hip, shoulder and elbow	"Stride-to-stride" SD; Lyapunov exponent	Larger variability and randomness observed with fatigue
(Falla and Farina, 2007)	Isometric shoulder elevation	5 + 4 healthy M & F	Elevation at 20% MVC for 6 min with and without 2 s interruptions every 30 s by increases of exertion to 25% MVC.	Surface EMG from a 13 × 5 electrode grid on the upper trapezius muscle	Centroid position of EMG RMS map at 30 s intervals	Centroid shifted in the cranial direction during variable but not during constant force contractions; MVC was reduced after constant force contractions but not after variable.
(Farina et al., 2008)	Isometric 90° arm abduction	11 healthy M	Abduction until exhaustion	Surface EMG from a 13 × 5 electrode grid on the upper trapezius muscle	Entropy and time-related shifts of the centre of gravity (CoG) in the EMG RMS map	At exhaustion, entropy had decreased and CoG moved in the cranial direction. Extent of shift in CoG correlated positively with endurance time; CoG shift correlated negatively to both initial and final entropy
(Fuller et al., 2011)	Repetitive pointing	8 + 6 healthy M & F	Pointingat 1 Hz between two targets placed at shoulder level until considerable perceived fatigue	whole body kinematics; Upper trapezius surface EMG	Cycle-to-cycle variability of average joint positions and body centre of mass (COM)	Variability of end-point position remained unchanged with fatigue; variability of joint positions and COM changed before signs of trapezius muscle fatigue occurred and variability of the shoulder and elbow increased with fatigue. Variability in COM average position was unchanged in the direction of movement, but increased in the 2 orthogonal directions
(Huysmans et al., 2008)	Manual target pursuit	11 healthy F	2 min computer mouse tracking task immediately before and after fatiguing wrist extensions	End-point precision in tracking a moving target	SD of distance to target	SD of distance to target was increased after fatigue
(Selen et al., 2007)	Manual tracking task; horizontal elbow flexion/ extension	10 healthy subjects	Four 2 min tracking trials, followed by 4 sessions comprising a 10 min upper arm fatiguing protocol and 2 min tracking; followed finally by four 2 min tracking trials	Distance totarget in tracking cycle	SD of distance to target averaged over tracking cycle time	Kinematic variability increased due to fatigue; subjects changed control strategy to maintain performance
(Skurvydas et al., 2010)	Isokinetic knee extension at 30°/s	11 healthy M	Extensions performed 2 min, 60 min, 24 h and 14 days after 10 x12 repetitions of eccentric knee extensions (EE) intended to result in soreness.	Maximal isokinetic knee extensor torque; Knee angle	SD and autocorrelation coefficient of repeated torque exertions	Higher torque SD associated with less fatigue (less decrease in maximal torque)
(van Dieen et al., 2009)	Isoelectric trunk extension	12 healthy subjects	30 min contractions at 2% and 5% MVC with EMG feedback from one electrode site; subjects instructed to maintain constant level of activation	Surface EMG from 3 locations on the left and right lumbar extensors	CV of EMG amplitude	Lower CV at the feedback electrode than at other EMG locations. Larger decrease in EMG mean power frequency at the feedback site and its ipsilateral sites than at other locations at both 2% and 5% contractions
(van Dieen et al., 1993)	Isometric trunk extension	7 healthy subjects	Contraction at 70% MVC for 4 s followed by 2 s of rest; performed until exhaustion	Surface EMG from several locations over the erector spinae muscle	CV of EMG amplitude	Subjects with high endurance showed more variability and more shifts in EMG activity between different muscle parts

M – male subjects, F – female subjects, MVC – maximum voluntary contraction, SD – standard deviation, CV – coefficient of variation, MV – motor variability, RMS – root mean square.
[a] Only those variables that are used in subsequent variability analyses are reported here.

muscles together was relatively constant. Hence, the series of lifts was performed according to instructions, and the variability in individual muscle activities had little effect on net spinal compression.

These observations on motor behaviour have led to the theory of 'compensatory variability', i.e. that skilled and consistent performance is not accomplished by fixed and stereotyped movements but by a motor strategy adjusting variability in one parameter by compensatory variability in other parameters (Bootsma and Vanwieringen, 1990).

In two different studies of basketball shooting (Button et al., 2003; Robins et al., 2006), elbow–wrist coordination variability between throws was shown to be greatest towards the end of the shooting action, i.e. at the time of the ball release, when one would otherwise expect coordination to be most consistent. However, this movement variability did not have an adverse effect on the ball release parameters. Studies on pistol aiming, ball throwing and dart throwing (Arutyunyan et al., 1969; Kudo et al., 2000; Muller and Loosch, 1999) suggest that compensatory movement variability may actually be *required* to maintain a consistent target performance. Also, these studies suggest that motor learning during skill development may involve a gradual increase in this compensatory variability, specific to the trained task. Thus, the relationship between motor variability and performance is closely connected to motor learning. It has been proposed that an optimal strategy when facing an unknown movement is to allow for a generally "large" motor variability in the beginning, and then preferentially correct those deviations that interfere with task goals, while allowing more variability in redundant or task-irrelevant directions (Todorov and Jordan, 2002).

These changes in motor strategy while performing a particular task are possible because of the availability of redundant degrees of freedom in coordinated, multi-joint movements, allowing, in principle, many possible ways of realizing a task with the same target performance. Theories like the Uncontrolled Manifold Hypothesis (UCM) (Scholz and Schoner, 1999) suggest that successful task performance is then achieved, not by selecting a single possible solution, but by selecting a less controlled task sub-space within which movement

Table 4
Motor variability vs. performance: design and results of selected key studies.

Study	Task	Subjects	Study design	Motor variable(s)[a]	Motor variability metric(s)	Results
(Balasubramaniam et al., 2000)	Controlled stand-still	6 + 6 healthy M & F	Align a laser pointer and keep standing still for 30 s. Target oriented in: Plane parallel to the coronal plane of the body (Medio-Lateral ML); Plane perpendicular to the coronal plane (Anterio-Posterior AP); 30 trials recorded in each condition	Body centre of pressure (COP) displacements in the AP and ML directions	For COP displacements: RMS variability; Entropy; Recurrence Quantification Analysis (RQA); & Average Mutual Information (AMI)	ML and AP sways were independent in both target directions. With target in ML direction, RMS variability of ML sway decreased while AP sway increased and was more recurrent, deterministic, complex and stationary than sway in the ML direction. The inverse was found with target in AP direction.
(Button et al., 2003)	Basketball shooting	6 healthy F of different skill levels	30 attempts to shoot the ball through the ring without touching the rim	Shoulder, elbow and wrist kinematics; Ball release parameters such as release height and performance	Shot-to-shot SD of elbow displacement; angle-angle plots to determine variability in elbow–wrist coordination (cross correlation ratios within each shot, and shot-to-shot SD of correlation)	Performance improved with skill; elbow angle variability was not affected while elbow–wrist coordination variability decreased with increased skill Elbow displacement variability was minimal at the start of the shot and at the time of ball release; coordination variability of elbow–wrist was maximal at the time of ball release
(Gates and Dingwell, 2008)	Repeated simulated sawing	14 healthy subjects	Repeated sawing movements at 15% of pushing/pulling MVC, at approximately 1 Hz until exhaustion	Arm movement kinematics; EMG from 9 muscles in the shoulder, upper arm and lower arm; Push/pull force in sawing	Cycle-to-cycle SD of movement speed, distance and timing errors; Goal Equivalent Manifold (GEM) analysis for movement distance and speed	Subjects maintained overall performance. However, speed errors and timing errors were corrected more often when subjects were fatigued; Deviations perpendicular to the GEM were corrected more often than those aligned with the GEM
(Mirka and Marras, 1993)	Repetitive bending	5 healthy M	Isometric bending to 5 and 40° forward flexion, isokinetic bending at angular velocity of 20°/s and Isoinertial bending at angular acceleration of $40°/s^2$; 10 repetitions of each task condition	EMG from 10 trunk muscles (right and left erector spinae, latissimus dorsi, rectus abdominis, internal and external obliques); spinal loads estimated from muscle activities in a biomechanical model	SD of EMG amplitude and spinal loads	Variability of anterio-posterior and lateral shears similar to the variabilities in trunk muscle activities; individual muscle variabilities were significant, but compressive force variability was very small; the sum of the right and left primary extensor muscle activities was correlated to the external torque
(Valero-Cuevas et al., 2009)	Index finger tapping	5 + 3 healthy M & F	Task consisted of: a hold phase of 4 s at 2 N, a slowly varying phase of force for 10 s and another hold phase of 10 s	Finger force & Intra-muscular EMG from 7 muscles acting on the index finger	Temporal change of variance in muscle coordination patterns projected on to task-relevant (3 degrees-of-freedom; DOF) and task-irrelevant (4DOF) subspaces	Variability consistently smaller in the task-relevant than in the task-irrelevant movement direction

