



HAL
open science

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

Clarisse Gaudez, Martine Gilles, Jonathan Savin

► **To cite this version:**

Clarisse Gaudez, Martine Gilles, Jonathan Savin. Intrinsic movement variability at work. How long is the path from motor control to design engineering?. *Applied Ergonomics*, 2016, 53, pp.71-78. 10.1016/j.apergo.2015.08.014 . hal-01227119

HAL Id: hal-01227119

<https://hal.science/hal-01227119v1>

Submitted on 17 Nov 2015

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

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

Authors in alphabetical order:

Gaudez C (clarisse.gaudez@inrs.fr) 33 3 83 50 85 45

Gilles MA (martine.gilles@inrs.fr)

Savin J (jonathan.savin@inrs.fr)

INRS – Institut national de recherche et de sécurité

1 rue du Morvan

CS 60027

54519 Vandoeuvre cedex

France

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 theories and factors influencing movement execution, and indicates how intrinsic movement variability is part of task completion. These background clarifications should help ergonomists and workstation designers to gain a better understanding of these concepts, which can then be used to improve design tools. We also question which techniques - kinematics, kinetics or muscular activity – and descriptors are most appropriate for describing intrinsic movement variability and for integration into 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, and has been observed between individuals as well as for a single individual (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). Task repetitiveness could 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 interference which 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, and inter- 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, taking operators' movement variability into account from the stage of workstation design seems necessary to more precisely apprehend operators' real activity. Real activity depends, among other things, on the 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 review is the fruit of reflections by 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 tools in order to consider movements 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 details some 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 proposed with the aim of improving how movement variability is taken into consideration when simulating as well as analysing occupational activities.

2 - MOVEMENT VARIABILITY AND MOTOR CONTROL

This paper relates to voluntary movement which designates 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 sensory stimulation.

In recent decades, a number of studies have developed theories taking the intrinsic variability of human movement into 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 performed and the subject's capacity to interpret this information with 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 task could be performed. Muscular synergies and segmental strategies chosen through 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 perform the same task by exercising different muscles activities or joint amplitudes.

Motor control, to be efficient, must be able to select the appropriate input from among the huge amount of sensory information to achieve some required output consistent with the environment where 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 understanding was 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 sensory information 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 predicted as a function of the final posture that the forearm or hand must adopt at the end of the action. These authors hypothesised 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 based on procedural memory, i.e., the person needs to really perform the action rather than simply observing it or imagining doing it (Walsh and Rosenbaum, 2009). Thus, the more experience the person has in performing a task, 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 forearm and that of the eye during movement of the upper limb (Harris and Wolpert, 1998). Finally, the optimal feedback control model takes observed 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 its success (Todorov, 2004; Todorov and Jordan, 2002). All these models are based on kinetic or kinematic information. In addition to these models, a neurophysiological approach based on joint coordinates has also been proposed as a possible means to reduce the cost of motor control. With this 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 joint levels (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 approach considers motor redundancy through the principle of abundance derived from Bernstein (1967) and states that redundancy should no longer be considered as a problem to be solved, but as a benefit. Indeed, redundancy makes it possible to adapt movements to the main constraints, i.e., the objective of the task, and to the secondary environmental constraints, which include perturbations or 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 others have 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, and all 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 when executing a given task. If we extend this idea, in line with our interest in the field of occupational activities, we can hypothesise that workers have the choice between a 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 variability during an elbow flexion endurance task in asymptomatic men and women. They observed that forces produced by women were less variable than those produced by men. In her review, Côté (2012) suggested that the reduced motor variability in women compared to men could partly explain why women are at higher risk of developing musculoskeletal symptoms, especially in the neck / shoulder region.

