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Abstract.
Movement variability is an essential characteristic of human movement. However, despite its prevalence, it is almost completely ignored in workstation design. Neglecting this variability can lead to skip over parts of the future operator's movements, thus bring to incomplete assessment of biomechanical risk factors.

This paper starts with a focus on movement variability in occupational activities. Then, as an example of feasibility, it describes a Digital Human Model framework intended to simulate the movement variability induced by muscle fatigue. The demonstrator is based on several simulation environments, namely 1) XDE, a virtual human simulation software tool previously used for ergonomics analyses, 2) a dynamic three-compartment model of muscle fatigue and recovery, and 3) OpenSim, a dynamic musculoskeletal simulation software.

The demonstrator is a first step towards tools to assist designers in considering movement variability for improved ergonomics at the workstation.

Keywords:
Movement Variability · Digital Human Models · Ergonomics assessment · Workstation Design · Muscle Fatigue

1 Introduction

Movement variability (MV) is a characteristic of human movement: whether for a given person at different times, or for different people, a prescribed movement is never performed in exactly the same way twice. MV exists in all situations, and particularly in occupational activities. It is an essential element to ensure flexibility and adaptability of the sensorimotor system to the constraints related to the person, to the task and to the environment in which a task is performed. MV may also help protect the locomotor system, for instance by delaying the appearance of fatigue which is reported to be involved in the onset of work-related musculoskeletal disorders. However, the scientific community has long neglected MV, considering it to be non-significant noise or interference while also being difficult to quantify and analyse. Thus, in the field of workstation design, MV is still almost completely ignored. Indeed, the requirements of methods such as "lean manufacturing" or "total quality management" drive workstation designers to favour standardisation of operators' activity to avoid non-conformities and errors. Actually, neglecting MV at the design stage can lead to poor planning for the future activity performed by operators, leading to incomplete assessment of biomechanical risk factors. Thus, it seems necessary to take operators' MV into account from the stage of workstation design to more precisely apprehend their real activity.

The objective of our study is to propose a software tool based on Digital Human Models (DHM) allowing workstation designers to simulate not only the trajectories, postures and efforts linked to a given task, but also the envelope of those trajectories, postures and efforts associated with foreseeable MV from the earliest stages of design. As a first step towards this general goal, this paper presents a feasibility study on a proposed DHM architecture simulating MV induced by muscle fatigue.

The first section of this paper presents what is currently known about movement variability. The second section deals with modelling a source of MV, namely muscle fatigue. The software elements used to perform simulation are described in the third section, and future validation experiments and further uses of this DHM for movement analysis and ergonomics are discussed in the final section.

2 What is Movement Variability?

The study of MV is at the interface between several scientific domains: neuroscience, biomechanics, ergonomics, physiology, motor control, etc. These communities address various aspects of movement and each has their own terminology. Thus, in the literature, notions such as natural variations [1], inherent variability [2], motor variability [3] or MV [4] are encountered. In this paper, we define MV as differences in body segment movements and/or muscle activities between repeats of a task, with cyclic or intermittent task repetitiveness throughout the day. MV is linked to motor control, i.e., the constant interactions between a subject, the environment in which they act and the task to be performed. A comprehensive presentation of MV can be found in Gaudez et al. [4] and Srinivasan and Mathiassen [5].

2.1 **MV and Motor Control**

Movement is planned by the central nervous system (CNS) based on sensory information related to the environment in which the task is performed, and on the subject's capacity to interpret this multifaceted information. But redundancy in the degrees of freedom of the human locomotor system make an infinite number of solutions possible when performing a movement or task. Consider, for example, the number of combinations possible thanks to joint redundancy, involvement of different muscles for the same joint, different muscle fascicles in the same muscle, different motor units in the same fascicle, application of different electrical activation patterns to motor units, existence of different control levels and strategies, etc.