M – male subjects, F – female subjects, MVC – maximum voluntary contraction, SD – standard deviation, CV – coefficient of variation, MV – motor variability, RMS – root mean square.
[a] Only those variables that are used in subsequent variability analyses are reported here.

variability will have little effect on performance, whereas variations orthogonal to this sub-space would be detrimental to performance and are therefore strictly controlled (Latash et al., 2002). This idea of partitioning total movement variability into two components has been used to investigate biological principles of movement organization and coordination in complex tasks such as bimanual pointing (Domkin et al., 2002), control of whole body movements (Reisman et al., 2002), multi-finger force production (Latash et al., 2002) and pistol shooting (Scholz et al., 2000).

Recently, partitioning of total movement variability into two components has been used in a study of fatigue effects on task performance in simulated repetitive sawing (Gates and Dingwell, 2008). Using a principle similar to UCM called the goal-equivalent manifold (GEM) hypothesis, subjects were observed to correct speed and timing errors in sawing more often when they were fatigued, but deviations important to production were corrected more often than those not affecting performance. So subjects did alter their movement patterns with fatigue, but speed and timing errors did not differ between baseline and fatigue. Subjects apparently managed to maintain the task goals of speed and timing by selectively correcting those fatigue effects on movements that would otherwise have led to errors. This 'minimum intervention' principle of motor control, implying that deviations from average behaviour are corrected only when they interfere with task goals (Todorov, 2004), was recently supported by another study of a finger-force production task using intra-muscular EMG recordings from all seven index finger muscles (Valero-Cuevas et al., 2009).

Motor variability thus plays a key role in preserving task performance in the face of perturbations, either through compensatory control strategies or by selective stabilization of some movement degrees of freedom. In understanding these control mechanisms, methods like UCM and GEM offer information that is not provided by analyses only reporting an overall size of motor variability.

4. Can motor variability be manipulated?

4.1. Personal factors

4.1.1. Motor variability and training

As reviewed in the previous sections, several studies suggest that motor variability differs systematically between individuals. These differences seem to have significant effects on fatigue, pain and performance during repetitive work, and may, as a reasonable hypothesis, even be predictive of the individual's susceptibility to MSD. Thus, a crucial issue of interest to occupational health and performance is whether it is possible to train or educate the individual to perform his/her work with a proper motor variability.

This possibility has been tested mainly in the shoulder region, partly because MSDs from repetitive work are highly prevalent there (Nordander et al., 2009), and partly because this region is likely to show a particularly flexible motor control, considering that it comprises several muscles and muscle subdivisions with partially overlapping biomechanical roles (Jensen and Westgaard, 1997; Mathiassen and Winkel, 1990, 1996; Palmerud et al., 1995, 1998). This motor redundancy has motivated studies investigating whether people can voluntarily redistribute muscle activity without compromising task performance. In one study, subjects maintained the arm in an isometric, abducted position while receiving feed-back on the EMG amplitude of the descending part of the trapezius muscle (Palmerud et al., 1995). When instructed to reduce that amplitude but still keep the isometric posture, subjects managed to lower trapezius EMG by 22–47%. The target posture was maintained by redistributing activity to the rhomboids and transverse part of trapezius (Palmerud et al., 1998).

In a similar approach, recent studies have investigated whether it is possible selectively activate different neuromuscular compartments within the trapezius muscle using biofeedback techniques. When subjects were trained for 1 h with biofeedback on the EMG amplitude of four anatomical subdivisions within the trapezius muscle (Holtermann et al., 2008), 11 out of 15 subjects learned to selectively activate at least one of the four muscle subdivisions. Whether this ability persisted without the biofeedback was not addressed. In a study of breaks in computer work (Samani et al., 2010) (Table 5), a more sophisticated active biofeedback technique based on trapezius activity obtained from multi-channel EMG was shown to lead to increased spatial variability of trapezius muscle activation.

These findings suggest that different subdivisions of the human trapezius muscle can be independently activated by voluntary command, and thus encourage the prospects of using specific 'training' protocols to pursue desired motor control characteristics. However, to our knowledge, no studies have investigated whether kinematic motor variability can be changed by specific training in a sustainable manner.

4.1.2. Motor variability and experience

The previous section discussed whether training can lead to a voluntary increase in motor variability during task performance in the short term. Several studies (Table 6) suggest that long-term experience or 'skill development' in performing specific tasks or movements may be associated with the development of more variable motor strategies.

In a study of repeated lifting exertions, experienced manual material handlers exhibited increased within-subject variability of spinal loads when compared to inexperienced subjects (Granata et al., 1999). This observation was contrary to the authors' hypothesis that increased spinal load variability was harmful as it represented a greater probability of the spinal load exceeding maximum tissue tolerance. The authors concluded that the relationship between variability and injury risk required further investigation. Experienced workers have been found to exhibit higher motor variability than novices in studies of simulated cutting, and in that study, as mentioned above, the authors suggested increased motor variability to be a protective strategy against disorders (Madeleine et al., 2008a,b).

Some studies have investigated the relationship between motor variability and skills in sports, with practical implications for performance assessment and training protocols. In basketball shooting (Button et al., 2003), movement variability in a free-throw was examined as a function of skill level. Although the elbow–wrist angle relationship was more consistent in skilled athletes, there was no decrease in the elbow angle variability with skill. In contrast, the variability in kinematic time series of hip and ankle joint variables were found to *increase* with skill level during race walking (Preatoni et al., 2010).

In a study of basketball shooting (Robins et al., 2006), the relationship between coordination variability and skill was shown to be U shaped. Novices and experts exhibited similar magnitudes of variability at the shoulder joint at the time of ball release, which was significantly greater than that of intermediate subjects. However, the increase in shoulder joint variability was accompanied by increased compensatory control in the expert players (cf. Section 3.4), but no evidence of such compensatory control was found in novices. The authors claim that the variability of novices is less functionally related to performance, since it is explained either by neuromotor noise or by the subject exploring solutions to the task, whereas similar levels of variability in experts is a functional variability needed to maintain performance. Their observations are in line with another study of ball throwing (Kudo et al., 2000), which showed that ball release parameters were complementarily coordinated, and the degree of coordination increased as a function of practice. Similar results were also reported by a study of the triple jump (Wilson et al., 2008).

Thus several studies suggest that motor variability changes as a natural part of skill development in repetitive tasks. However, none of these studies specifically trained motor variability, and so the issue of whether motor variability can be manipulated by informed training programs, and how, in that case, such a program should be designed, remains unresolved.

4.2. Factors at work

The previous section reviewed some studies supporting that it might be possible to manipulate motor variability at the individual level by personalized training programs and skill development. Another potential way of influencing motor variability in repetitive occupational work would be to intentionally manipulate factors at work that would influence motor variability without interfering with production. This opens the question of which factors affect motor variability among those accessible to interventions such as work-station design, weights of tools and components, precision requirements, work pace, cognitive demands associated with work tasks, and spatial and temporal autonomy in task performance.