The observations described by Gaudart (2000) showed that younger workers have a more variable work cycle time than older workers. Younger workers alternated periods of relaxation with periods of acceleration more than older workers. In contrast, Madeleine et al. (2008) demonstrated that experienced operators presented greater variability in work cycle time even if the overall time was shorter for novices. These authors highlighted 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 of the implementation of specific motor programs. Moreover, with age, the characteristics of motor adaptation change, mainly due to alterations to muscular 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 in fatigue comes in addition to cumulative exposure duration. Moreover, as reported by Gaudart (2000), operators are aware of their, more or less declining, physical and cognitive capacities. They develop their strategies based on their 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; Hufnuss 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 in shoulder, 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 onset of 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 have greater endurance. Along these lines, Palmerud et al. (1998) suggested that the redistribution of load between the synergistic muscles of the shoulder could avoid or delay the onset of muscular fatigue. Thus, people having a greater ability of motor variability can slow down or prevent the development of fatigue and are less sensitive to the risk of developing musculoskeletal 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 extent of variability of the head-shoulder displacement than those without discomfort. A greater extent of 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 generates greater 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, worker characteristics - such as gender, age, novice/expert status, presence of fatigue, discomfort or pain - influence intrinsic movement variability. When designing working 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 the physical condition and the condition with additional cognitive demands. Bosch et al. (2011) compared movement variability 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 characterise movement variability. 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 movement variability 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 information on the force exerted by the worker, resulting from the activity of several muscles. Kinematics and visual observation inform on how each body segment is involved in a movement. 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 any signal processing performed and the descriptors selected. 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 of motor 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 variability may 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 into workstation design, the descriptors chosen must be usable in design tools.

All the studies cited in this section show 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 factors are interconnected, superimposed and difficult to distinguish during work activities. Therefore, identifying the various factors influencing movement variability is a prerequisite for any research into intrinsic movement variability. Indeed, depending on the characteristics of the population studied, these personal factors may be different for each subject in the population. On top of this, the working environment could also add some sources 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 major question 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 to design and plan products and industrial processes have led to the concept of the "digital factory" (Arndt, 2006), and have progressively become predominant in manufacturing industry due 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. VR has been used for years in manufacturing industries, and numerous application cases can be found in the literature. This tool allows 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 assess the future constraints of a work situation (anthropometry, reaching zones, physical performances, time analysis). By using DHM, a workstation designer can define and assess the 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 help to design more ergonomic workstations (Falck and Rosenqvist, 2012).

However, these tools do not yet allow designers to take movement variability into account. As VR relies upon human operators, it takes 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 cannot render real exertions, which is an issue for ergonomics studies. Digital manikins, in contrast, incorporate ergonomic indicators based on the analysis of static postures, and thus cannot fully take the overall movement performed by an operator into account, although doing so would improve the precision of the ergonomic evaluation (Andreoni et al., 2009; Andreoni et al., 2011). DHM are also incompatible with the incorporation of potential variants in movement, although it has been shown that the presence of obstacles impeding the subject's trajectories modifies movement 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 allocated to 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 actually executed 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 one indicated 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 increase the 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 movement and motor control to animate 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 used to simulate a unique movement to perform the task and none of them has yet 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 completely ignored in DHM.

5 - A BETTER UNDERSTANDING OF MOVEMENT VARIABILITY FOR 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. Because European 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 approached through 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 advantages of focusing on what was long considered irrelevant noise. They allowed great strides in particular in research into the factors influencing this variability and the most relevant descriptors and signal processing to characterise variability.

However, we need a complementary approach based on the same literature. Intrinsic movement variability should be considered holistically, integrating as wide a range as possible of personal factors that could be encountered when performing a task. 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 would define all the possible movements that can be performed to complete a task without distinguishing personal features. Then, the goal would be to simulate this envelope of movements in design tools, which will require the development of models and algorithms. An important contribution to this goal will be to identify relevant and coherent descriptors to be used both for movement variability analysis and for simulation of future occupational situations.

6 - REFERENCES

Andreoni G, Mazzola M, Ciana O, Zambetti M, Romero M, Costa F et al. (2009) Method for Movement and Gesture Assessment (MMGA) in Ergonomics. In Duffy V (ed) Digital Human Modeling, Springer Berlin Heidelberg: 591-598

Andreoni G, Mazzola M, Orso E (2011) Ergonomic assessment of reaching tasks: a comparison between real and virtual human. First International Symposium on Digital Human Modeling, Lyon, Proceedings: 7

Arndt FW (2006) The Digital Factory Planning and simulation of production in automotive industry - Springer. In: Braz J, Araujo H, Viera A, Encarnação B, (ed) Informatics In Control, Automation And Robotics I: 27-29