Taking all the necessary information on board to plan and generate a movement comes at a considerable cost for the CNS and motor control theories try to understand the underlying rules. In the 1960s, Bernstein proposed an initial model for motor control based on reduction of the human system's complexity: muscular synergies and segmental strategies chosen through afferent information would be used to decrease the number of degrees of freedom required to efficiently control the system. Other models have then been proposed : minimum jerk, minimal effort, minimum torque change, optimal feedback control, the muscle equilibrium-point model, etc. Some of these models have been used to simulate human movement: for instance, De Magistris [6] used Fitt's law, Todorov's speed profiles model, minimum jerk optimisation, and minimum exertion to model an industrial assembly task. Those models, which lead to an "optimal" movement, assume that some signal-dependant noise appears alongside neuro-muscular activation, which is responsible for the variability observed. Churchland et al. [7] also showed that significant MV arises in the motor preparation stage. Recently, an additional approach was introduced, derived from Bernstein and based on the principle of abundance [8]. Abundance would make it possible to adapt movements to the main constraints (the task's objective) and to the secondary environmental constraints (perturbations or parallel tasks) cropping up as the movement is performed. Thus, any task would not have a single optimal solution, but a family of equivalent solutions.

It is most likely that motor control is achieved through mechanisms compatible with several of these models, depending on the situation. Applying these models and theories to the field of occupational activities, workers may have a large panel of possible movements, leading to the observed MV.

2.2 **Factors Influencing MV**

The literature presents many experiments highlighting movement variability, particularly during upper limb movements. This MV depends on various factors related either to the characteristics of the task, or of the person. In the field of occupational activities, task characteristics include pace, cognitive demand, geometry of the workstation, physical characteristics of the tools used (weight, size), job organization, etc. Designers can influence all those parameters. In contrast, designers have no influence on individual characteristics, such as gender, age, learning and experience, pain or fatigue. We call the MV due to the differing characteristics of each *individual* observed during repeats of a task *intrinsic movement variability*.

2.3 Accounting for MV as part of Occupational Risk Prevention

In terms of workstation design, prevention relies on the identification, assessment and avoidance of risks. Indeed, inadequate design choices may adversely affect future operators' health and safety: operators working at an unsuitable workstation may suffer from muscle fatigue and musculoskeletal discomfort, potentially leading to work-related musculoskeletal disorders. Hence, designers should account for operators' real activity as early as possible in the design process. In Europe, regulatory requirements in this direction have been formalised in the "Directive on Machinery" 2006/42/CE [9] with which designers must comply. Thus, designers are required to ensure that any operator can work at his/her workstation, whatever his/her characteristics.

Common ergonomic assessment tools used in workstation design rely on the operators' posture (joint angles), the efforts exerted (joint torques and/or forces applied to or exerted by the operator) and the cycle time for the task. This information can be obtained by analysing operators' activity on a comparable workstation, if it exists, or with the help of simulation tools such as virtual reality (VR) [10] and DHM [6]. Unfortunately, as MV is almost completely ignored in workstation design, design tools include no feature to address it. Prevention of occupational biomechanical risk factors could be improved by developing simulation tools to calculate all possible movements likely to be performed and postures likely to be adopted by operators while completing a task, without distinguishing individual characteristics.

3 Integrating a Source of MV into a DHM: the Example of Muscle Fatigue

The previous section showed that movement variability is a complex and multifactorial phenomenon, while also being an essential feature of human movement. MV should therefore be considered in workstation design tools such as DHM. As a feasibility study, we chose to integrate a source of intrinsic MV, namely muscle fatigue, into a DHM control. Indeed, studies show that the kinematics of movement can be modified due to fatigue. For instance, during repeated sawing movements, the amplitude of the elbow angle decreases. This decrease is compensated for by alterations to shoulder, wrist and torso movement amplitudes over time [11]. In static working conditions, similar compensatory strategies have also been observed [12].

3.1 What is Muscle Fatigue?

Muscle fatigue is linked to repeated muscle contractions. It is defined as a reduction in the maximum force-production or motor power capacity, linked to the execution of a task or an exercise [13]. The opposite phenomenon to fatigue is recovery, during which the locomotor system may retrieves its performance after a certain amount of time.

