Simulation of fatigue-induced movement variability during a repetitive pointing task with a dynamic virtual human

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***Abstract*— Movement variability is an essential characteristic of human movement. It occurs in all kind of activities including work-place tasks. However it is almost ignored in workstation design, where expected movements are highly standardized for productivity and quality considerations. Neglecting this variability may bring designers to skip over parts of the future operator's movements, thus leading to incomplete assessment of biomechanical risk factors. This article describes a model-based virtual human controller intended to simulate the movement variability induced by muscle fatigue during a repetitive activity. The simulation of a repetitive pointing activity is described. Our demonstrator reproduces some of the adaptive behaviors described in the literature. This controller is still to be validated by experimental human data, but it opens interesting perspectives to DHM software improvements and more reliable ergonomics assessments from the early stages of workstation design.**

Keywords*— *DHM simulation, movement variability, muscle fatigue, workstation design

I. Introduction

Movement variability is an intrinsic feature of human movement [1]. Yet, despite its prevalence, workstation designers are hardly aware of this variability. Actually, neglecting this variability may bring designers to skip over parts of the future operator's movements, thus leading to incomplete assessment of biomechanical risk factors. Providing designers with tools accounting for this variability is hence a great challenge. As a preliminary step toward this ambitious goal, this paper describes a virtual human controller intended to simulate the effect of one source of variability during a repetitive activity, namely muscle fatigue.

II. Simulation of fatigue-induced movement variability

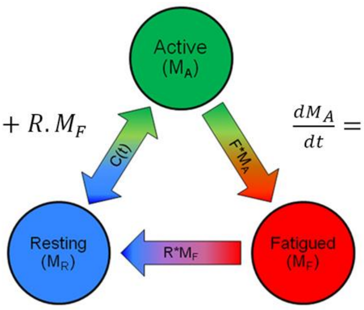
Muscle fatigue is a known source of movement variability. It may modify general postures, ranges of motion, perceived posture and task precision which may be critical features in occupational activities where cycle-time and quality requirements are to be fulfilled.

A. *Muscle fatigue model*

Among the different models of muscle fatigue, so-called "biophysical" compartment models appear more suitable for integration in digital manikin software [2] with respect to computation time, number and complexity of their parameters as well as their ability to account for time-history of muscle loading.

The fatigue model chosen for our demonstrator was that proposed by Xia and Frey-Law [3], [4]. In this model, which we call XFL, muscle is composed of a constant number of fibers M_0. At each moment, part of the fibers at rest (M_R) changes to active state (M_A), part of the fibers in active state changes to fatigue state (M_F) and part of the fatigued fibers returns to rest state (cf. Fig. 1). Two complementary descriptors of muscle fatigue can be defined: the residual capacities *RC*, i.e. the effort potentially exerted if all the non-fatigued fibers M_A+M_R were solicited together at the same instant, and the central command *BE* (Brain Effort) defined as the ratio between the current exertion M_A and the residual capacities *RC*. It is also supposed to account for the perceived effort. The XFL model can also be implemented at the joint level. For more details, please refer to [3], [4].

$$\frac{dM_R}{dt} = -C(t) + R.M_F$$



$$\frac{dM_A}{dt} = C(t) - F.M_A$$

$$\frac{dM_F}{dt} = F.M_A - R.M_F$$

Fig. 1. Diagram of the principle of the XFL model from [4]

B. *Virtual human model and control*

The physics engine used is XDE, which has already been used to simulate activity at a workstation [5], [6]. The virtual human is composed of 17 rigid body segments, actuated by 39 degrees of freedom assumed to be perfect hinges. The control of the virtual human is based on optimizing elementary "tasks" used to describe the simulated activity (for instance, maintaining balance, reaching a point or a speed, exerting a force, maintaining a contact) subjected to "constraints" (e.g the fundamental equation of dynamics, bounded joints range of motion or actuating torques). Constraints are always fulfilled. On the opposite, tasks may not be perfectly achieved. Since tasks may be concurrent, a weight ω is associated to each of them so that significant actions or behaviors can be prioritized. At each simulation step, the multi-objective linear-quadratic programming (LQP) algorithm described in [7] computes the instantaneous expected torques. The XDE physical engine then computes the system's dynamics to solve the next state of the virtual human. The simulated motion is hence the trade-off between the constraints and the weighted tasks described in the controller.

