# A Model to Assess Fatigue at Joint-Level Using the Half-Joint Concept

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*In this paper we focus on the modeling and evaluation of performance factors as human fatigue at joint level. We introduce the concept of half-joint pair to calculate fatigue at joint level, that is, at muscle groups level. The fatigue model is designed to enable to a posture optimization algorithm to adapt the human posture so that when fatigue appears it can be reduced. An Inverse Kinematics solver gets values of joints fatigue and evaluates whether it is necessary to minimize fatigue values. We use an activation/deactivation pattern for each half-joint to set/unset a fatigue reduction constraint when fatigue value reaches an established threshold. We make a comparison between experiments performed using several male and female and simulations generated by our animation environment.*

## 1. Introduction

The human body is continuously under the influence of forces. External forces include gravity and loads. External forces result in internal forces as compressive, tensile and contraction of skeletal muscles. Force application could result on beneficial effect (i.e bone remodeling) or prejudicial ones (i.e fractures). Fatigue can be considered as a decrease in physical performance due to external and internal forces or, on the contrary, a mental process [Hashimoto et al., 71]. We aim to estimate fatigue apparition due to the stress produced by own body segment's mass and external load carrying. Our work lets the user know how different muscle groups of the human body are affected by fatigue and how the musculo-skeletal body reacts so that fatigue sensation may diminish.

The musculo-skeletal system is an example of highly developed organization which makes really difficult to evaluate properties as postural fatigue. It has so many interrelated components that participate in the movement production. One obstacle for estimation of human body's properties as muscular strength is the diversity of data resulted from different research works. Chaffin collected data from different researchers [Chaffin, 88]. We have incorporated Chaffin's data to our model.

The parameters of our model are normalized torque, joint strength and the maximum holding time that a posture can be maintained. Fatigue levels are exploited by a posture control algorithm. We propose to calculate fatigue at joint level, more precisely at *muscle groups* level. To do that, we introduce the concept of *half-joint pair*. This concept is described in the following sections. This paper discusses experiments performed in several males and females in order to know people's reactions when they feel fatigue. We have made a comparison between results from experiments and simulations.

The organization of the paper is as follows. In section two we present the related work. In section three, we describe the own process of fatigue assessment. In section four, we explain how fatigue values are exploited in the postural control architecture. Section five describes experiments and simulations. Lastly, conclusions and future work are given in section six.

## 2. Related Work

If you use your muscles a lot and they don't get enough oxygen, then they feel tired. This is named muscle fatigue. A work has focused on model quadriceps muscle fatigue obtained the relationship between the intracellular pH and force exerted by the muscle. The force-pH relationship was fitted by an exponential function [Giat et al., 96]. Komura [Komura et al., 99] exploited Giat's model to simulate the fatigue of each individual muscle for a musculotendon model of the leg. He also formulated the dynamic equation relating a muscle exertable force to its current length, contraction velocity, activation level and normalized fatigue. The normalized fatigue term is computed differently depending on the current state of the muscle, either *fatiguing* or *recovering*.

Compared to this model, assessing individual muscle fatigue, we work on fatigue assessment in a more constrained way, that is fatigue is evaluated at muscle groups level. However Komura's model has been designed for the motion retargeting of the lower body [Komura et al., 00] and we aim to a postural control of the entire body.

Another research searched for less fatigued postures by guarantying that the ratio of joint torque to joint strength is minimal but they didn't model fatigue evolution over time [Lee, 93] [Badler et al., 93]. Muscular strength evaluation has also been used to determine the relationship between degraded muscular strength and alteration of lifting motion strategy [Zhang et Buhr, 02]. It can be used to assess postural deficiencies in daily activities to reduce the number of industrial workers suffering from back injuries.

A CAD tool for the ergonomic design of vehicle interiors, named RAMSIS, analyzes and compares different sitting positions with regard to the comfort of particular parts of the human body, fatigue and stress on the spinal column [Company, 03].

## 3. Fatigue assessment

### 3.1. Muscular activation in the human body: the half-joint concept

To make a joint move in two directions, we need two muscles that can pull in opposite directions. Antagonistic muscles are pairs of muscles that work against each other. One muscle contracts (agonist, or prime mover) while the other one relaxes (antagonist) and vice versa.