Because of the complexity of the phenomena involved, the literature most often deals with specific situations (isometric, isotonic or isokinetic contraction, etc.) and studies aiming to predict fatigue have long been limited to the static analysis of the relationships between the intensity of an effort and the maximum endurance time (MET). These data are very dependent on the task studied and the subjects involved, and they are not good models for occupational activity, where we are seeking to avoid exhaustion and where the muscular efforts exerted are dynamic.

3.2 Modelling Muscle Fatigue

For a long time, studies compared the intensity of the effort and the MET when attempting to predict muscular fatigue. Since the work of Rohmert in the 1960s up until the early part of this century, adjustments to these methods were proposed, but the advances were limited. Since the start of this century, this field of research has undergone a revival and new models have now been published. For example, Ding et al. [14] use a biochemical approach, Böl et al. [15] apply a "finite elements" approach, and a biophysical approach is developed by Liu et al. [16] in their three-compartment model. Of all these approaches, the three-compartment model appears the best adapted to integration into DHM-type tools, and the literature presents several studies of this type of model with virtual humans in specific conditions (static effort, estimation of MET) [12, 17, 18].

For this work, we retain the model of fatigue proposed by Frey-Law et al. [17]. This model takes phenomena related to fatigue and recovery into account by considering the whole force-generation chain, from the CNS to the various muscle fibres. The muscle is modelled by a limited and constant number of fibres, M_0. At rest, all the fibres are in an inactive state. At any time point, a proportion of the resting fibres can become active under the influence of an order from the CNS. Similarly, due to fatigue and recovery, a proportion of the activated fibres can enter the fatigued state and a proportion of the fatigued fibres can return to the resting state. The passage from one state to another is defined by three coefficients noted ***C***, ***F***, and ***R*** (Command, Fatigue, Recovery, respectively, see **Fig. 1**).

The sum of the number of active fibres, M_A, of fatigued fibres, M_F, and resting fibres, M_R, is constant. The model assumes that only active fibres produce force. For a muscle containing an adequate number of motor units, the model makes the approximation that each of them contributes through a similar elementary effort, u_0, which is constant while activated. The ***F*** and ***R*** parameters are assumed to be constant. Parameter ***C*** is bidirectional and non-linear, depending on the expected effort (Target Load - *TL*) and on the current level of fatigue. For a comprehensive description of this model, see [17].

An application of this model is illustrated in **Fig. 2** for a constant isometric exertion equal to 70% of the maximum voluntary exertion. Exerted force increases rapidly because muscle is not fatigued. The expected exertion is reached and can be maintained as long as resting fibres can replace fatigued on. Since recovery is slower than fatigue, the current maximum exertable force decreases thus limiting the exerted force.

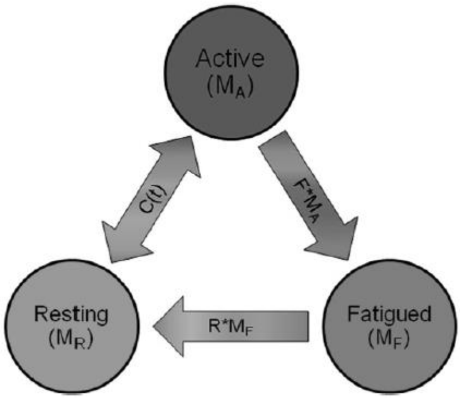

Fig. 1. States and state-transitions diagram for the 3-compartment muscle fatigue model (from Frey-Law et al. [18]).