C. Fatigue-driven control: additional tasks and constraints

In order to account for fatigue, we included XFL model instances to our virtual human model. Each fatigable joint was described by a pair of XFL models according to the semi-articulation method [8].

The controller was designed to mimic two hypothesized behaviors: firstly, we suppose that exerted efforts are limited with the offset on fatigue (the more fatigued a joint, the more its force production decreases). This loss of force production capacities is dealt with joint torque limitation constraints: at each instant, joints torques τ_k are limited to the residual capacity RC_k calculated by the XFL model. Secondly, we suppose that the musculoskeletal control tries to preserve fatigued joints by transfer-ring part of exertions to other joints (the more fatigued a joint, the more the system seeks to lower its actuation). This behavior has been translated into actuation redistribution tasks which weights ω_k are modulated depending on the central command BE_k calculated by the XFL model so that efforts are transferred from fatigued joints to the rest of the body. The LQP controller processes the set of these complementary fatigue-driven tasks and constraints added to those describing the activity without fatigue, as illustrated in Fig. 1.

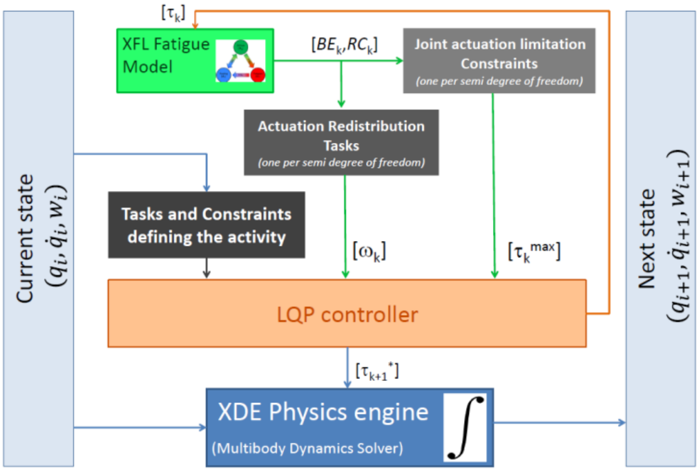


Fig. 1. Diagram of the principle of our controller

III. SIMULATION OF A REPETITIVE POINTING ACTIVITY

As a simulation case study, we considered the repetitive pointing activity with fatigue derived from the one described in[9], [10]. We simulated this experiment with a unique virtual human, alternatively pointing a proximal and a distal target, respectively placed at 30% and 100% of the length of an outstretched arm, with an expected cycle time of 2 seconds (cf. Fig. 2).