We calculate fatigue at *muscle group* level. We break down each single *dof* joint (*dof* is short for *degree of freedom*) into two coordinated *half-joints* constituting a *half-joint pair*. The two half-joints of a pair simulate the activity of the group of muscles associated to one degree of freedom but acting in opposite *pulling* directions. That's the reason why there are two different strength curves for elbow in the sagittal plane. This approach enables us to compute and visualize independent fatigue values for each antagonist muscle group [Rodríguez et al., 03]. The half-joint approach uses 3-DOF (degree of freedom) joints modeled using three 1-DOF joints.

Table 1 shows an example of an original joint working in the sagittal plane, that is, the joint permits flexion and extension movement. The native joint is split in two half-joints that comprise its entire range of motion.

<table>
<tr><td rowspan="2">ORIGINAL JOINT<br>(flexion/extension movements)<br>$\theta_{cur}$: current value of angle<br>Range of motion: [$\theta_{min}$ , $\theta_{max}$]</td><td>FIRST-HALF-JOINT<br>It moves from $\theta_{cur}$ to $\theta_{max}$ in the same direction as the original joint (flexion)</td></tr>
<tr><td>SECOND-HALF-JOINT<br>It moves from $\theta_{cur}$ to $\theta_{min}$ in the opposite direction as the original joint (extension)</td></tr>
</table>

*Table 1. Original joint is broken down in a pair of joints*

Note that the two half-joints have dynamic limits due to the updating of current value of angle $\theta_{cur}$. The first half-joint range of motion is [$\theta_{cur}$ , $\theta_{max}$]. However the second half-joint is defined as a transformation concatenated *after* the first half-joint's, thus its range of motion relative to the first half-joint's state is the following: [ 0 , $\theta_{cur}$ - $\theta_{min}$].

### 3.2. Parameters involved in the model

Our model collects a set of basic components in the scenario where fatigue apparition wants to be evaluated. These components are joint strength, current joint torque and time. The joint strength and the current joint torque are used to calculate a value of normalized torque. The normalized torque is used to calculate the maximum holding time that the posture can be sustained (in a static context). Finally the current value of the maximum holding time and the time increment are used to update joint fatigue. Figure 1 shows the input parameters and the process followed to define joint fatigue level. A more detailed description of this model can be found in [Rodríguez et al., 02a] .

Each of the five following paragraphs summarizes each step (shape in Figure 1) in the fatigue model formulation:

- Input parameters are muscular strength and current joint torque. Joint strength value $st$ is obtained from strength curves [Chaffin, 88] and current joint torque is computed from the Jacobian transpose using the principle of virtual work [Craig, 86]. F represents an external Cartesian forces, P represents the body weight acting at the center of mass, $J_i^T$ the transposed Jacobian for the end effector i, $J_G^T$ is the transposed Jacobian dedicated to the position control of the center of mass [Baerlocher et Boulic, 02] and $\tau$ is a vector storing joints torques.

- Once these two vectors have been calculated, for each joint $i$ the normalized torque $T_{N\,i}$ is calculated as the quotient of joint torque $\tau_i$ and joint strength $st_i$. A study on maximum holding time that a posture can be sustained stated it as a function of normalized torque [Manenica, 86].

- Then fatigue level is expressed as the holding time *ht* normalized by maximum holding time *mht*.

- As we want to estimate how fatigue evolves over the elapsed time, a variational expression of fatigue is defined where the fatigue variation is a function of the time increment duration *Δt* and of the current maximum holding time *mht*. Fatigue level at time k is defined as fatigue level at time k-1 plus a term that expresses an additional fatigue increment produced during Δt.

- The final formulation of fatigue is given in the last shape. Rohmert estimated that fatigue apparition is produced when the normalized torque is above a threshold of 15% of the muscular strength [Rohmert, 60]. We propose to scale the fatigue increment with a fatigue factor $F_f$ representing the gradual manifestation of fatigue. A negative term approximates the effect of a static recovery produced by a period of rest. Based on a study from Milner, we define the minimum duration of recovery *mdr* as the maximum holding time multiplied by the current fatigue level. This term is also affected by a recovery factor $R_F$. [Milner et al., 86]