- Authier M, Gagnon M, Lortie M (1995) Handling Techniques: The Influence of Weight and Height for Experts and Novices. *International Journal of Occupational Safety and Ergonomics* 1(3): 262-275
- Bartlett R, Wheat J, Robins M (2007) Is movement variability important for sports biomechanics. *Sports Biomechanics* 2(6): 224-243
- Bernstein N (1967) *The coordination and regulation of movement*. Pergamonpress, Oxford
- Berthoz A (1997) *Le sens du mouvement*. Odile Jacob, Paris: 345p
- Bizzi E, Hogana N, Mussa-Ivaldia FA, Gisztera S (1992) Does the nervous system use equilibrium-point control to guide single and multiple joint movements? *Behavioral and Brain Sciences* 15 (4): 603-613
- Blakemore SJ, Frith CD, Wolpert DM (1999) Spatio-temporal prediction modulates the perception of self-produced stimuli. *Journal of Cognitive Neuroscience* 11 (5): 551-559
- Bosch T (2011) *Fatigue and performance in repetitive industrial work*. University Amsterdam. ISBN 978-90-6464-471-9
- Bosch T, Mathiassen SE, Visser B, De Looze MP, Van Dieën JH (2011) The effect of work pace on workload, motor variability and fatigue during simulated light assembly work. *Ergonomics* 54 (2): 154-168
- Buckle Pw, Devereux JJ (2002) The nature of work-related neck and upper limb musculoskeletal disorders. *Applied Ergonomics* 33 (3): 207-217
- Cashaback JG, Cluff T, Potvin JR (2013) Muscle fatigue and contraction intensity modulates the complexity of surface electromyography. *J ElectromyogrKinesiol* 23: 78-83
- CEN 1005-4 (2009) *Safety of machinery – Human physical performance – Part 4: Evaluation of working postures and movements in relation to machinery*. European Committee for Standardization, Brussels
- CEN 1005-5 (2007) *Safety of machinery – Human physical performance – Part 5: Risk assessment for repetitive handling at high frequency*. European Committee for Standardization, Brussels
- CEN 12100 (2011) *Safety of machinery - General principles for design - Risk assessment and risk reduction*. European Committee for Standardization, Brussels
- Chaffin DB (1997) Development of Computerized Human Static Strength Simulation Model for Job Design. *Human Factors and Ergonomics in Manufacturing* 7 (4): 305-322
- Chassaing K (2004) Vers une compréhension de la construction de la gestuelle des tôliers d'une entreprise automobile. *PISTES* 6: 21
- Chau T (2001a) A review of analytical techniques for gait data. Part 1: fuzzy, statistical and fractal methods. *Gait & Posture* 13: 49-66
- Chau T (2001b) A review of analytical techniques for gait data. Part 2: neural network and wavelet methods. *Gait & Posture* 13: 102-120

- Claudon L, Marsot J (2009) Prise en compte de l'ergonomie lors de l'utilisation de systèmes de temps prédéterminés. État de l'art et perspectives. Hygiène et Sécurité du Travail, Note Documentaire ND 2320, INRS: 7 p
- Collette C (2009) Commande dynamique d'humains virtuels : équilibre robuste et gestion des tâches. Note Scientifique et Technique NS 287, INRS: 173 p
- Côté JN (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(2): 173-182
- Côté JN, Feldman AG, Mathieu PA, Levin MF (2008) Effects of fatigue on intermuscular coordination during repetitive hammering. *Motor Control* 12 (2): 79-92
- Côté JN, Mathieu, PA, Levin MF, Feldman AG (2002) Movement reorganization to compensate for fatigue during sawing. *Experimental Brain Research* 146 (3): 394-398
- Côté JN, Raymond D, Mathieu PA, Feldman AG, Levin MF (2005) Differences in multi-joint kinematic patterns of repetitive hammering in healthy, fatigued and shoulder-injured individuals. *Clin Biomech (Bristol, Avon)* 20(6): 581-590
- De Magistris G, Micaelli A, Andriot C, Savin J, Marsot J (2011) Dynamic virtual manikin control design for the assessment of the workstation ergonomics. First International Symposium on Digital Human Modeling, Lyon: 7
- De Magistris G, Micaelli A, Évrard P, Andriot C, Savin J, Gaudez C, Marsot J (2013), Dynamic control of DHM for ergonomic assessments, *International Journal of Industrial Ergonomics* 43 (2): 170-180
- De Magistris G, Micaelli A, Savin J, Gaudez C, Marsot J (2015), Dynamic digital human models for ergonomic analysis based on humanoid robotics techniques. *International Journal of the Digital Human* 1 (1): 81-109
- De Schutter J (2009) Invariant Description of Rigid Body Motion Trajectories. *Journal of Mechanisms and Robotics* 2 (1): 9 p
- De Schutter J, Di Lello E, De Schutter JFM, Matthyssen R, Tuur B, De Laet T (2011) Recognition of 6 DOF Rigid Body Motion Trajectories using a Coordinate-Free Representation. *IEEE International Conference on Robotics and Automation*. Shanghai: 2071-2078
- De Zwart BCH, Frings-Dresen MHW, Van Dijk FJH (1995) Physical workload and the ageing worker: a review of the literature. *Arch Occup Environ Health* 68: 1-12
- Derosier C, Leclercq S, Rabardel P, Langa P (2008) Studying work practices: a key factor in understanding accidents on the level triggered by a balance disturbance. *Ergonomics* 51 (12): 1926-1943