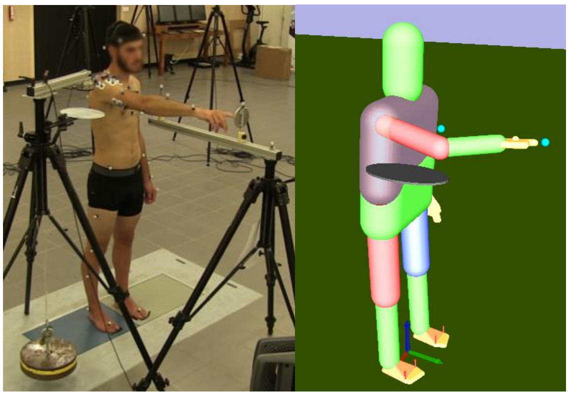


Fig. 2. Experimental set-up and simulation of the repetitive pointing activity

A. Simulation results

Simulated exhaustion time was 333 s. These results are consistent with experimental observations based on the same task (450 ± 180 s in [9], 413 ± 162 s in [10], 360 ± 120 s in [10]). Torque limitation constraints induced changes in movement only at the very end of the simulation, shortly before exhaustion (last 4 targets hits), otherwise, joint angles and trajectories remained identical. Torque limitation tasks induced more progressive variations in the movement on various joints. For instance, shoulder flexion and upper-trunk lateral inclination changed with the onset of fatigue on the order of 5° (cf. Fig. 6); fore-arm pronation and hand abduction angles decreased on the order of 3°; the altitude of the right shoulder increased by about 16 mm. These results are partly consistent with the observations found in [9]: shoulder elevation of about 12 mm, shoulder angle decreases by about 8°. Parts of these results need further comparison. For instance, simulation also showed a rotation and a lateral inclination of the upper-trunk, not documented in the cited experiments, as well as a shift of the pelvis by about 15 mm towards the dominant side (cf. Fig. 3).

IV. DISCUSSION AND PERSPECTIVES

Our virtual human controller implements joint torque limitation constraints and actuation redistribution driven by the modeled state of muscle fatigue. It has been used to simulate a repetitive pointing task, but it may also be used to other activities since it can cope with other kinds of tasks, including external wrench tasks.

With a priori parameterization and without any task-specific control derived from observed adaptation strategies, our demonstrator induced progressive variations of the movement, partly consistent with experimental results in terms of exhaustion time and kinematics variations between the beginning and the end of the experiment.

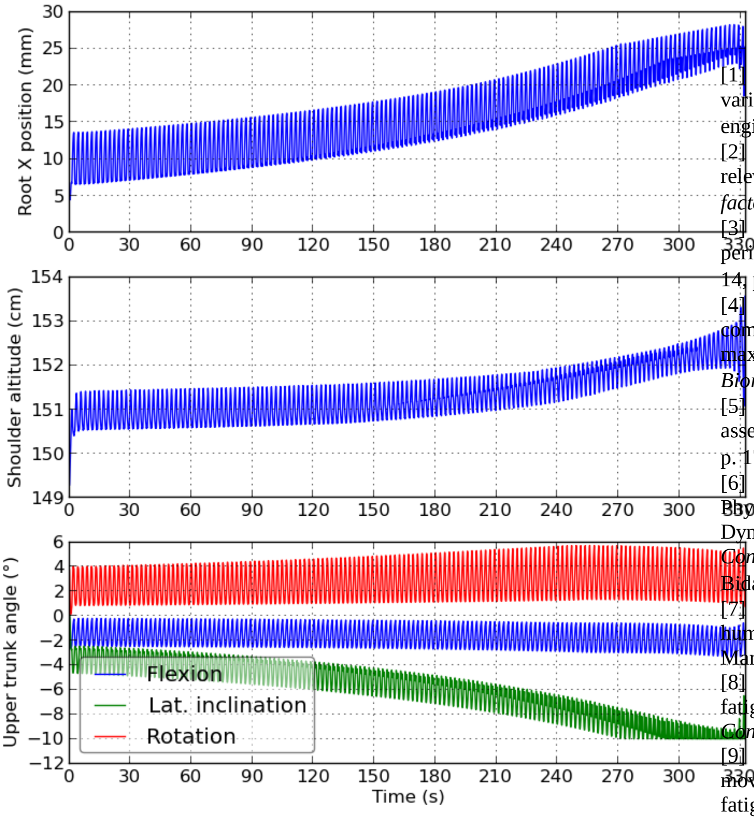


Fig. 3. Some adaptations of the movement simulated by the fatigue-driven controller

However, we only had reference data for beginning/end comparison. That's why an experiment has recently been carried out and is currently being analyzed to compare intermediate variations as well (not only beginning/end), identify subject-specific strategies to compensate the effects of muscle fatigue during the performance of the pointing task considered, and implement these strategies to enrich the control of the demonstrator.

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