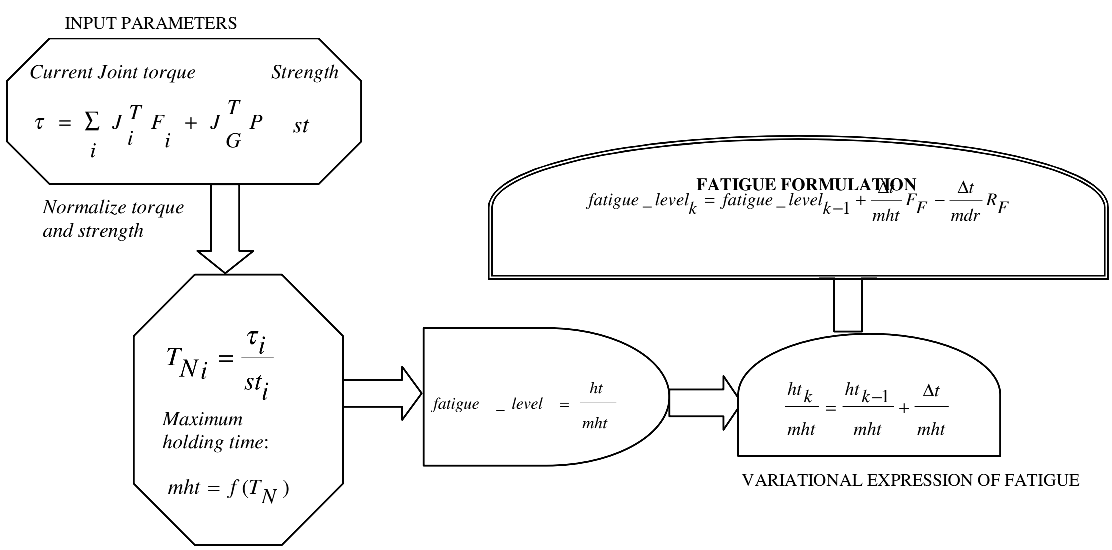


*Figure 1. Steps in the fatigue model formulation*

## 4. Fatigue exploitation: the Inverse Kinematics engine

Inverse Kinematics (IK) is used to compute goal configurations from target reference frames. This technique allows the user to position a figure by specifying a desired goal location for a particular segment of the figure. Given a position of a part of the body to be controlled, the IK engine will set up body segments correctly to achieve the requested position. Then, the user makes adjustment to an animated character with direct manipulation. We use Inverse Kinematics for postural control to achieve one or more tasks [Baerlocher et Boulic, 02][Badler et al., 93].

Figure 2 depicts how the IK solver gets current values of joints fatigue and evaluates if it is necessary to minimize fatigue. We introduce an activation/deactivation pattern for each half-joint to set/unset a fatigue reduction constraint whenever necessary. They are ensured with a higher priority than all the other IK tasks. When a half-joint fatigue level is above the fatigue threshold, a joint variation is calculated to reduce the half-joint torque by a small increment compatible with the corresponding time increment (under the assumption of slow motion). The constraint is deactivated, that is, exists until the half-joint recovery level is reached.