- Diniz A, Wijnants MI, Torre K, Barreiros J, Crato N, Bosman AM, Hasselman F, Cox RF, Van Orden GC, Delignières D (2011) Contemporary theories of 1/f noise in motor control. *Hum MovSci* 30(5): 889-905
- Enders H, Maurer C, Baltich J, Nigg BM (2013) Task-Oriented Control of Muscle Coordination during Cycling. *Med Sci Sports Exerc* 45: 2298-2305
- Enoka R, Duchateau J (2008) Muscle fatigue: what, why and how it influences muscle function. *J Physiol* 586 (1): 11-23
- European Union (2006) Directive 2006/42/EC of the European Parliament and of the Council of 17 May 2006 on machinery, Official Journal of the European Union, June 9th 2006, 157: 24-86
- Falck A, Rosenqvist M (2012) What are the obstacles and needs of proactive ergonomics measures at early product development stages? – An interview study in five Swedish companies. *International Journal of Industrial Ergonomics* 42(5): 406-415
- 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. *Journal of Electromyography and Kinesiology* 18(1):16-25
- Feldman AG (1966) Functional tuning of the nervous system with control of movement or maintenance of a steady posture. III. Mechanographic analysis of the execution by man of the simplest motor tasks. *Biophysics II*: 766-775
- Flash T, Hogan N (1985) The coordination of arm movements: an experimentally confirmed mathematical model. *The Journal of Neuroscience* 5(7): 1688-1703
- Forestier N, Nougier V (1998) The effects of muscular fatigue on the coordination of a multi-joint movement in human. *Neuroscience Letter* 252(3):187-190
- Fritzsche L, Jendrusch R, Leidholdt W, Bauer S, Jäckel T, Pirger A (2011) Introducing EMA (Editor for Manual work Activities) – A New Tool for Enhancing Accuracy and Efficiency of Human Simulations. In VG Duffy (ed) *Digital Human Modeling, Lecture Notes in Computer Science* 6777: 272-281
- Fuller JR, Lomond KV, Fung J, Côté JN (2009) Posture-movement changes following repetitive motion-induced shoulder muscle fatigue. *Journal of Electromyography and Kinesiology* 19 (6):1043-1052
- Gates DH, Dingwell JB (2008) The effects of neuromuscular fatigue on task performance during repetitive goal-directed movements. *Experimental Brain Research* 187 (4): 573-585
- Gaudart C. (2000) Conditions for maintaining ageing operators at work--a case study conducted at an automobile manufacturing plant. *AppliedErgonomics* 31(5): 453-462.
- Gaudart C (2003) La baisse de la polyvalence avec l'âge : question de vieillissement, d'expérience, de génération? *PISTES* 5 (2): 25 p

Gaudez C (2015) A better way of fitting clips? A comparative study with respect to physical workload. *Applied Ergonomics* 51: 236-243.

