Intrinsic movement variability at work. How long is the path from motor control to design engineering?

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Abstract

For several years, increasing numbers of studies have highlighted the existence of movement variability. Before that, it was neglected in movement analysis and it is still almost completely ignored in workstation design. This article reviews motor control theoriesand factors influencing movement execution,and indicateshowintrinsic movement variability is partof task completion. These background clarifications shouldhelp ergonomists and workstation designers to gain a better understanding of these concepts,which can then beusedto improve design tools. We also question whichtechniques - kinematics, kinetics or muscular activity – and descriptors are most appropriate for describing intrinsic movement variability and for integrationinto design tools. By this way, simulations generated by designers for workstation design should be closer to the real movements performed by workers. This review emphasises the complexity of identifying, describing and processing intrinsic movement variability in occupational activities.

Keywords: Intrinsic movement variability, motor control, workstation design

Highlights:

Intrinsic movement variability is an essential feature of human motion.

Motor control theories can explain the existence of intrinsic movement variability.

Task and personal characteristics influence intrinsic movement variability.

Intrinsic movement variability should be taken into account in workstation design

1 - INTRODUCTION

Movement variability is an essential feature of human motion (Berthoz, 1997; Glazier et al., 2006). It seems to be linked to the process of controlling and regulating movement (Diniz et al., 2011; Latash et al., 2002) with the aim of providing adaptability and flexibility, which are essential for responding to personal and task characteristics as well as environmental constraints (Glazier et al., 2006). Movement variability is present in all actions controlled by the sensorimotor system, andhas been observed between individualsas well as for a singleindividual (Jackson et al., 2009; Madeleine et al., 2003a; Madeleine et al., 2003b; Mathiassen et al., 2002; Mathiassen et al., 2003).Movement variability is usually highlighted as differences in body segment movements and/or muscle activities between repeats of a task(Terrier and Schutz, 2003). Taskrepetitivenesscould be cyclic or intermittent throughout the day. Movement variability is present during repetitive occupational work(Madeleine, 2010; Srinivasan et al., 2015c).

However, movement variability has long been neglected by the scientific community investigating motor activity, movements performed in work situations and, more specifically, biomechanical risk factors leading to the development of musculoskeletal disorders. Indeed, motor variability has often been considered to be non-significant noise or interferencewhich is difficult to quantify and analyse (Bartlett et al., 2007). Because of the way it is considered, it has been totally ignored in workstation design. Thus, no design tools currently exist which take movement variability into account. In manufacturing companies, the main objective of organising production is to ensure optimal productivity and quality. Therefore, production system designers currently seek primarily to ensure that practices are performed uniformly. As a consequence, workstation designers attempt to define a single succession of postures and movements to be performed by the operator to optimise production and/or safety criteria, without offering any alternative. This results in highly prescriptive operating procedures in terms of the order of operations, how they are to be performed, and the time required for each step of the task, andinter- and intra-operator intrinsic movement variability is not taken into account.

Several occupational studies have shown that even controlled repetitive tasks are associated with considerable motor variability in the laboratory, and even more so in the field (Srinivasan and Mathiassen, 2012). Thus, takingoperators' movement variability into account from the stage of workstation design seems necessary to more precisely apprehendoperators'real activity. Real activity depends, among other things, onthe environment in which workers perform their task, the task to be performed,interactions between workers,and their characteristics (for example gender, age, novice or experienced, with or without pain).

This reviewis the fruit of reflectionsby a multidisciplinary team in the fields of design engineering, neurophysiology and biomechanics. The aim of this team is to gain a better understanding of movement variability due to characteristics of each individual observed during repeats of the task. We called this variability intrinsic movement variability. This knowledge will help to improve design toolsin order to considermovements likely to be performed by workers. This paper first presents a review of motor control theories as a possible explanation for intrinsic movement variability. Then, it detailssome studies highlighting factors influencing intrinsic movement variability and mentions warning points to characterise it in occupational activities. Thereafter, it introduces the issue of intrinsic movement variability during workstation design. Finally, future research directions are proposedwith the aim of improvinghowmovement variability is taken into considerationwhen simulating as well as analysing occupational activities.