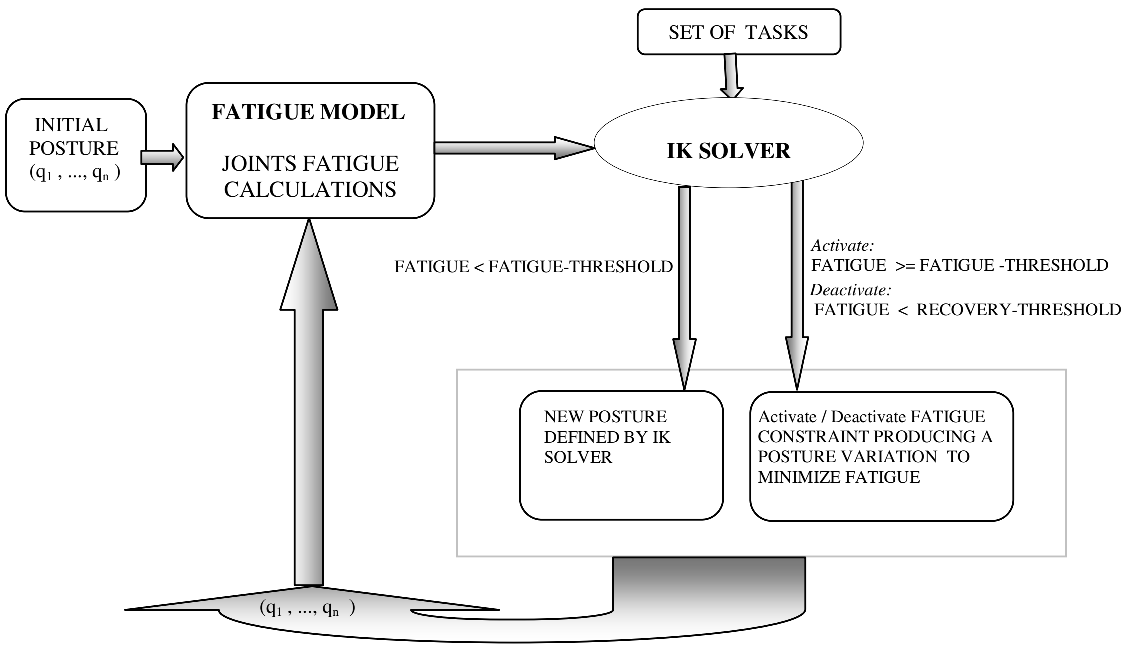


*Figure 2. Process of fatigue exploitation*

The fatigue constraint for fatigue minimization is constructed using the joint torque of the most fatigued joint, $\tau_f$. In order to do torque minimization we define a gradient vector $Vq$ storing the partial derivatives of $\tau_f$ with respect to all the joints.

$$Vq = \left(\frac{\partial \tau_f}{\partial q_0}, ..., \frac{\partial \tau_f}{\partial q_n}\right)$$

## 5. Results

This section provides a comparison between results of an experiment performed using 12 male and female and simulations generated by our animation environment.

### 5.1. Experiment protocol

Subjects' age ranged from 25 to 40 year old. The objective of this experiment was to explore what and how many positions of recovery they found when they felt fatigued. The experiment consisted of three parts: a previous training experiment, performance of definitive experiment and get feedback from subjects. It was used to familiarize the subjects with the basic elements of the experiment. He only had to explore the middle line, without the load, using a sphere with an orange marker attached to his wrist. In addition we wanted to set the initial posture situating a square red marker in the initial position.

The experiment consisted in maintaining the wrist in a vertical, horizontal or oblique line marked in the wall. In fact, we made use of three lines but the subject had to follow only the middle one, the other two actuated as guidance. The orange sphere, positioned at the subject's wr ist, had to be kept in the line. A video camera recorded a side view of the subject. The subject looked at a monitor situated in front of him. In front of the subject a mirror prevented movements like abduction. Note that we worked in the sagittal plane. Figure 3 shows the situation in the room of the elements used in the experiment.

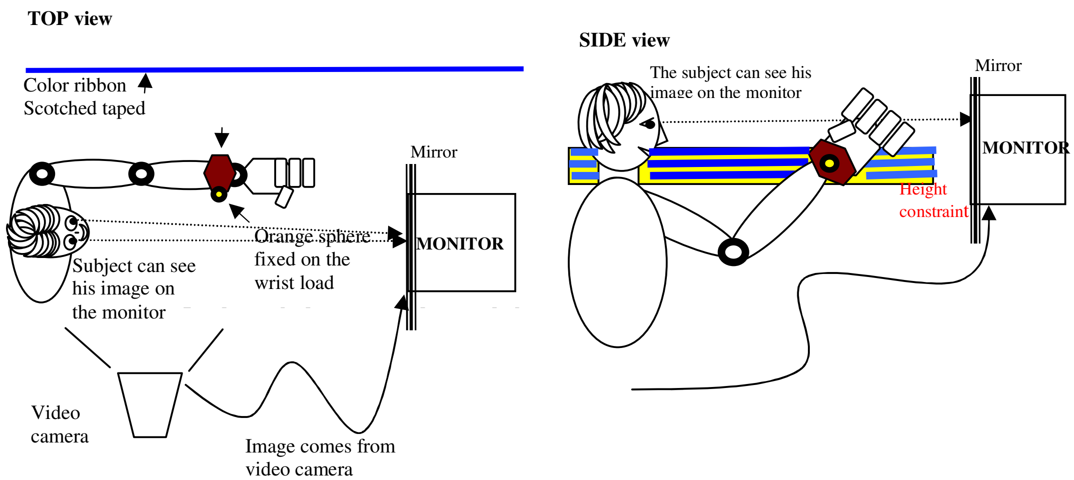


*Figure 3. Layout of the experiment*

### 5.2. Comparison between experiment and simulations

Several experiments with vertical, horizontal, -25 ° oblique and -45° oblique line cases were recorded and analyzed. The subject had to stay in the initial position as long as he could. When he felt fatigue, he tried to find a posture where he could find rest; and if he was enough recovered, he felt free to move along the line. Experiment stopped when the subject was not able to find recovery along the line. We have selected to show only some of the experiments performed. A more detail description can be found in a technical report [Rodríguez et al., 02b].