Glazier PS, Wheat JS, Pease DL, Bartlett R (2006) Dynamic system theory and the functional role of movement variability. In (Davids K, Bennett S, Newell K ed) *Movement System Variability*, Human Kinetics Publishers, Champaign (IL): 49-72

Granata C, Ibanez A, Bidaud Ph (2015) Human activity understanding: a multilayer approach combining body movements and contextual descriptors analysis. *International Journal of Advanced Robotic Systems* 12 (89): 13 p

Haesen B (2009) Betterlift - Introducing a semi-automatic exhaust manipulator to reduce a high absenteeism rate. In (European Agency for Safety and Health at Work ed) *Assessment, elimination and substantial reduction of occupational risks*: 36-43

Harris CM, Wolpert DM (1998) Signal-dependent noise determines motor planning. *Nature* 394:780-784

Hasan Z (1986) Optimized movement trajectories and joint stiffness in unperturbed, inertially loaded movements. *Biological cybernetics* 53(6):373-382

Hogan N (1984) An organizing principle for a class of voluntary movements. *The Journal of Neuroscience* 4(11):2745-2754

Holtermann A, Mork PJ, Andersen LL, Olsen HB, Sjøgaard K (2010) The use of EMG biofeedback for learning of selective activation of intra-muscular parts within the serratus anterior muscle A novel approach for rehabilitation of scapular muscle imbalance. *Journal of Electromyography and Kinesiology* 20: 359–365

Huffenus AF, Amarantini D, Forestier N (2006) Effects of distal and proximal arm muscles fatigue on multi-joint movement. *Experimental brain research* 170(4):1-10

Jackson JA, Mathiassen SE, Dempsey PG (2009) Methodological variance associated with normalization of occupational upper trapezius EMG using sub-maximal reference contractions. *J Electromyogr Kinesiol.* 19(3): 416-427

Jacquier-Bret J (2009) Analyse biomécanique du mouvement de préhension contraint et altéré : indices quantitatifs de la gestion de la redondance motrice. thèse de doctorat Sciences du mouvement humain - spécialité « Biomécanique », Université du Sud Toulon – Var 209 p

Kerlirzin Y, Dietrich G, Vieilledent S (2009) *Le contrôle moteur : organisation et contrôle du mouvement* – PUF éd: 237 p

Kilbom A (1994) Repetitive work of the upper extremity Part II: 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

- Kuo CF, Wang MJ (2009) Motion generation from MTM semantics. *Computers in Industry* 60:339-348
- Latash ML (2012) The bliss (not the problem) of motor abundance (not redundancy). *Exp. Brain Res.* 217: 1-5
- Latash ML, Scholz JP, Schröner G (2002) Motor control strategies revealed in the structure of motor variability. *Exerc. Sport Sci. Rev.* 30: 26–31
- Leplat J (1987) Les habiletés et leur analyse. Terrain et laboratoire. In (Laurent M, Therme P ed) *Recherches en APS 2 Apprentissage et développement des actions motrices complexes*, UEREPS Aix-Marseille 2: 325-341
- Leplat J, Pailhous J (1981) L'acquisition des habiletés mentales : la place des techniques. *Trav. Hum.* 44: 275-328
- Lomond KV, Côté JN (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
- Luger T, Bosch T, Veeger D, de Looze M (2014) The influence of task variation on manifestation of fatigue is ambiguous – a literature review. *Ergonomics* 57(2): 162-174
- 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 Physiologica* 199: 1-46
- Madeleine P, Farina D (2008) Time to task failure in shoulder elevation is associated to increase in amplitude and to spatial heterogeneity of upper trapezius mechanomyographic signals. *Eur. J. Appl. Physiol.* 102: 325-333
- Madeleine P, Lundager B, Voigt M, Arendt-Nielsen L (2003a) The effects of neck-shoulder pain development on sensory-motor interactions among female workers in the poultry and fish industries. A prospective study. *Int. Arch. Occup. Environ. Health* 76:39-49
- Madeleine P, Lundager B, Voigt M, Arendt-Nielsen L (2003b) 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, Madsen, TM (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, Mathiassen SE, Arendt-Nielsen L (2008) Changes in the degree of motor variability associated with experimental and chronic neck-shoulder pain during a standardized repetitive arm movement. *Exp. Brain Res.* 185:689-698
- Madeleine P, Nielsen M, Arendt-Nielsen L (2011) Characterization of postural control deficit in whiplash patients by means of linear and nonlinear analyses – A pilot study. *J. Electromyogr. Kinesiol.* 21:291-297