2 - MOVEMENT VARIABILITY AND MOTOR CONTROL

This paper relates to voluntary movementwhichdesignates a movement performed for the purpose of completing a specific task. Voluntary movement must be distinguished from reflex movement, which is a stereotyped motor response triggered by sensorystimulation.

In recent decades, a number of studies have developed theories taking the intrinsic variability of human movementinto account (Kerlirzin et al., 2009; Stenard, 2009).The bases of these theories, grouped as motor control theory,rely on several disciplines including biomechanics, movement physiology, behavioural neurosciences and cognitive sciences. Motor control is defined as the constant interaction between a subject, the environment in which they act and the task to be performed. Movement is therefore planned by the central nervous system (CNS) based on sensory information related to the environment in which the task is performedand the subject's capacity to interpret this informationwith the best possible yield. The more expert the subject, the better they will be able to achieve their objective, maximising the probability of success and minimising production and implementation costs (Leplat, 1987; Leplat and Pailhous, 1981). This theory raises many questions with respect to its application. Some questions remain unanswered, for instance concerning the CNS's ability to process and control such a large amount of sensory information within a period as short as that of reaction time.

To answer these questions, Bernstein (1967) proposed an initial explanation,based on the notion of reducing the complexity of the "human" system. The association of complex kinematic chains with combinations of activation of joints and different muscles gives rise to an infinite number of possible configurations in which the same taskcould be performed. Muscular synergies and segmental strategies chosenthrough afferent information can then be used to decrease the number of degrees of freedom required to efficiently control the system. This control loop system makes it possible to performthe same task by exercising different muscles activities or joint amplitudes.

Motor control, to be efficient, must be able to select the appropriate input fromamong the huge amount ofsensory information to achieve some required output consistent with the environmentwhere the worker acts and the task to be performed. Depending on the information selected, the movement performed can be different.To select the appropriate input, a model of understandingwas proposed based on multiple paired forward and inverse models. This model was considered an interesting way to achieve motor learning and control (Wolpert and Kawato, 1998; Harris and Wolpert, 1998; Wolpert et al., 1998, Blakemore et al., 1999; Wolpert et al, 2003). For Berthoz (1997), the brain continuously generates hypotheses on the movement to come, allowing it to formulate preparatory movements or postural adjustments. These hypotheses are based on the sensoryinformation provided based on the environment, linked to the memory of the movement acquired through experience. Along the same lines, for Rosenbaum et al. (1999), movement is predictedas a function of the final posture that the forearmor hand must adopt at the end of the action. These authorshypothesised that each new posture encountered is stored in memory so that it can be re-used during a similar situation in the future. Furthermore, these plans of action are basedon procedural memory, i.e.,the personneeds to really perform the action rather than simply observing it or imagining doing it(Walsh and Rosenbaum, 2009). Thus, the more experience the personhas in performingatask, the better he/she will be able to select the relevant information from the environment and to readjust his/her movement, doing so as fast as possible while performing the task. The person will be able to better adapt to environmental conditions. This adaptation can be done in the short-term, during the movement itself, or in the medium to long-term, as a result of learning.

However, taking all this information on board to generate a movement comes at a considerable cost for the CNS. Five main models are admitted as possible ways to reduce this cost. The minimum jerk model focuses on minimising variations in effector acceleration (Flash and Hogan, 1985; Hogan, 1984). In the minimal effort model, neuromuscular behaviour is compared to a spring for which the equilibrium point depends on the simultaneous activation of agonistic and antagonistic muscles and joint stiffness (Hasan, 1986). The minimum torque change model is based on the value of the torque or external forces applied to the system (Uno et al., 1989). In a fourth model, the cost of a movement is estimated by the CNS based on the minimal variance between the final position of the forearmand that of the eye during movement of the upper limb (Harris and Wolpert, 1998). Finally, the optimal feedback control model takesobserved movement variability into account only if it is likely to jeopardise the movement's final goal. According to this model, variability is an integral part of the movement and of itssuccess (Todorov, 2004; Todorov and Jordan, 2002). All these models are based on kinetic or kinematic information. In addition to these models, aneurophysiological approach based on joint coordinates has also beenproposed asa possible means to reduce the cost of motor control. Withthis approach, control is achieved through proprioceptive muscle feedback by determining an equilibrium position for the limb and stiffness around the joint (Feldman, 1966; Bizzi et al., 1992).