Figure 4 shows snapshots from video-recordings and simulations of the oblique -25° case. This case showed that subjects only found one position of recovery.

The oblique -45 case (see Figure 5) showed that subjects also found one position of recovery. Although in this case some subjects tried to go downward to find recovery. We asked them why they did that and their feedback was that they didn't know why. One explanation can be found in Berthoz studies. He stated that the mentally simulated action of a contraction lead to the mentally simulated perception of a temporary higher muscle tension required to contract more the biceps at the very beginning of the motion [Berthoz, 96]. That explains that at the beginning of the experiment some subjects chose the opposite direction. However when they realized that the downward movement was even more fatiguing they went upward; this is the direction that minimize the moment arm and in consequence fatigue.

Another explanation of subjects' reaction can be found in the well-known muscle length and force relationship (see Figure 6). When muscle length is its first half, a decrease of length produces a diminution of force that requires increasing the muscular tension in order to maintain a constant force, needed to maintain static conditions. This feeling of increased tension might drive the subject to feel that the upward direction, that muscle length decreases, was not good to recover.

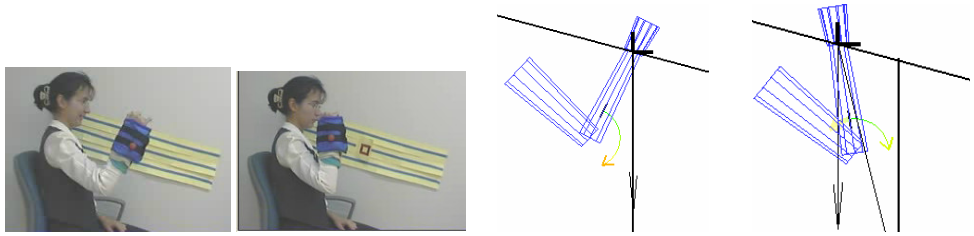

*Figure 4. Oblique -25°case. 2.5 kg load. Postures from experiment versus simulation. From left to right: initial and recovery posture*

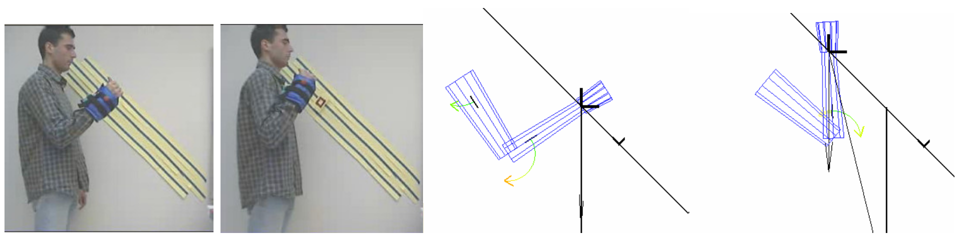

*Figure 5. Oblique -45°case. 2.5 kg load. Postures from experiment versus simulation. From left to right: initial and recovery posture*

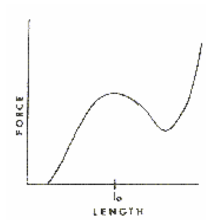


*Figure 6. Force–length relationship (reprinted from [Winter, 90])*

## 6. Conclusions and future work

From the experiment performed we can conclude that the strategy followed by the subjects to decrease fatigue or to find recovery is similar to the generated by our simulations. Thus, there is good evidence that we have found a workable algorithm to propose postural changes driving to less fatigued postures. Therefore we provide a tool for understanding the behaviour of human body joints under stressed conditions. It also needs to be noted that the complexity of the human body control makes a general approach very difficult, thus it is required more specific treatments depending on the characteristics of the posture and body members involved in it.

We have to remark that the method described in this paper is not the final solution for postural control, because some postures need of a higher level control, that is, a behavioural control, to readapt fatiguing postures. We are studying the exploitation of the passive or resistive torque that appears near to joint limits. It would help to an algorithm of fatigue optimization to drive a fatigued joint to the limit where it can find some rest due to that passive torque.

As part of our future work, we will look at further data collection and refinement referent to planes of movement as frontal or horizontal ones. There is promising new work to investigate that would be the dynamic case. We are particularly interested in enhancing our system to cover a wide range of postures, generalizing the scope of the system. We plan to perform more experiments in order to do new comparisons with results from our simulations.

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