- Madeleine P, Sjøgaard K, Holtermann A, Samani A(2012) Level of self-reported neck/shoulder pain and biomechanical workload in cleaners. *Work* 41:447-452
- Mansour D, Micaelli A, Lemerle P (2011) A computational approach for push recovery in case of multiple noncoplanar contacts. *Intelligent Robots and Systems (IROS), 2011 IEEE/RSJ International Conference:* 3213-3220
- Mathiassen SE (2006) Diversity and variation in biomechanical exposure: what is it, and why would we like to know? *Appl. Ergon.* 37:419-427
- Mathiassen SE, 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. Occup. Physiol.* 76:434-444
- Mathiassen SE, Burdorf A, Van Der Beek AJ (2002) Statistical power and measurement allocation in ergonomic intervention studies assessing upper trapezius EMG amplitude. A case study of assembly work. *J.Electromyogr.Kinesiol.* 12:45-57
- Mathiassen SE, Möller T, Forsman M (2003) Variability in mechanical exposure within and between individuals performing a highly constrained industrial work task. *Ergonomics* 46:800-824
- Miall RC (1995) Motor Control, Biological and Theoretical. In (M. A. Arbibed.) *The Handbook of brain theory and neural networks*, Cambridge, MIT Press: 597-600
- Muscillo R, Conforto S, Schmid M, Caselli P, D'alessio T(2007) Classification of motor activities through derivative dynamic time warping applied on accelerometer data. *Engineering in Medicine and Biology Society (EMBS) 29th Annual International Conference of the IEEE (22-26 Aug. 2007):* 4930-4933
- Ohlsson K, Hansson GA, Balogh I, Stromberg U, Palsson B, Nordander C, Rylander L, Skerfving S (1994) Disorders of the neck and upper limbs in women in the fish processing industry. *Occup. Environ. Med.* 51:826-832
- Østensvik T, Veiersted KB, Nilsen P (2009) A method to quantify frequency and duration of sustained low-level muscle activity as a risk factor for musculoskeletal discomfort. *J ElectromyogrKinesiol.* 19(2):283-94
- Palmerud G, Sporrang 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
- Park J, Singh T, Zatsiorsky V, Latash M(2012) Optimality versus variability: effect of fatigue in multi-finger redundant tasks. *Exp. Brain Res.* 216: 591-607
- Park J, Zatsiorsky V, Latash M (2010) Optimality versus variability: an example of multi-finger redundant tasks. *Exp. Brain Res.* 207: 119-132
- Pontonnier C, Dumont G, Duval T (2014) Ergonomics and Virtual Reality: VISIONAIR Project examples. EuroVR 2014, Bremen, Germany

Pontonnier C, Samani A, Badawi M, Madeleine P, Dumont G (2013) Assessing the ability of a VR-based assembly task simulation to evaluate physical risk factors. *IEEE Transactions on Visualization and Computer Graphics*, Institute of Electrical and Electronics Engineers (IEEE): 664 - 674

Putz-Anderson V(1998) *Cumulative Trauma Disorders, a manual for the musculoskeletal diseases of the upper limb*. Taylor et Francis, London

Roquelaure Y, Mechali S, Dano C, Fanello S, Benetti F, Bureau D, Mariel J, Martin YH, Derriennic F, Penneau-Fontbonne D (1997) Occupational and personal risk factors for carpal tunnel syndrome in industrial workers. *Scand. J. Work Environ. Health* 23: 364-369

Rosenbaum DA, Meulenbroek RJ, Vaughan J(1999) Remembered positions: stored locations or stored postures? *Exp. Brain Res.* 124:503-512

Samani A, Holtermann A, Sjøgaard K, Madeleine P(2010) Advanced biofeedback from surface electromyography signals using fuzzy system. *Med. Biol. Eng. Comput.* 48:865-873

Silverstein B.A, Fine LJ, Armstrong TJ(1986) Hand wrist cumulative trauma disorders in industry. *Br. J. Ind. Med.* 3:779-784

Sluiter JK, Rest KM, Frings-Dresen MH(2001) Criteria document for evaluating the work-relatedness of upper-extremity musculoskeletal disorders. *Scand. J. Work Environ. Health* 27:1-102

Srinivasan D, Mathiassen SE (2012) Motor variability in occupational health and performance. *Clinical Biomechanics* 27: 979-993

Srinivasan, D., Mathiassen, S. E., Samani, A., & Madeleine, P. (2015a). Effects of concurrent physical and cognitive demands on arm movement kinematics in a repetitive upper-extremity precision task. *Human Movement Science*, 42, 89-99