Studies of the effects of occupational factors on motor variability are summarized in Table 7. The basic pacing principle in a repetitive assembly task has been shown to influence the temporal movement strategy, line-paced work surprisingly being more variable than more autonomous pacing principles (Dempsey et al., 2010). The effect of work pace on motor variability and fatigue development was also studied by in light manual assembly work (Bosch et al., 2011). While a faster work pace did not lead to a more variable cycle time, it led to larger variability in some kinematic variables. However, this was accompanied by more errors in production. In a study of butchers performing repetitive meat cutting work (Christensen et al., 2000), workers were classified as being either 'slow' or 'fast' depending on their work cycle times. Representative samples of EMG from the forearm muscles indicated that there was a trend for the fast group to have higher variability than the slower group, but the difference was not statistically significant.

In a study of people walking at 5 different walking speeds (60–140% of each individual's preferred walking speed) (Dingwell and Marin, 2006), kinematic motor variability in gait increased at both slower

Table 5
Motor variability vs. training: design and results of selected key studies.

Study	Task	Subjects	Study design	Motor variable(s)[a]	Motor variability metric(s)	Results
(Samani et al., 2010)	Computer work	13 healthy subjects	10 min computer mouse work sessions, interrupted by bio-feedback driven 'active' (isometric exercise) or 'passive' (relaxation) pauses, or not interrupted (control).	Surface EMG from a 13×5 electrode grid on the upper trape zius muscle	Centre of gravity (CoG) changes and entropy of EMG RMS maps Permuted Sample Entropy (PeSaEn) for 0.5 s long non-overlapping EMG epochs	Active pauses in response to biofeedback associated with higher entropy (increased PeSaEn) of RMS maps and CoG shift in the cranial direction than in passive or control conditions, signifying more heterogenous coordination of the trapezius muscle, But PeSaEn of each individual channel decreased in response to active pauses, implying more homogenous temporal activation within each subdivision of the trapezius

M – male subjects, F – female subjects, MVC – maximum voluntary contraction, SD – standard deviation, CV – coefficient of variation, MV – motor variability, RMS – root mean square.
[a] Only those variables that are used in subsequent variability analyses are reported here.

and higher speeds when compared to the preferred walking speed, whereas local dynamic stability was found to be 'better' at slower than higher speeds, as indicated by lower values of short-term and long-term finite-time Lyapunov exponents. In similar studies of the structure of variability in human walking and running as a function of speed (Jordan and Newell, 2008; Jordan et al., 2007), the authors reported a U shaped curve for so called "long-range correlations" in gait patterns as a function of movement speed, with the minimum at the preferred movement speed. This minimum long-range correlation was interpreted by the authors as each stride being minimally influenced by the strides preceeding it, and hence gait at the preferred speed as being more adaptable to perturbations than when walking at other speeds. Thus, some studies are available to suggest that work pace is a determinant of motor variability, even if several questions as to the structure of this dependency are still unsettled.

The effects of coginitive loads on motor variability has been investigated in a number of studies of gait and posture control. Thus, in a recent study (Montero-Odasso et al., 2012), the effect of performing a simultaneous cognitive task on gait cycle variability was assessed in both control subjects and patients with mild cognitive impairment. Cycle-to-cycle variability in stride-duration increased in the presence of a concurrent cognitive task, and variability was significantly influenced by the complexity of this cognitive task, both in controls and among the patients. An earlier study (Hollman et al., 2007) reported similar results; i.e. that the stride-to-stride variability in gait velocity increased when healthy subjects performed a cognitive task when walking. In a posture control study (Huxhold et al., 2006) of still standing, a mild cognitive task decreased body centre of pressure (COP) displacements. Increasing the complexity of the concurrent cognitive task however increased posture variability, and this effect was more pronounced in older adults. While

Table 6
Motor variability vs. skill/experience: design and results of selected key studies.

Study	Task	Subjects	Study design	Motor variable(s)[a]	Motor variability metric(s)	Results
(Granata et al., 1999)	Repetitive lifting	12 healthy M, including 5 experienced manual material handlers and 7 novices	2 box weights (13.6, 27.3 kg), 2 levels of task asymmetry (sagittally symmetric, 60° skewed to the right), 2 lifting velocities (preferred & faster speed); 10 repetitions of lifting in each combination of task conditions	Sagittal, lateral and twisting kinematics and moments of the lumbar trunk; 3D spinal compressive forces, and lateral and anterio-posterior (AP) shears	Cycle-to-cycle SD	Variability in sagittal trunk moment and spinal loads in all 3 dimensions increased with experience (effects of work factors on variability described in Table 7)
(Preatoni et al., 2010)	Race walking	$4+4$ M & F competitive race walkers at different skill levels	Walking on a 15 m walkway in the laboratory; 20 trials analysed	Hip, knee and ankle joint angles & Ground reaction forces in vertical and anterior-posterior directions	Sample entropy	Hip and ankle joints and vertical ground reaction forces showed higher sample entropy in the more skilled group compared with the less skilled group
(Robins et al., 2006)	Basketball shooting	10 novice, 10 intermediate and 10 expert basketball players	30 trials from each of 3 shooting distances: 4.25, 5.25 and 6.25 m	Arm movement kinematics	Shot-to-shot SD of shoulder, elbow and wrist angles at the time of ball release	Shoulder angle variability exhibited a U shaped function of skill–high in both novices and experts, low in intermediate players. Among experts only accompanied by increased 'functional' compensatory control and better performance; shoulder angle variability at the time of ball release increased with increase in shooting distance in expert players but not in intermediates or novices
(Wilson et al., 2008)	Triple jump	5 expert triple jumpers with varying levels of skill	10 triple jump trials after a warm up session	3D kinematics of stance leg ankle, knee and hip joints of and swing leg knee and hip during the hop-step transition	Vector coding techniques to quantify coordination variability	Coordination variability of the ankle-knee and knee-hip couplings of the stance leg exhibited a U shape function of skill level: variability was high in the least skilled and most skilled participants, and low in the intermediate level participants

M – male subjects, F – female subjects, MVC – maximum voluntary contraction, SD – standard deviation, CV – coefficient of variation, MV – motor variability.
[a] Only those variables that are used in subsequent variability analyses are reported here.

these studies indicate that cognitive demands on top of a repetitive task might influence motor variability, we are not aware of any studies of effects on motor variability of occupationally relevant combinations of cognitive and biomechanical demands. Also, the influence of other relevant mental stressors, such as time pressure or anxiety, is not known at present.

Additional factors at work that might influence motor variability have scarcely been investigated. In studies of repetitive lifting exertions, the magnitude of the load and the symmetry of the lifting conditions (sagittally symmetrical lift vs. lift skewed 60° to the right) have been found to influence the variabilities of lifting kinetics, kinematics as well as spinal load variability (Granata et al., 1999; Mirka and Baker, 1996). Factors such as precision requirements and work-station design have, to our knowledge, not been subject to research so-far.

5. Discussion

5.1. Motor variability in an occupational context

Motor variability has been of focal interest to neuroscience researchers for almost a century, including its sources, effects and implications to sensorimotor control mechanisms. However, the awareness of possible physiological benefits of variable motor patterns, and the interest in finding practicable ways of capitalizing on intrinsic movement variability

Table 7
Motor variability vs. occupational factors: design and results of selected key studies.