Even if motor control theories are still being discussed, intrinsic movement variability seems to be a natural feature of human movement. The theories developed thus far show that variability could be present at muscle and jointlevels(Côté et al., 2008; Madeleine and Farina, 2008; Holtermann et al., 2010). These theories can also serve as the bases for control algorithms used to simulate human motion by workstation design engineers. For instance, De Magistris et al. (2013, 2015) used Fitt’s law, Todorov’s speed profiles model, minimum jerk optimisation, and minimum exertion to model human movement in an industrial assembly task.

More recently, an additional approach was introduced. This approachconsiders motor redundancy through the principle of abundance derived from Bernstein (1967) and states thatredundancy should no longer be considered as a problem to be solved, but as a benefit. Indeed, redundancymakes it possibleto adapt movements to the main constraints, i.e., the objective of the task,and to the secondary environmental constraints,which include perturbationsor parallel tasks cropping up as the movement is performed(Latash, 2012). This approach differentiates state variables characterising the system, such as joint angle or muscle activation, and performance variables that describe performance of the task, such as an exerted force or a trajectory of the final effector (Park et al., 2010; Park et al., 2012).Some of the state variables significantly affect task performance and should be controlled, while othershave little effect and can be more loosely constrained. During a perturbation or while performing a secondary task, the CNS can stabilise the main state variables for the principle task by bringing other variables into play. Thus,a task does not have a single, optimal solution, but a family of equivalent solutions, providing the system with “goal equivalent” variability.

All these theories aim to understand how movement is planned and performed. However, none of them provides a fully satisfactory response for all situations, andall of the models proposed have advantages and disadvantages. As Miall (1995) suggested, it is likely that motor control is achieved through mechanisms compatible with several control theories depending on the situation.According to all these considerations, there is no unique solution whenexecuting a given task. If we extend this idea, in line withour interest in the field of occupational activities, we can hypothesise that workers have the choice betweena large panel of possible movements depending on the various solutions. This range of options can lead to intrinsic movement variability.

3 - INTRINSIC MOVEMENT VARIABILITY AND FACTORS INFLUENCING IT

The theories of motor control cited in the previous section can explain why intrinsic movement variability is present during task performance. This section reviews various experiments highlighting the presence of intrinsic movement variability, particularly during upper limb movements,based on various factors related either to the characteristics of the person, or of the task.

For the person’s characteristics, Svendsen and Madeleine (2010) studied variabilityduring an elbow flexion endurance task in asymptomatic men and women. Theyobserved that forces produced by women were less variable than those produced by men. In her review, Côté (2012) suggestedthatthe reducedmotor variability in women compared to men could partly explain why women are at higher risk of developing musculoskeletal symptoms, especially inthe neck / shoulder region.

The observations describedby Gaudart (2000) showed that younger workers have a more variable work cycle time than older workers. Younger workers alternatedperiods of relaxation with periods of accelerationmore than older workers. In contrast,Madeleine et al. (2008) demonstrated that experienced operators presented greater variability inwork cycle time even if the overall timewas shorter for novices. These authorshighlighted a greater kinematic variability, but lower variability in terms of muscular activity for more experienced workers. They explained that this reduction in variability of muscular activity could be the result ofthe implementation of specific motor programs. Moreover, with age, the characteristics of motor adaptation change, mainly due to alterations tomuscular capacities (De Zwart et al., 1995; Enoka and Duchateau, 2008). These capacities are generally diminished by progressive loss of the muscles'viscoelastic properties and the increase in recovery time following an effort. Movement variability can either increase due to accumulated fatigue, or decrease due to the reduction of adaptation capacities. In all cases, with age, the increase infatigue comes in addition tocumulativeexposure duration. Moreover, asreported by Gaudart (2000),operators are aware of their,more or less declining,physical and cognitive capacities. They develop their strategies based ontheir experience and their capacities.