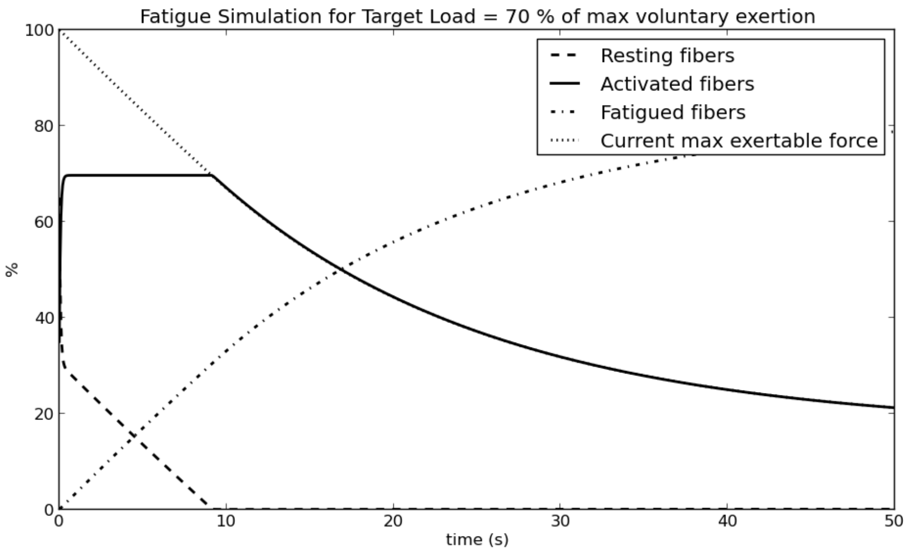

Fig. 2. Time evolution of muscle fibres state with fatigue for a target load equal to 70% of the maximum voluntary exertion.

Our demonstrator is based on the simulation engine XDE which has been used in several studies to generate human movement and assess the ergonomics of occupational tasks [6, 19]. XDE manages the physical simulation of a virtual human and its environment as a whole, practically in real-time, including accurate and robust constraint-based methods for contact and collision resolution [20]. A comprehensive description of the DHM and its optimization-based control can be found in [21].

The DHM is driven by a multi-objective linear-quadratic programming (LQP) controller, which manages the tasks to be performed such as balance, reference posture, ground contact, interaction forces, trajectory tracking, and the physical constraints of the system, such as joint angles bounds, maximum torques, etc. At each simulation step, usually 0.01 *s*, current state parameters are updated so that the tasks' cost functions are optimized subject to equality and inequality constraints: equation of motion; joint range of motion, bounded velocities, accelerations or torques, contact conditions, etc. as described in equation (1):

$$\min_{X} \sum_{i} \omega_i E_i(\boldsymbol{X}) \ subject\ to \begin{cases} M\ddot{q} + C(q,\dot{q}) + g = St + W \\ G\boldsymbol{X} \leq h \\ \boldsymbol{X} = [t, w_C, \ddot{q}]^T \end{cases} \quad \textbf{(1)}$$

where E_i is the error between the current state of the system and the goal of the task T_i, ω_i is the associated weight, M is the inertia matrix, C stands for centripetal and Coriolis forces, g the gravity forces, S the actuation selection matrix and W the external and contacts wrenches).

In our proposed framework, control constraints parameters may vary as fatigue sets in. As a first step, let us consider joint torques. At each simulation step, a "dummy" controller first calculates the desired actuation torques, τ^{des}, which optimize the defined tasks subject to the defined constraints (this controller doesn't modify the current state of the system). In the meanwhile, Γ_{max}, the maximum voluntary joint torques are computed thanks to the OpenSim musculoskeletal simulation software [22]. Γ_{max} is computed for the current posture and velocities of the DHM, so the demonstrator can manage dynamic movements, and not only isometric activities. τ^{des} and Γ_{max} are then used as input to update the fatigue model, yielding $\tau_{max}(f)$, the *current maximum exertable* joint torques, subject to fatigue. Finally $\tau_{max}(f)$ is imposed as a constraint to the actual DHM controller, yielding to potentially new state postures, trajectories and torques if $\tau_{max}(f) < \tau^{des}$.