Study	Task	Subjects	Study design	Motor variable(s)[a]	Motor variability metric(s)	Results
(Christensen et al., 2000)	Meat cutting	48 M meat cutters	Meat cutting during an 8 h work shift 6 “fast” and 6 “slow” workers identified based on cycle times during cutting and observed for ~7 cycles at the beginning, middle and end of the work day	Surface EMG from extensor and flexor carpi radialis of the arm holding the knife	Cycle-to-cycle SD of mean EMG amplitude	Fast group showed trends of higher variability in both the flexor carpi radialis and the extensor carpi radialis than the slow group, but the difference was not statistically significant
(Dingwell and Marin, 2006)	Treadmill walking	11 healthy subjects	Walking for 3 min at 60%, 80%, 100%, 120% and 140% of preferred walking speed	3D kinematics from a single marker on vertebra T1	Stride-to-stride SD; short-term and long-term Lyapunov exponents	SD increased both for slow and fast speeds when compared to the preferred walking speed Local dynamic stability was better (smaller values of short- and long-term Lyapunov exponents) at slower than faster speeds
(Granata et al., 1999)	Repetitive lifting	12 healthy M, including 5 experienced manual material handlers and 7 novices	2 box weights (13.6, 27.3 kg), 2 levels of task asymmetry (sagittally symmetric, 60° skewed to the right), 2 lifting velocities (preferred & faster speed); 10 repetitions of lifting in each combination of task conditions	Sagittal, lateral and twisting kinematics and moments of the lumbar trunk; 3D spinal compressive forces, and lateral and anterio-posterior (AP) shears	Cycle-to-cycle SD	Trunk kinematic variability: Sagittal extension velocity and acceleration decreased with increased box weight but twisting velocity & acceleration and lateral acceleration became more variable with task asymmetry; cariability of trunk moments: Task asymmetry and increased box weight had no effect on variability in sagittal and lateral moment, while variability increased in the transverse plane moment; variability of spinal loads: Compressive loads and AP shear variabilities increased with box weight; AP shear variability increased with task asymmetry; lifting velocity did not affect trunk moment or spinal load variabilities (effects of experience on variability described in Table 6)
(Jordan and Newell, 2008; Jordan et al., 2007)	Treadmill walking	11 healthy F	12 min walking sessions at 80%, 90%, 100%, 110% and 120% of preferred speed	Vertical ground reaction force registrations giving Step length, Step interval, Stride length; Stride Interval, Force impulse	Cycle-to-cycle CV of gait variables; long-term correlations using alpha values from Detrended Fluctuation Analysis (DFA)	Variability of stride interval, stride length, step interval, step length and impulse decreased with speed; alpha DFA values of all gait parameters showed a U shaped function with speed, the minimum (indicating enhanced stability and adaptability) falling near the pre ferred speed
(Mirka and Baker, 1996)	Repetitive lifting	7 healthy M	Repetitive lifting in sagittally symmetric postures at 7 load levels (from 4.5 to 31.5 kg) and 3 coupling levels (poor, fair, good); 3 min of lifting with 4 lifts per minute performed for each task combination	Angular position, velocity & acceleration of lumbar trunk in sagittal, coronal and transverse planes; biomechanical model used to compute L5/S1 joint torque	Cycle-to-cycle SD and CV of peak kinetic and kinematic parameters	Variability of peak velocity and acceleration in the sagittal plane and peak joint torque increased with increasing load; coupling did not affect the magnitude of variability

M – male subjects, F – female subjects, MVC – maximum voluntary contraction, SD – standard deviation, CV – coefficient of variation, MV – motor variability.
[a] Only those variables that are used in subsequent variability analyses are reported here.

without compromising the quality of task performance has grown in both occupational, sports science and motor control literature only within the last decade.

This development has coincided with the recent agreement by both research and legislating bodies that disorders caused by repetitive work are a major issue in occupational life, and epidemiological evidence that increased exposure variation might be beneficial to musculo-skeletal health. Thus, within the last decade, a number of complementary research efforts in ergonomics, physiology and motor control, some of which explicitly devoted to occupational issues, have increased the understanding of the relevance and possible contributions of motor variability to health in working life (Bosch et al., 2011; Cote et al., 2005, 2008; Dempsey et al., 2010; Madeleine, 2010; Madeleine and Madsen, 2009; Madeleine et al., 2008a,b; Mathiassen, 2006; Mathiassen et al., 2003). We claim that the current standings of knowledge on the determinants and effects of motor variability, as reviewed in the preceding sections of the paper, give a firm and encouraging basis for a continued focus on motor variability in an occupational context.

Although the reviewed studies suggest that there is a good potential for utlizing motor variability to obtain benefits to health and performance in occupational work involving repetitive tasks, a majority of the studies have appeared in the areas of motor control research, sports sciences and rehabilitation. Thus, their results, while encouraging, need be confirmed in studies specifically devoted to tasks and conditions occurring in occupational life. In addition, several issues in motor variability research of relevance to occupational life have only been partially addressed till date or have yet to be addressed. Some of these issues are identified and discussed in more detail below.

5.2. How can motor variability be measured in occupational tasks?

A number of issues pertinent to occupational factors have not so far been investigated properly because of the absence of sophisticated methods to quantify and interpret motor variability in occupational settings. Studies of variability in repetitive tasks in the ergonomics literature have used relatively primitive variables for quantification, such as standard deviations of the postures of single body segments (Mathiassen, 2006). In contrast, motor control research has developed several highly refined methods to analyse motor variability. For example, methods to study coordination variability between multiple body segments involved in a certain task, or methods for modeling relationships between variability in single task components and variability in overall task performance offer the opportunity to analyse motor variability using motor control theories such as the minimum intervention principle, the principle of compensatory control and the variability-overuse hypothesis. However, these methods have so-far only been applied in controlled experiments on simple tasks conducted in lab settings. Bridging this disconnect between research methods available in the motor control literature and methods currently applied in occupational research might lead to wider understanding and more informed interpretion of motor variability from perspectives of high relevance to occupational health and performance.

Also, as pointed out in Section 2, the wide variety of methods available for representing motor variability implies that comparing results from different studies may not be straight-forward. For instance, motor variability quantified as cycle-to-cycle standard deviation has been shown to provide a different information than estimates of complexity/stability obtained from non-linear analysis methods such as Lyapunov exponents (Dingwell and Marin, 2006; Jordan and Newell, 2008; Sondergaard et al., 2010). The exact research question on variability in a specific study may motivate different analysis techniques to be used in each case, and the pros and cons of each analysis method should be contemplated, including how to properly interpret the obtained data in the context of relevant outcomes in occupational studies. At the same time, this methods development need take place with due consideration to the need for metrics that are commonly accepted by the research community; a standardized set of metrics would greatly facilitate comparison and compilations of studies.

5.3. Do individuals differ in motor variability during occupational work?

This review has clearly shown that individuals do differ in motor variability while performing a specific task, and even that some personal characteristics may be determinants of this variability. Individual differences can be expected since the motor control repertoire depends on anatomical and physiological factors known to differ between individuals, such as muscle strength, muscle morphology, endurance, sensory capacities, and clinical conditions.

An important issue in an occupational context is, however, whether a difference between individuals when performing one specific task is consistent across (occupational) tasks; i.e. are some individuals “repeaters” who consistently show a low motor variability in cyclic tasks, while others are “replacers” who, for some reason, utilize the flexibility of the motor system to a greater extent when performing stereotyped tasks? As suggested in previous studies (Cote, 2012; Madeleine, 2010; Mathiassen et al., 2003), and in Section 5.5 below, a reasonable hypothesis would, in that case, be that “repeaters” are more at risk for developing MSD than “replacers”.

An additonal interesting issue to pursue, for the purpose of identifying individuals that may then be particularly prone to MSDs, is possible determinants of motor variability, such as gender (Svendsen and Madeleine, 2010), age, motor development during childhood, or physical activity level.

5.4. What are the relationships between motor variability, fatigue and performance in occupational tasks?

Section 3.3 pointed out that motor variability could play a significant functional role in preventing, delaying or alleviating fatigue. Other studies reviewed in the same section also indicate that movement reorganization, characterised by increased motor variability, may help in maintaining optimal task performance, especially in the presence of fatigue. This raises an unresolved cause-effect issue; i.e. whether changes in motor variability occur proactively to counteract expected negative effects of fatigue, or as a reaction to an effect that has already set in. If the latter is true, it is still an open issue whether the changes in motor variability are an active attempt to preserve performance despite the presence of fatigue or a sign of the motor system failing to resist decreases in performance caused by fatigue. Research in this direction, to understand the complex relationships between fatigue, performance and motor variability, and how such relationships change along the time-course of performing repetitive tasks, would hold important implications for the design of jobs, both from the perspectives of MSD risks (Section 5.5) as well as from a production standpoint.