Other studies show that the kinematics of movement can be modified with fatigue, for example during repetitive throwing(Forestier and Nougier, 1998;Huffenus et al., 2006), hammering (Côté et al., 2005;Côté et al., 2008) sawing (Côté et al., 2002; Gates and Dingwell, 2008) and during reaching movements (Fuller et al., 2009; Lomond and Côté, 2010). During repeated sawing movements,elbow angle amplitude is reduced and offset by a more advanced and lower position of the shoulder as well as an increase inshoulder, wrist and torso movement amplitudes (Côté et al., 2002). Furthermore, Gates and Dingwell (2008) showed that these movement patterns were modified without affecting the production rate. Various studies have shown that the presence of temporal and/or spatio-temporal variability in muscular activity and posture can have a preventive effect on the onsetof fatigue (Bosch et al., 2011; Côté et al., 2005; Farina et al., 2008; Fuller et al., 2009; Van Dieën et al., 2009). Van Dieën et al. (2009) showed that increased variability in the activity of the posterior extensor muscles reduced the development of fatigue. These authors suggested that persons who can alternate muscular activity between the different portions of the posterior extensor muscles will havegreater endurance. Along theselines, Palmerudet al. (1998)suggested that the redistributionof load between the synergetic muscles of the shoulder could avoid or delay the onsetof muscular fatigue. Thus, people having a greaterability of motor variability can slow down or prevent the development of fatigue and are less sensitive to the risk of developingmusculoskeletal disorders(Kilbom, 1994; Madeleine et al., 2008; Mathiassen, 2006; Mathiassen and Aminoff, 1997). Muscle fatigue and musculoskeletal discomfort are reported to be involved in initiating work-related musculoskeletal disorders (Madeleine, 2010). For workers performing a deboning activity, those with neck-shoulder discomfort showed smaller work cycle duration and extentof variability of the head-shoulder displacementthan those without discomfort.A greater extentof variability of the elbow-hip displacement was also noted for the former group. However,studies using surface electromyography have shown that musculoskeletal discomfort may or may not lead to changes in muscle activation (Ostensvik et al., 2009; Szeto et al., 2005; Vasseljen and Westgaard, 1996, Westgaard et al., 2001). Madeleine et al. (2008) also highlighted that variability could be modified by the presence of pain. Acute pain generatesgreater motor variability than chronic pain, suggesting motor reorganisation.

These cross-sectional studies do not give consistent evidence for a positive effect of movement variability on musculoskeletal complaints. Prospective longitudinal studies involving large worker cohorts will be necessary to establish a cause-effect relationship between them.The existence of an optimal level of variability could also be questioned. For Stergiou et al. (2006), optimal variability is located between two limits. Above the upper limit, the system is too unstable and sensitive to perturbations. Below the lower limit, the system is too stereotyped and thus less able to adapt to perturbations. To go further, determining the limits of intrinsic movement variability for healthy workers could reveal the transition towards discomfort and pain, as suggested by Madeleine (2010),and could help to identify early warning signs indicating the development of work-related musculoskeletal disorders.

So, workercharacteristics - such as gender, age, novice/expert status, presence of fatigue, discomfort or pain - influence intrinsic movement variability.When designingworking equipment, designers should ensure that any operator should be able to work at his/her workstation, whatever his/her characteristics.