3.3 First implementation

As we are at the first stage of our work, the whole architecture is currently not fully implemented. As a first-stage application, we describe hereafter a simulation for a fictional experiment where an operator must maintain his hand's position while undergoing a perturbation force. In this fictional static experiment, operator's upper limb fatigue performances are not simulated but obey the evolution described in Figure **2**.

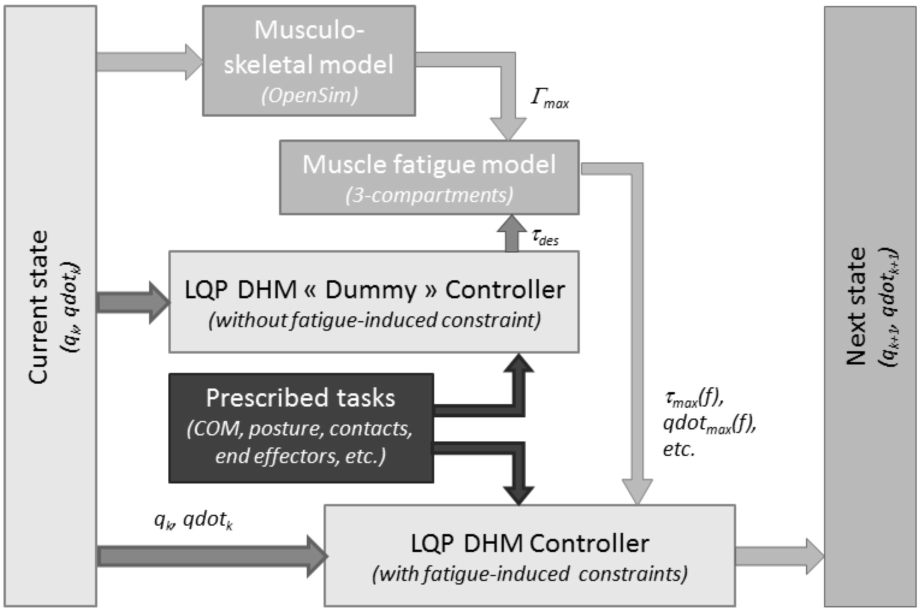

Fig. 3. Proposed framework for the demonstrator described here. Light grey elements correspond to the existing control. Darker grey elements represent new computations related to muscle fatigue. The black element indicates the control parameters prescribed for the motion (center of mass control, reference posture, contact forces, end-effector trajectories, etc.).

The manikin is standing, his right elbow is flexed at about 90°. The controller's most weighted tasks are to maintain the positions of the right hand and of the center of mass, as well as contact points with the floor. An horizontal perturbation force of 15 N is applied, pushing the manikin's right hand to the right. Fatigue is applied on the right shoulder abduction and rotation joints when the manikin is stabilized. As fatigue grows, maximum shoulder abduction joint torque decreases slowly. The manikin adapts its posture (right elbow joint angles) and the upper-trunk generates torques to compensate the loss of performance induced by fatigue, as shown in **Fig 4** and **Fig 5**.

4 Discussion

In this paper, we described a framework intended to account for fatigue-induced movement variability at the first stage of workstation design. Our demonstrator is expected to generate various simulated MV indicators such as range of postures, trajectories enveloppes, range of joint moments, etc. As we are only at the very first stage of its software implementation, no validation simulation is available yet.

Scheduled validation steps are focused on the upper limbs, based on literature and laboratory experiments. Firstly, we plan to simulate the repetitive reaching task described by Fuller et al. [23]. As in the fictional simulation described in section 3.3, we expect our demonstrator to mimic the compensatory behaviour described (shoulder elevation, decreased average shoulder abduction angle, lateral shift of the body's center of mass towards the non-reaching arm). Secondly, we plan to simulate a task combining movement and external forces exertion phases. At this stage, time is not considered as a quantitative parameter (the aim is not to simulate precisely *when* fatigue induces a given posture or movement, but rather to ensure that variants of postures or movements induced by fatigue can effectively be accounted for during the ergonomic assessment of the task in its entirety).