5.5. What are the relationships between motor variability and MSD?

As a sensible hypothesis, low motor variability may lead to overuse of tissues involved in producing stereotypical movements, and thus a development of chronic symptoms with time. Symptoms may be explained by peripheral adaptations associated with MSDs such as reduced capillary-to-fibre ratio and mitochondrial disturbance (Cote, 2012), and significant degradation of information representation in the somatosensory cortex as revealed by cortical mapping studies (Byl et al., 1997). For muscles, this notion of overuse is compatible with the Cinderella recruitment hypothesis (Hägg, 1991), stating that certain low-threshold motor units will be continuously active even at a very low overall activation of the muscle containing those motor units, and that loads need be transferred to other muscle (parts) for these motor units to recover.

Within a specific muscle, transfer of load between motor units has been shown to be possible, as expressed by the concept of motor unit rotation (Sale, 1987), i.e. that fatigued low-threshold motor units are substituted by higher-threshold motor units and then back-substituted by the original units in a cyclical fashion during long-term contractions. Studies have shown that such motor unit rotation can be stimulated by small changes in muscle activity levels, and this phenomenon has been suggested to play an important protective role for motor units in postural muscles required to perform prolonged low-level work (Westgaard and de Luca, 1999, 2001). While motor unit rotation would alleviate the negative effects of a strict Cinderella recruitment, it is still a matter of debate which external and, possibly, personal factors that determine the motor unit recruitment principle in occupationally relevant tasks.

While the notion of kinetic and kinematic variation leading to neurophysiological benefits is widely accepted, it needs to be confirmed in epidemiological field studies of repetitive work. Only one study has, to our knowledge, demonstrated that operators – in case, assembly workers – performing their work with more variation than others were also less at risk for developing MSD (Kilbom and Persson, 1987).

As shown in Section 3.2, pain has been associated with lower motor variability, but whether lower motor variability is a risk factor for pain development or if pain decreases motor variability has been debated in the literature. A further development of methods of variability analysis stemming from the dynamic systems approach may prove useful in the detection and diagnosis of injuries and painful conditions, and also help in resolving the cause-effect relationship (Hamill et al., 1999). Further development of research in this direction may open up ways to use changes in motor variability not only as an outcome metric accompanying a painful condition, but also as information contributing to understanding the underlying causes of pain.

5.6. Which factors at work influence motor variability, and can they be manipulated so as to change variability to any significant extent?

While the effect of work pace, magnitude of loads and, to some extent, cognitive demands on spatial and temporal motor variability has been investigated for occupational tasks, no concerted effort has until now been devoted to whether motor variability is influenced by other factors that can reasonably be manipulated in occupational settings. Systematic investigations into the effects on motor variability of factors such as precision requirements, work station design, spatial and temporal autonomy in task performance, and different combinations of biomechanical and mental loads are needed to understand whether it is feasible to introduce more motor variability by manipulating such elements in work tasks or work organisation, yet without interfering with production.

The importance of variability analysis has also been recognized in posture and motion simulation for the purpose of predicting the output and ergonomics quality of production systems. Temporal cycle-to-cycle variability is a well-known determinant of loss time on an assembly line (Wild, 1975), while variability between and within subjects in movement patterns is only gradually being accepted as an equally important component when predicting system performance. Quoting from (Perez and Nussbaum, 2006), “A designer with information on average movements can make rough estimates of performance and injury risk and assess whether other work environment objects could obstruct or constrain movements. But a designer with variability envelopes for movements can generate estimates of probability functions and thereby determine the proportion of individuals that would be constrained in their performance or at a risk of musculoskeletal injuries. In this context, varaibility analysis and modeling can maximise the effectiveness of task deisgn by accommodating a range of individuals”.

In conclusion, we claim that available literature in the fields of motor control, sports and occupational biomechanics gives a firm support for motor variablity being an important issue in occupational life and thus in occupational research. There is, however, a great need for studies of motor variability justified specifically by occupational needs, and we suggest a future research agenda to focus particularly on the following issues:

- Methods for measuring motor variability adapted to the needs and conditions of occupational research.
- Magnitude of motor variability in occupational tasks and the effect of occupationally relevant factors that could be expected to influence motor variability (e.g. work pace, precision demands, mental load).
- Relationships between motor variability in occupational tasks and occupationally relevant outcomes (e.g. fatigue, pain, performance).
- Relationships between motor variability in occupational tasks and changeable personal factors (e.g. experience, specific training).

Conflict of interest statement

This study was supported by grants from the Swedish Council for Working Life and Social Research (2009–1761 and 2011–0075). The sponsors did not influence the collection, analysis and interpretation of data, writing of the manuscript or the decision to submit the manuscript for publication.

The authors declare that there are no financial and personal relationships with other people or organizations that could inappropriately influence or bias their work.

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References

Arutyunyan, G.H., Gurfinkel, V.S., Mirskii, M.L., 1968. Investigation of aiming at a target. Biophysics 13, 536–538.

Arutyunyan, G.H., Gurfinkel, V.S., Mirskii, M.L., 1969. Organization of movements of a man carrying out an exactitude posture task. Biophysics 14, 1103–1107.

Aune, T.K., Ingvaldsen, R.P., Ettema, G.J., 2008. Effect of physical fatigue on motor control at different skill levels. Percept. Mot. Skills 106, 371–386.

Balasubramaniam, R., Riley, M.A., Turvey, M.T., 2000. Specificity of postural sway to the demands of a precision task. Gait Posture 11, 12–24.

Barrett, R., Noordegraaf, M.V., Morrison, S., 2008. Gender differences in the variability of lower extremity kinematics during treadmill locomotion. J. Mot. Behav. 40, 62–70.

Bartlett, R., Wheat, J., Robins, M., 2007. Is movement variability important for sports biomechanists? Sports Biomech. 6, 224–243.

Bernard, B., 1997. Musculoskeletal disorders and workplace factors. A critical review of epidemiologic evidence for work-related musculoskeletal disorders of the neck, upper extremity, and low back. U.S. Department of health and human services/NIOSH.

Bootsma, R.J., Vanwieringen, P.C.W., 1990. Timing an attacking forehand drive in table tennis. J. Exp. Psychol. Hum. Percept. Perform. 16, 21–29.

Bosch, T., Mathiassen, S.E., Visser, B., de Looze, M.P., van Dieen, J.H., 2011. The effect of work pace on workload, motor variability and fatigue during simulated light assembly work. Ergonomics 54, 154–168.

Buckle, P.W., Devereux, J.J., 2002. The nature of work-related neck and upper limb musculoskeletal disorders. Appl. Ergon. 33, 207–217.

Button, C., Macleod, M., Sanders, R., Coleman, S., 2003. Examining movement variability in the basketball free-throw action at different skill levels. Res. Q. Exerc. Sport 74, 257–269.

Buzzi, U.H., Stergiou, N., Kurz, M.J., Hageman, P.A., Heidel, J., 2003. Nonlinear dynamics indicates aging affects variability during gait. Clin. Biomech. 18, 435–443.

Byl, N.N., Merzenich, M.M., Cheung, S., Bedenbaugh, P., Nagarajan, S.S., Jenkins, W.M., 1997. A primate model for studying focal dystonia and repetitive strain injury: effects on the primary somatosensory cortex. Phys. Ther. 77, 269–284.

Chau, T., Young, S., Redekop, S., 2005. Managing variability in the summary and comparison of gait data. J. Neuroeng. Rehabil. 2, 22.

Christensen, H., 1986. Muscle-activity and fatigue in the shoulder muscles during repetitive work — an electromyographic study. Eur. J. Appl. Physiol. Occup. Physiol. 54, 596–601.

Christensen, H., Sogaard, K., Pilegaard, M., Engineer, H.B.O., 2000. The importance of the work/rest pattern as a risk factor in repetitive monotonous work. Int. J. Ind. Ergon. 25, 367–373.

Cignetti, F., Schena, F., Rouard, A., 2009. Effects of fatigue on inter-cycle variability in cross-country skiing. J. Biomech. 42, 1452–1459.

Cote, J.N., 2012. A critical review on physical factors and functional characteristics that may explain a sex/gender difference in work-related neck/shoulder disorders. Ergonomics 55, 173–182.

Cote, J.N., Raymond, D., Mathieu, P.A., Feldman, A.G., Levin, M.F., 2005. Differences in multi-joint kinematic patterns of repetitive hammering in healthy, fatigued and shoulder-injured individuals. Clin. Biomech. 20, 581–590.