In terms of task characteristics, Srinivasan et al. (2015a) studied the effects of additional concurrent cognitive demands on repetitive and precision arm movements. They found no changes in shoulder and elbow movement variability between thephysical condition and the condition with additional cognitive demands.Bosch et al. (2011) compared movementvariability during simulated light assembly work performed at different work paces. Work pace is usually determined by designer’s recommendations or in accordance with production constraints. These authors showed that increasing the work pace led to an increase in the variability of wrist speed and acceleration. This result is consistent with other studies showing that kinematic variability increases as the speed at which movements are performed increases (Harris and Wolpert, 1998). In contrast, Srinivasan et al. (2015d) showed that motor variability in the shoulder and elbow decreased when the pace of repetitive work was increased. The apparent contradiction between the results presented by Srinivasan et al. (2015d), and Bosch et al. (2011) could be due to different pace increases and errors in performance. Furthermore, Srinivasan et al. (2015b) showed that decreasing accuracy while simultaneously increasing pace in short-cycle repetitive work led to decreased motor variability in arm movements.

In their study, Bosch et al. (2011) used kinematics and muscular activity measurements to characterisemovementvariability. Their results showed that variability in muscle activity did not differ as a function of work pace. Thus, depending on the techniques used, the presence of movementvariability is highlighted to a greater or lesser degree. However, visual observation or kinetics can also be used to analyse movement variability at work (Gaudart, 2000, 2003; Svendsen et al., 2011). All these techniques provide various levels of information about the movement performed by the worker. Muscular activity measurements could inform about motor units within a muscle, a muscle subdivision or the whole muscle. Kinetics gives informationon the force exerted by the worker, resulting from the activity of several muscles. Kinematics and visual observation inform onhow each body segment is involved in amovement. These techniques provide sometimes convergent and sometimes divergent information (Bosch et al., 2011; Gaudez et al., 2015). Thus, defining the appropriate technique or combination of techniques to characterise movement variability at work is a major issue before starting any investigation. The technique should be chosen in line with the information sought and the desired level of accuracy. Movement variability studies are also affected by anysignal processing performed and the descriptorsselected. Statistical descriptive magnitudes such as mean, standard deviation and coefficient of variance have often been used to analyse movement in work situations (Winter, 1991). Fractal and entropy analyses, deterministic chaos and wavelet transform approaches resulting from the theories of non-linear systems, are other tools which may facilitate our understanding of the structure and origin of variability (Cashaback et al., 2013; Chau, 2001a, 2001b; Enders et al., 2013; Madeleine et al., 2011; Madeleine et al., 2012; Samani et al., 2010; Stergiou and Decker, 2011; Svendsen et al., 2011). For Madeleine (2010), methods developed in non-linear dynamics are of particular interest to assess the complexity and dimensionality of motor control. Finally, mathematical tools such as Dynamic Time Warping (Muscillo et al., 2007), geometric invariants (De Schutter, 2009; De Schutter et al., 2011) and other pattern recognition tools can be used to measure similarity between several repetitions of a movement and to categorise them (Granata et al., 2015). A wide range of studies ofmotor variability have been conducted for different purposes, yet there is currently no consensus on the most relevant descriptors to use in one situation or another (Srinivasan et al., 2015b; Srinivasan et al., 2015c). Indeed, movement variabilitymay be difficult to comprehend since in a given condition some descriptors can indicate an increase in movement variability while others indicate a decrease (Srinivasan et al., 2015b). Moreover, when it comes to integrating movement variability intoworkstation design, the descriptors chosen must be usable in design tools.

All the studies cited in this sectionshow that many factors contribute to intrinsic variability. These factors can be linked to the person's physiological state (gender, age,presence of pain, fatigue or discomfort, or prevention of their onset), to their expertise and to the characteristics of the task to be performed. Unlike personal factors, factors related to task characteristics can be manipulated by designers. However, all factorsare interconnected, superimposed and difficult to distinguish during work activities. Therefore, identifying the various factors influencing movement variability is a prerequisitefor any research into intrinsic movement variability. Indeed, depending on the characteristics of the populationstudied, these personal factors may be different for each subjectin thepopulation.On top of this, the working environment could also add somesources of variability.