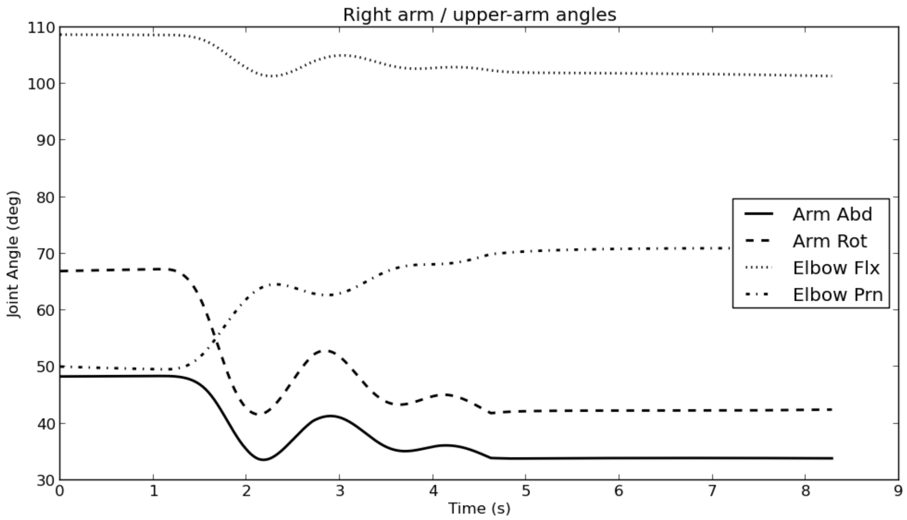

Fig. 4. Joint angle evolution of the upper limb with fatigue: right arm abduction and rotation, right elbow flexion and pronation joint angles.

If these two experiments are properly simulated, further model adjustments may be explored. Our demonstrator could be enriched with other models of MV sources in its controller, for instance, some statistical characteristics of MV, as described in the literature [24, 25].

Ultimately, this demonstrator could be integrated into workstation design tools such as commercial DHM in order to yield simulated indicators of movement variability to workstation designers. These physical quantities, for instance range of postures, trajectories enveloppes or range of joint moments are expected to better describe the operator's future activity and improve biomechanical risk factors assessment at the first stage of workstation design.

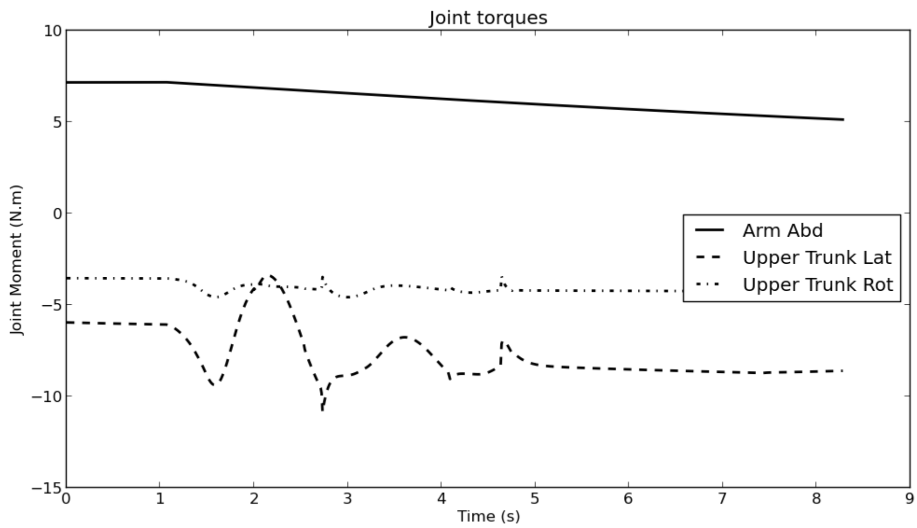

Fig. 5. Joint torques evolution with fatigue: right arm abduction torque decreases, generating changes in upper-trunk lateral tilt and axial rotation joint torques.

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