Cote, J.N., Feldman, A.G., Mathieu, P.A., Levin, M.F., 2008. Effects of fatigue on intermuscular coordination during repetitive hammering. Mot. Control 12, 79–92.

Cusumano, J.P., Cesari, P., 2006. Body-goal variability mapping in an aiming task. Biol. Cybern. 94, 367–379.

Davids, K., Glazier, P., Araujo, D., Bartlett, R., 2003. Movement systems as dynamical systems: the functional role of variability and its implications for sports medicine. Sports Med. 33, 245–260.

Davids, K., Bennett, S., Newell, K.M., 2006. Movement system variability. Human Kinetics, Champaign, IL.

de Looze, M., Bosch, T., van Dieen, J., 2009. Manifestations of shoulder fatigue in prolonged activities involving low-force contractions. Ergonomics 52, 428–437.

Dempsey, P.G., Mathiassen, S.E., Jackson, J.A., O'Brien, N.V., 2010. Influence of three principles of pacing on the temporal organisation of work during cyclic assembly and disassembly tasks. Ergonomics 53, 1347–1358.

Dingwell, J.B., Cusumano, J.P., 2000. Nonlinear time series analysis of normal and pathological human walking. Chaos 10, 848–863.

Dingwell, J.B., Marin, L.C., 2006. Kinematic variability and local dynamic stability of upper body motions when walking at different speeds. J. Biomech. 39, 444–452.

Dingwell, J.B., Cusumano, J.P., Cavanagh, P.R., Sternad, D., 2001. Local dynamic stability versus kinematic variability of continuous overground and treadmill walking. J. Biomech. Eng. 123, 27–32.

Domkin, D., Laczko, J., Jaric, S., Johansson, H., Latash, M.L., 2002. Structure of joint variability in bimanual pointing tasks. Exp. Brain Res. 143, 11–23.

Domkin, D., Laczko, J., Djupsjobacka, M., Jaric, S., Latash, M.L., 2005. Joint angle variability in 3D bimanual pointing: uncontrolled manifold analysis. Exp. Brain Res. 163, 44–57.

Falla, D., Farina, D., 2007. Periodic increases in force during sustained contraction reduce fatigue and facilitate spatial redistribution of trapezius muscle activity. Exp. Brain Res. 182, 99–107.

Falla, D., Arendt-Nielsen, L., Farina, D., 2008. Gender-specific adaptations of upper trapezius muscle activity to acute nociceptive stimulation. Pain 138, 217–225.

Farina, D., Leclerc, F., Arendt-Nielsen, L., Buttelli, O., Madeleine, P., 2008. The change in spatial distribution of upper trapezius muscle activity is correlated to contraction duration. J. Electromyogr. Kinesiol. 18, 16–25.

Fethke, N.B., Anton, D., Cavanaugh, J.E., Gerr, F., Cook, T.M., 2007. Bootstrap exploration of the duration of surface electromyography sampling in relation to the precision of exposure estimation. Scand. J. Work Environ. Health 33, 358–367.

Forestier, N., Nougier, V., 1998. The effects of muscular fatigue on the coordination of a multijoint movement in human. Neurosci. Lett. 252, 187–190.

Fuller, J.R., Lomond, K.V., Fung, J., Cote, J.N., 2009. Posture-movement changes following repetitive motion-induced shoulder muscle fatigue. J. Electromyogr. Kinesiol. 19, 1043–1052.

Fuller, J.R., Fung, J., Cote, J.N., 2011. Time-dependent adaptations to posture and movement characteristics during the development of repetitive reaching induced fatigue. Exp. Brain Res. 211, 133–143.

Gallagher, K.M., Nelson-Wong, E., Callaghan, J.P., 2011. Do individuals who develop transient low back pain exhibit different postural changes than non-pain developers during prolonged standing? Gait Posture 34, 490–495.

Gates, D.H., Dingwell, J.B., 2008. The effects of neuromuscular fatigue on task performance during repetitive goal-directed movements. Exp. Brain Res. 187, 573–585.

Gates, D.H., Dingwell, J.B., 2010. Muscle fatigue does not lead to increased instability of upper extremity repetitive movements. J. Biomech. 43, 913–919.

Georgoulis, A.D., Moraiti, C., Ristanis, S., Stergiou, N., 2006. A novel approach to measure variability in the anterior cruciate ligament deficient knee during walking: the use of the approximate entropy in orthopaedics. J. Clin. Monit. Comput. 20, 11–18.

Granata, K.P., Marras, W.S., Davis, K.G., 1999. Variation in spinal load and trunk dynamics during repeated lifting exertions. Clin. Biomech. 14, 367–375.

Habes, D., Carlson, W., Badger, D., 1985. Muscle fatigue associated with repetitive arm lifts: effects of height, weight and reach. Ergonomics 28, 471–488.

Hagberg, M., 1992. Exposure variables in ergonomic epidemiology. Am. J. Ind. Med. 21, 91–100.

Hägg, G.M., 1991. Static Work Loads and Occupational Myalgia — A New Explanation Model. In: Anderson, P.A., Hobart, D.J., Dainoff, J.V. (Eds.), Electromyographical Kinesiology. Elsevier Science Publishers, Amsterdam.

Hamill, J., van Emmerik, R.E., Heiderscheit, B.C., Li, L., 1999. A dynamical systems approach to lower extremity running injuries. Clin. Biomech. 14, 297–308.

Hammarskjold, E., Harmsringdahl, K., Ekholm, J., 1990. Shoulder arm muscular-activity and reproducibility in carpenters work. Clin. Biomech. 5, 81–87.

Hausdorff, J.M., Mitchell, S.L., Firtion, R., Peng, C.K., Cudkowicz, M.E., Wei, J.Y., et al., 1997. Altered fractal dynamics of gait: reduced stride-interval correlations with aging and Huntington's disease. J. Appl. Physiol. 82, 262–269.

Heiderscheit, B.C., 2000. Movement variability as a clinical measure for locomotion. J. Appl. Biomech. 16, 419–427.

Heiderscheit, B.C., Hamill, J., van Emmerik, R.E.A., 2002. Variability of stride characteristics and joint coordination among individuals with unilateral patellofemoral pain. J. Appl. Biomech. 18, 110–121.

Henning, R.A., Jacques, P., Kissel, G.V., Sullivan, A.B., Alteraswebb, S.M., 1997. Frequent short rest breaks from computer work: effects on productivity and well-being at two field sites. Ergonomics 40, 78–91.

Hodges, P., van den Hoorn, W., Dawson, A., Cholewicki, J., 2009. Changes in the mechanical properties of the trunk in low back pain may be associated with recurrence. J. Biomech. 42, 61–66.

Hollman, J.H., Kovash, F.M., Kubik, J.J., Linbo, R.A., 2007. Age-related differences in spatiotemporal markers of gait stability during dual task walking. Gait Posture 26, 113–119.

Holtermann, A., Sogaard, K., Christensen, H., Dahl, B., Blangsted, A.K., 2008. The influence of biofeedback training on trapezius activity and rest during occupational computer work: a randomized controlled trial. Eur. J. Appl. Physiol. 104, 983–989.

Huffenus, A.F., Forestier, N., Amarantini, D., 2006. Effects of distal and proximal arm muscles fatigue on multi-joint movement organization. Exp. Brain Res. 170, 438–447.

Huxhold, O., Li, S.C., Schmiedek, F., Lindenberger, U., 2006. Dual-tasking postural control: aging and the effects of cognitive demand in conjunction with focus of attention. Brain Res. Bull. 69, 294–305.

Huysmans, M.A., Hoozemans, M.J., van der Beek, A.J., de Looze, M.P., van Dieen, J.H., 2008. Fatigue effects on tracking performance and muscle activity. J. Electromyogr. Kinesiol. 18, 410–419.

Jackson, J.A., Mathiassen, S.E., Dempsey, P.G., 2009. Methodological variance associated with normalization of occupational upper trapezius EMG using sub-maximal reference contractions. J. Electromyogr. Kinesiol. 19, 416–427.