4 - INTRINSIC MOVEMENT VARIABILITY AND DESIGN ENGINEERING

The previous sections of this review show that intrinsic movement variability is a natural characteristic of human movements and activities. This is particularly important in the field of workstation design, since inadequate design choices may have harmful consequences on future operators' health and safety. For instance, operators working at an unsuitable workstation may suffer from muscle fatigue and musculoskeletal discomfort, potentially leading to work-related musculoskeletal disorders (Madeleine, 2010). Hence, an efficient occupational risk prevention approach must account for operators' real activity, and this approach should be applied as early as possible in the design process, as stated in the general principles for design (CEN 12100, 2011). In Europe, workstation designers must comply with the Directive on Machinery 2006/42/CE (European Union, 2006) and its associated standards (CEN 1005-4, 2009; CEN 1005-5, 2007). These regulations raise a majorquestion as to how well intrinsic movement variability is known or taken into consideration in the field of workstation design today.

Over the last twenty years, the design process has changed radically to better take into account new industrial constraints such as reduced product life-cycles, rapidly evolving markets and customers'demands for more personalised products. In this context, simulation software tools todesign and plan products and industrial processeshave led to the concept of the "digital factory" (Arndt, 2006),and have progressively become predominant in manufacturing industrydue to advances made in computer technology (Claudon and Marsot, 2009).Among these tools, virtual reality (VR) and digital manikins,also known as digital human models (DHM), have made significant progress. VRhas been used for years in manufacturing industries, and numerous application cases can be found in the literature. This toolallows designers to immerse human operators in virtual environments simulating future workstations in order to validate their design and assess their ergonomics (Pontonnier et al., 2014). DHMs allow designers, engineering offices (Haesen, 2009) and consultants (Urbatic, 2007) to represent and place virtual operators in situations with given characteristics,to assessthe future constraints of a work situation (anthropometry, reaching zones, physical performances, time analysis). By using DHM, a workstation designer can define and assessthe movements of the future operator. Even before the production of physical prototypes of the future workstation, VR and DHM can contribute from the design phase to the application of the safety principles set out by the abovementioned Directive on Machinery and its associated standards. These tools can also be used as a means of communication between the different stakeholders in a project,including designers, engineers, health and safety prevention officers, users and decision-makers.Thus,these tools can helpto design more ergonomic workstations (Falck and Rosenqvist, 2012).

However,these tools do not yetallow designersto take movement variability into account. As VR relies upon human operators, ittakes movement variability into account to a certain extent. Nevertheless, ergonomic studies based on VR are not fully reliable because interaction devices modify postures and motions (Pontonnier et al., 2013), and force-feedback devices cannotrender real exertions,which is an issue for ergonomics studies. Digital manikins, in contrast, incorporate ergonomic indicators based on the analysis of static postures, andthus cannot fully take the overall movement performed by anoperatorinto account,although doing sowould improve the precision of the ergonomic evaluation (Andreoni et al., 2009; Andreoni et al., 2011). DHM are also incompatible withthe incorporation ofpotentialvariants in movement, although it has been shown that the presence of obstacles impeding the subject's trajectories modifiesmovement variability(Jacquier-Bret, 2009). Moreover, users and publishers of this type of software are not very aware of this aspect of occupational activity.Indeed, they usually hypothesise that there is one "best way" to achieve tasks, which will be the same for all workers, regardless of gender, age, experience or state of fatigue. As the main objective of current forms of production organisation in industrial companies is to ensure productivity and quality, workstation designers attempt to define a single succession of postures and movements to be performed by the operator to optimise production and/or safety criteria, without offering any alternative. This results in highly prescriptive operating procedures with respect to the order of operations, how they are to be performed, and the time allocatedto each step of the task. The expected movement is thus standardised.

In spite of this standardised prescription, differences still exist between the movement prescribed by designers and the movements actuallyexecuted by operators (Authier et al., 1995; Buckle and Devereux, 2002; Chassaing, 2004; Kilbom and Persson, 1987;Mathiassen, 2006; Ohlsson et al., 1994;Putz-Anderson, 1998; Roquelaure et al., 1997;Silverstein et al., 1986; Sluiter et al. 2001).Indeed, movement variability is ever-present in occupational life (Madeleine and Madsen, 2009; Mathiassen, 2006; Mathiassen et al., 2003; Van Dieën et al., 2009). In the area of sport, Bartlett et al. (2007) showed that there was probably no single movement that optimises the performance of a given task. Therefore, they felt it was logical to allow athletes to explore a number of possible solutions, rather than to limit the movement to the oneindicated by the coach. Similarly, it appears relevant to propose a number of possible movements in occupational situations. Today, the design of work situations consists in a single operating procedure that operators must follow, whereas it appears preferable to provide them with several possible working procedures.

