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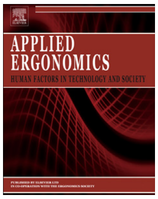

Review article

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

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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.

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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,b; 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-

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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