Jeng, S.F., Holt, K.G., Fetters, L., Certo, C., 1996. Self-optimization of walking in nondisabled children and children with spastic hemiplegic cerebral palsy. J. Mot. Behav. 28, 15–27.

Jensen, C., Westgaard, R.H., 1997. Functional subdivision of the upper trapezius muscle during low-level activation. Eur. J. Appl. Physiol. Occup. Physiol. 76, 335–339.

Jordan, K., Newell, K.M., 2008. The structure of variability in human walking and running is speed-dependent. Exerc. Sport Sci. Rev. 36, 200–204.

Jordan, K., Challis, J.H., Newell, K.M., 2007. Walking speed influences on gait cycle variability. Gait Posture 26, 128–134.

Kilbom, A., 1994a. Repetitive Work of the Upper Extremity .1. Guidelines for the Practitioner. Int. J. Ind. Ergon. 14, 51–57.

Kilbom, A., 1994b. Repetitive Work of the Upper Extremity .2. The Scientific Basis (Knowledge-Base) for the Guide. Int. J. Ind. Ergon. 14, 59–86.

Kilbom, A., Persson, J., 1987. Work technique and its consequences for musculoskeletal disorders. Ergonomics 30, 273–279.

Kilbom, A., Persson, J., Jonsson, B., 1986. Risk factors for work-related disordersof the neck and shoulder - with special emphasis on working postures and movement. In: Corlett, E.N., Wilson, J.R., Manenica, I. (Eds.), Ergonomics of Working Postures. Taylor & Francis, London.

Kudo, K., Ito, T., Tsutsui, S., Yamamoto, Y., Ishikura, T., 2000. Compensatory coordination of release parameters in a throwing task. J. Mot. Behav. 32, 337–345.

Latash, M.L., Scholz, J.F., Danion, F., Schoner, G., 2002. Finger coordination during discrete and oscillatory force production tasks. Exp. Brain Res. 146, 419–432.

Lomond, K.V., Cote, J.N., 2010. Movement timing and reach to reach variability during a repetitive reaching task in persons with chronic neck/shoulder pain and healthy subjects. Exp. Brain Res. 206, 271–282.

Lomond, K.V., Cote, J.N., 2011. Differences in posture-movement changes induced by repetitive arm motion in healthy and shoulder-injured individuals. Clin. Biomech. 26, 123–129.

Madeleine, P., 2010. On functional motor adaptations: from the quantification of motor strategies to the prevention of musculoskeletal disorders in the neck–shoulder region. Acta Physiol (Oxf.) 199 (Suppl. 679), 1–46.

Madeleine, P., Madsen, T.M.T., 2009. Changes in the amount and structure of motor variability during a deboning process are associated with work experience and neck–shoulder discomfort. Appl. Ergon. 40, 887–894.

Madeleine, P., Lundager, B., Voigt, M., Arendt-Nielsen, L., 2003. Standardized low-load repetitive work: evidence of different motor control strategies between experienced workers and a reference group. Appl. Ergon. 34, 533–542.

Madeleine, P., Mathiassen, S.E., Arendt-Nielsen, L., 2008a. Changes in the degree of motor variability associated with experimental and chronic neck–shoulder pain during a standardised repetitive arm movement. Exp. Brain Res. 185, 689–698.

Madeleine, P., Voigt, M., Mathiassen, S.E., 2008b. The size of cycle-to-cycle variability in biomechanical exposure among butchers performing a standardised cutting task. Ergonomics 51, 1078–1095.

Mathiassen, S.E., 2006. Diversity and variation in biomechanical exposure: what is it, and why would we like to know? Appl. Ergon. 37, 419–427.

Mathiassen, S.E., Aminoff, T., 1997. Motor control and cardiovascular responses during isoelectric contractions of the upper trapezius muscle: evidence for individual adaptation strategies. Eur. J. Appl. Physiol. 76, 434–444.

Mathiassen, S.E., Winkel, J., 1990. Electromyographic activity in the shoulder-neck region according to arm position and glenohumeral torque. Eur. J. Appl. Physiol. Occup. Physiol. 61, 370–379.

Mathiassen, S.E., Winkel, J., 1996. Physiological comparison of three interventions in light assembly work: reduced work pace, increased break allowance and shortened working days. Int. Arch. Occup. Environ. Health 68, 94–108.

Mathiassen, S.E., Moller, T., Forsman, M., 2003. Variability in mechanical exposure within and between individuals performing a highly constrained industrial work task. Ergonomics 46, 800–824.

Maylor, E.A., Wing, A.M., 1996. Age differences in postural stability are increased by additional cognitive demands. J. Gerontol. B Psychol. Sci. Soc. Sci. 51, P143–P154.

McLean, L., Tingley, M., Scott, R.N., Rickards, J., 2001. Computer terminal work and the benefit of microbreaks. Appl. Ergon. 32, 225–237.

Menz, H.B., Lord, S.R., Fitzpatrick, R.C., 2003. Age-related differences in walking stability. Age Ageing 32, 137–142.

Mientjes, M.I.V., Frank, J.S., 1999. Balance in chronic low back pain patients compared to healthy people under various conditions in upright standing. Clin. Biomech. 14, 710–716.

Mirka, G.A., Baker, A., 1996. An investigation of the variability in human performance during sagittally symmetric lifting tasks. IIE Trans. 28, 745–752.

Mirka, G.A., Marras, W.S., 1993. A stochastic-model of trunk muscle coactivation during trunk bending. Spine 18, 1396–1409.

Missenard, O., Mottet, D., Perrey, S., 2008. The role of cocontraction in the impairment of movement accuracy with fatigue. Exp. Brain Res. 185, 151–156.

Mok, N.W., Brauer, S.G., Hodges, P.W., 2004. Hip strategy for balance control in quiet standing is reduced in people with low back pain. Spine (Phila Pa 1976) 29, E107–E112.

Mok, N.W., Brauer, S.G., Hodges, P.W., 2007. Failure to use movement in postural strategies leads to increased spinal displacement in low back pain. Spine (Phila Pa 1976) 32, E537–E543.

Moller, T., Mathiassen, S.E., Franzon, H., Kihlberg, S., 2004. Job enlargement and mechanical exposure variability in cyclic assembly work. Ergonomics 47, 19–40.

Montero-Odasso, M., Muir, S.W., Speechley, M., 2012. Dual-task complexity affects gait in people with mild cognitive impairment: the interplay between gait variability, dual tasking, and risk of falls. Arch. Phys. Med. Rehabil. 93, 293–299.

Moseley, G.L., Hodges, P.W., 2006. Reduced variability of postural strategy prevents normalization of motor changes induced by back pain: a risk factor for chronic trouble? Behav. Neurosci. 120, 474–476.

Muller, H., Loosch, E., 1999. Functional variability and an equifinal path of movement during targeted throwing. J. Hum. Mov. Stud. 36, 103–126.

National Research Council, 2001. Musculoskeletal Disorders and the Workplace: Low Back and Upper Extremities. National Academy of Sciences.

Newell, K.M., Corcos, D.M., 1993. Variability and Motor Control. Human Kinetics, Champaign, IL.

Newell, K.M., Slifkin, A.B., 1998. The Nature of Movement Variability. In: Piek, J.P. (Ed.), Motor behavior and human skill. A multidisciplinary approach. Human Kinetics.

Nieminen, H., Hameenoja, S., 1995. Quantification of the static load component in muscle work using nonlinear filtering of surface EMG. Ergonomics 38, 1172–1183.

Nordander, C., Ohlsson, K., Akesson, I., Arvidsson, I., Balogh, I., Hansson, G.A., et al., 2009. Risk of musculoskeletal disorders among females and males in repetitive/constrained work. Ergonomics 52, 1226–1239.

Palmerud, G., Kadefors, R., Sporrong, H., Jarvholm, U., Herberts, P., Hogfors, C., et al., 1995. Voluntary redistribution of muscle-activity in human shoulder muscles. Ergonomics 38, 806–815.