Srinivasan D, Mathiassen SE, Samani A, Madeleine P (2015b) The combined influence of task accuracy and pace on motor variability in a standardised repetitive precision task. *Ergonomics* 58: 1388-1397

Srinivasan D, Rudolfsson T, Mathiassen SE (2015c) Between- and within-subject variance of motor variability metrics in females performing repetitive upper-extremity precision work. *J. Electromyogr. Kinesiol.* 25: 121-129

Srinivasan D, Samani A, Mathiassen SE, Madeleine P (2015d) The size and structure of arm movement variability decreased with work pace in a standardised repetitive precision task. *Ergonomics* 58: 128-139

Stenard D (2009) *Progress in motor control. Advances in experimental medicine and biology*, Springer Verlag: 629p

Stergiou N, Harbourne R, Cavanaugh J. (2006) Optimal movement variability: a new theoretical perspective for neurologic physical therapy. *J NeurolPhysTher.* 30(3):120-9

- Stergiou N, Decker LM(2011) Human movement variability, nonlinear dynamics, and pathology: Is there a connection? *Hum.Mov. Sci.* 30:869-888
- Svendsen JH, Madeleine P (2010) Amount and structure of force variability during short, ramp and sustained contractions in males and females. *Hum Mov Sci.* 29(1): 35-47
- Svendsen JH, Samani A, Mayntzhusen K, Madeleine P(2011) Muscle coordination and force variability during static and dynamic tracking tasks. *Hum.Mov. Sci.* 30:1039-1051
- Szeto GP, Straker LM, O'Sullivan PB (2005) A comparison of symptomatic and asymptomatic office workers performing monotonous keyboard work-1: neck and shoulder muscle recruitment patterns. *Man Ther.* 10(4):270-80
- Terrier P, Schutz Y (2003) Variability of gait patterns during unconstrained walking assessed by satellite positioning (GPS). *Eur. J. Appl. Physiol.* 90:554-561
- Todorov E (2004) Optimality principles in sensorimotor control (review). *Nature Neurosci.* 7:907-915
- Todorov E, Jordan M(2002) Optimal feedback control as a theory of motor coordination. *Nature* 5:1226-1235
- Uno Y, Kawato M, Suzuki R (1989) Formation and control of optimal trajectory in human multijoint arm movement. *Biol.cybern.* 61: 89-101
- Urbatic Concept France (2007) Une approche innovante de l'ergonomie. *Ergonoma Journal* 48: 22-23
- Van Dieën JH, Westebring-Van Der Putten EP, Kingma I, De Looze MP(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
- Vasseljen O Jr, Westgaard RH (1996) Can stress-related shoulder and neck pain develop independently of muscle activity? *Pain* 64 (2): 221-230
- Walsh MM, Rosenbaum DA(2009) Deciding how to act is not achieved by watching mental movies. *J.Exp.Psychol.Hum. Percept.Perform.* 35: 1481-1489
- Wang X (2008) Contribution à la simulation du mouvement humain en vue d'applications en ergonomie. Dissertation, University Claude Bernard of Lyon I
- Westgaard RH, Vasseljen O, Holte KA (2001) Trapezius muscle activity as a risk indicator for shoulder and neck pain in female service workers with low biomechanical exposure. *Ergonomics* 44(3): 339-353
- Winter DA(1991.) Biomechanics and motor control of human gait: normal, elderly and pathological. Waterloo, Canada: 143p
- Wolpert DA, Doya K, Kawato M (2003) A unifying computational framework for motor control and social interaction. *Philosophical Transactions of the Royal Society London B*, 358: 593-602

Wolpert DA, Kawato M (1998) Multiple paired forward and inverse models for motor control. *Neural Networks* 11 (7–8): 1317–1329

Wolpert DA, Miall RC, Kawato M (1998) Internal models in the cerebellum. *Trends in Cognitive Sciences* 2 (9): 338- 347

Yoshizaki W, Sugaira Y, Chiou AC, Hashimoto S, Inami M, Igarashi T et al. (2011) An actuated physical puppet as an input device for controlling a digital manikin. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, New York USA, ACM 2011*:637-646

Zhang B, Horvath I, Molenbroek JFM, Snijders C (2010) Using artificial neural networks for human body posture prediction. *Int. J. Ind. Ergon.* 40:414-424