Up to now, the only way to take intra- and inter-operator motor variability into account in workstation design was to increasethe number of simulations.With DHM, this option is difficult to apply due to the additional workload it implies. Indeed, using digital manikins is complex and very time-consuming. DHM simulations are generally made subjectively by the designer, using a computer keyboard and mouse. Various paths have been explored to facilitate this animation task:using optimisation algorithms (Chaffin, 1997; Zhang et al., 2010),experimental data from movement analyses (Fritzsche et al., 2011; Wang, 2008),more intuitive computer interfaces (Yoshizaki et al., 2011),and the automated translation of a codified operating procedure into postures and movements (Claudon and Marsot, 2009; Kuo and Wang, 2009).More recently, works in the area of humanoid robotics have used command laws based on some characteristics of human movementand motor control toanimate digital manikins that also comply with mechanical laws (Collette, 2009;De Magistris et al., 2011; Mansour et al., 2011).For example, as mentioned earlier, De Magistris' DHM controller (De Magistris et al., 2013)relies on Fitt's law, Todorov's speed profiles model, minimum jerk optimisation and minimum exertion. However, these developments can only be usedto simulate a unique movement to perform the task and none of them hasyet been integrated into digital manikin software applications available to designers.Indeed, movement variability remains an element which is given little attention in workstation design and is completelyignored in DHM.

5 - A BETTER UNDERSTANDING OF MOVEMENT VARIABILITYFOR IMPROVED INTEGRATION INTO WORKSTATION DESIGN

The first three parts of this review defined and described the concept of intrinsic movement variability. As shown, this concept mainly depends on personal and task characteristics.BecauseEuropean designers have an obligation to minimise risks at the workplace, intrinsic movement variability should be considered both reliably and early in design tools to be closer to real activities/tasks performed by an operator in a work situation. However, as presented in the previous section, designers are not sufficiently aware of movement variability, and current design tools lack appropriate features. Hence, a major challenge will be to enrich design tools so that they can simulate different ways in which a task can be performed by taking intrinsic movement variability into account. This will be no easy feat, and understanding and integrating movement variability into the workstation design process will likely be a long and ambitious task.

Indeed, in most recent studies, movement variability was only approachedthrough the comparison of two states, e.g.women vs.men (Svendsen and Madeleine, 2010) or novices vs.experts (Madeleine et al. 2008). These studies set the background for movement variability analysis. Their results showed the advantagesof focusing on what was long considered irrelevant noise. They allowed great stridesin particular in research into the factors influencing this variability and the most relevant descriptors and signal processing to characterisevariability.

However, we need a complementary approach based on the same literature.Intrinsic movement variability should be considered holistically, integratingas wide a range as possible ofpersonal factorsthat could be encounteredwhenperformingatask. Moreover, some characteristics and measures of intrinsic movement variability of a task should be studied. This approach could be related to what was suggested by Luger et al. (2014) regarding “natural movement variation” and workload exposure. They stated that “one should be aware of the amount of natural variation already present in tasks as these generally do not solely consist of one single movement” (Luger et al, 2014). In the same way, one should be aware of the existence of intrinsic movement variability. This knowledge could ultimately be valuable for design tools.

Thus, it appears necessary to characterise intrinsic movement variability in several workers as they perform a range of repetitive tasks. This characterisation woulddefine all the possible movements that can be performed to completeatask without distinguishing personal features. Then, the goal wouldbe to simulate this envelopeof movementsin design tools, which will requirethe development of models and algorithms. An important contribution to this goalwill be to identify relevant and coherent descriptors to be used both for movement variability analysis and for simulation of future occupational situations.

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