Palmerud, G., Sporrong, H., Herberts, P., Kadefors, R., 1998. Consequences of trapezius relaxation on the distribution of shoulder muscle forces: an electromyographic study. J. Electromyogr. Kinesiol. 8, 185–193.

Perez, M.A., Nussbaum, M.A., 2006. Posture and motion variability in non-repetitive manual materials handling tasks. Hum. Mov. Sci. 25, 409–421.

Preatoni, E., Ferrario, M., Dona, G., Hamill, J., Rodano, R., 2010. Motor variability in sports: a non-linear analysis of race walking. J. Sports Sci. 28, 1327–1336.

Reisman, D.S., Scholz, J.P., Schoner, G., 2002. Coordination underlying the control of whole body momentum during sit-to-stand. Gait Posture 15, 45–55.

Rempel, D.M., Harrison, R.J., Barnhart, S., 1992. Work-related cumulative trauma disorders of the upper extremity. JAMA 267, 838–842.

Riccio, G.E., 1993. Information in Movement Variability About the Qualitative Dynamics of Posture and Orientation. Variability and Motor Control.

Riley, M.A., Turvey, M.T., 2002. Variability and determinism in motor behavior. J. Mot. Behav. 34, 99–125.

Robins, M., Wheat, J., Irwin, G., Bartlett, R., 2006. The effect of shooting distance on movement variability in basketball. J. Hum. Mov. Stud. 50, 217–238.

Sale, D.G., 1987. Influence of exercise and training on motor unit activation. Exerc. Sport Sci. Rev. 15, 95–151.

Samani, A., Holtermann, A., Sogaard, K., Madeleine, P., 2010. Active biofeedback changes the spatial distribution of upper trapezius muscle activity during computer work. Eur. J. Appl. Physiol. 110, 415–423.

Schieppati, M., Hugon, M., Grasso, M., Nardone, A., Galante, M., 1994. The limits of equilibrium in young and elderly normal subjects and in parkinsonians. Electroencephalogr. Clin. Neurophysiol. 93, 286–298.

Scholz, J.P., Schoner, G., 1999. The uncontrolled manifold concept: identifying control variables for a functional task. Exp. Brain Res. 126, 289–306.

Scholz, J.P., Schoner, G., Latash, M.L., 2000. Identifying the control structure of multijoint coordination during pistol shooting. Exp. Brain Res. 135, 382–404.

Schoner, G., 1995. Recent developments and problems in human movement science and their conceptual implications. Ecol. Psychol. 7, 291–314.

Selen, L.P.J., Beek, P.J., van Dieen, J.H., 2007. Fatigue-induced changes of impedance and performance in target tracking. Exp. Brain Res. 181, 99–108.

Skurvydas, A., Brazaitis, M., Kamandulis, S., 2010. Prolonged muscle damage depends on force variability. Int. J. Sports Med. 31, 77–81.

Sluiter, J.K., Rest, K.M., Frings-Dresen, M.H., 2001. Criteria document for evaluating the work-relatedness of upper-extremity musculoskeletal disorders. Scand. J. Work Environ. Health 27 (Suppl. 1), 1–102.

Sondergaard, K.H.E., Olesen, C.G., Sondergaard, E.K., de Zee, M., Madeleine, P., 2010. The variability and complexity of sitting postural control are associated with discomfort. J. Biomech. 43, 1997–2001.

Sparto, P.J., Parnianpour, M., Reinsel, T.E., Simon, S., 1997. The effect of fatigue on multijoint kinematics and load sharing during a repetitive lifting test. Spine 22, 2647–2654.

Stergiou, N., 2004. Innovative analyses of human movement. Human Kinetics, Champaign, IL.

Stergiou, N., Moraiti, C., Giakas, G., Ristanis, S., Georgoulis, A.D., 2004. The effect of the walking speed on the stability of the anterior cruciate ligament deficient knee. Clin. Biomech. 19, 957–963.

Stergiou, N., Harbourne, R., Cavanaugh, J., 2006. Optimal movement variability: a new theoretical perspective for neurologic physical therapy. J. Neurol. Phys. Ther. 30, 120–129.

Sterling, M., Jull, G., Wright, A., 2001. The effect of musculoskeletal pain on motor activity and control. J. Pain 2, 135–145.

Sundelin, G., 1993. Patterns of electromyographic shoulder muscle fatigue during MTM-paced repetitive arm work with and without pauses. Int. Arch. Occup. Environ. Health 64, 485–493.

Sundelin, G., Hagberg, M., 1989. The effects of different pause types on neck and shoulder EMG activity during VDU work. Ergonomics 32, 527–537.

Svendsen, J.H., Madeleine, P., 2010. Amount and structure of force variability during short, ramp and sustained contractions in males and females. Hum. Mov. Sci. 29, 35–47.

Todorov, E., 2004. Optimality principles in sensorimotor control. Nat. Neurosci. 7, 907–915.

Todorov, E., Jordan, M.I., 2002. Optimal feedback control as a theory of motor coordination. Nat. Neurosci. 5, 1226–1235.

Valero-Cuevas, F.J., Venkadesan, M., Todorov, E., 2009. Structured variability of muscle activations supports the minimal intervention principle of motor control. J. Neurophysiol. 102, 59–68.

van den Heuvel, S.G., de Looze, M.P., Hildebrandt, V.H., The, K.H., 2003. Effects of software programs stimulating regular breaks and exercises on work-related neck and upper-limb disorders. Scand. J. Work Environ. Health 29, 106–116.

van den Hoorn, W., Bruijn, S.M., Meijer, O.G., Hodges, P.W., van Dieen, J.H., 2012. Mechanical coupling between transverse plane pelvis and thorax rotations during gait is higher in people with low back pain. J. Biomech. 45, 342–347.

van Dieen, J.H., Vrielink, H.H.E.O., Toussaint, H.M., 1993. An investigation into the relevance of the pattern of temporal activation with respect to erector spinae muscle endurance. Eur. J. Appl. Physiol. Occup. Physiol. 66, 70–75.

van Dieen, J.H., Dekkers, J.J.M., Groen, V., Toussaint, H.M., Meijer, O.G., 2001. Within-subject variability in low back load in a repetitively performed, mildly constrained lifting task. Spine 26, 1799–1804.

van Dieen, J.H., Selen, L.P.J., Cholewicki, J., 2003. Trunk muscle activation in low-back pain patients, an analysis of the literature. J. Electromyogr. Kinesiol. 13, 333–351.

Van dieen, J.H., Westebring-Van Der Putten, E.P., Kingma, I., De Looze, M.P., 2009. Low-level activity of the trunk extensor muscles causes electromyographic manifestations of fatigue in absence of decreased oxygenation. J. Electromyogr. Kinesiol. 19, 398–406.

Veiersted, K.B., Westgaard, R.H., Andersen, P., 1993. Electromyographic evaluation of muscular work pattern as a predictor of trapezius myalgia. Scand. J. Work Environ. Health 19, 284–290.

Westgaard, R.H., de Luca, C.J., 1999. Motor unit substitution in long-duration contractions of the human trapezius muscle. J. Neurophysiol. 82, 501–504.

Westgaard, R.H., de Luca, C.J., 2001. Motor control of low-threshold motor units in the human trapezius muscle. J. Neurophysiol. 85, 1777–1781.

Westgaard, R.H., Winkel, J., 1996. Guidelines for occupational musculoskeletal load as a basis for intervention: a critical review. Appl. Ergon. 27, 79–88.

Westgaard, R.H., Jensen, C., Hansen, K., 1993. Individual and work-related risk factors associated with symptoms of musculoskeletal complaints. Int. Arch. Occup. Environ. Health 64, 405–413.

Wild, R., 1975. On the selection of mass production systems. Int. J. Prod. Res. 13, 443–461.

Wilson, C., Simpson, S.E., van Emmerik, R.E.A., Hamill, J., 2008. Coordination variability and skill development in expert triple jumpers. Sports Biomech. 7, 2–9.

Winkel, J., Westgaard, R., 1992. Occupational and individual risk factors for shoulder-neck complaints: Part II — the scientific basis (literature review) for the guide. Int. J. Ind. Ergon. 10, 85–104.