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Short communication

A model for musculoskeletal disorder-related fatigue in upper limb manipulation during industrial vegetables sorting

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ABSTRACT

In the agro-industrial sector there are many activities whose urgent rhythms can cause a considerable exposure to bio-mechanical risk factors. In the vegetable sorting sector the workers are subject to a several biomechanical risks, with due to repetitive movements of upper limbs, and operations that require a remarkable degree of strength.

Preventing the fatigue associated to repetitive movements of upper limbs means also prevent the risk of musculoskeletal disorders related to this kind of operations. A thorough study of the workers' exposure to repetitive manual movements has been carried out, with the aim of setting up the necessary measures to reduce the risk factors. This paper proposes an original model for assessing the musculoskeletal disorder-related fatigue resulting from vegetable sorting. The test of the model was carried out in a particular case and results plead in favor of the need of process re-evaluation in terms of risks and musculoskeletal disorder issues.

Relevance to industry: This study proposes an original model for assessing musculoskeletal disorder-related fatigue resulting from vegetable sorting. It states the relevance of process re-evaluation in terms of risks and timing issues. Results can be used as guidelines to adapt workplaces and work tasks.

1. Introduction

The problem of establishing compromises between production requirements and health caution is getting more and more importance in different industries. In this context, musculoskeletal disorders cause increasingly workers efficiency perturbations (Cecchini et al., 2010; Colantoni et al., 2012; Jang et al., 2006). The main known causes of musculoskeletal disorders are lower back inadequate support, prolonged unhealthy posture, continuous bending of the spinal cord and adverse work environment. In agricultural and vegetable harvesting framework, automation has indeed increased in recent years and several efforts have been made to achieve efficient and flexible manufacturing, nevertheless, manual work is still very important due to the need increase of customized products and human's body advantage beside machinery (Dickerson et al., 2008; Ebaugh et al., 2006).

Work-related musculoskeletal disorders (WMSDs) are one of the greatest occupational health topics today. e.g. a review by the National Institute for Occupational Safety and Health (NIOSH) of epidemiological studies related to WMSDs in the workplace has pointed out their association with the following workplace factors: 1) heavy physical work, 2) lifting and forceful movements, 3) bending and twisting (awkward postures), and 4) whole-body vibration (NIOSH, 1997). Recent innovations at a structural and organizational level, introduced by the European laws, have effectively led to an overall drop, over the last ten years, of the number of injuries and professional diseases (Johnson and Everson, 2011). However, although there has been a decrease for "traditional" pathologies, such as hypoacusis, there has been a remarkable increase of musculoskeletal disorders, caused mainly by the lifting and transport of heavy weights, wrong working positions (extreme postures and/or sudden movements) and repetitive movements.

There are many ergonomic analysis tools that claim to accurately measure some variables associated with WMSDs. They are essentially based on biomechanical, epidemiological, and physiological approaches and identify work activities that might cause

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WMSDs. These tools include: the OSHA checklist (Schneider, 1995), the strain index (Moore and Garg, 1995), the OCRA ((Occupational Repetitive Actions) index (Occhipinti and Colombini, 1997; Occhipinti, 1998), the ACGIH hand activity level (ACGIH, 2001), the OREGE (Outil de Repérage et d'Evaluation des Gestes), and the RULA (rapid upper limb assessment) (McAtamney and Corlett, 1993). The OCRA index is the model used by authors. This method comply with the standards that establish ergonomic recommendations for repetitive work tasks involving the manual handling of low loads at high frequency. It provides guidance on the identification and assessment of risk factors commonly associated with handling low loads at high frequency, thereby allowing evaluation of the related health risks to the working population.

Aim of this study is to set up an analytical method for assessing musculoskeletal disorder-related fatigue in repetitive movements during vegetable sorting. Model and governing equations are presented along with resolution protocol patterns. Solution plots are shown and discussed in Section 3.

2. Model presentation and governing equations

2.1. Model presentation

The presents model takes all the input data to evaluate the manual operation. Evaluation criteria of all the aspects of the manual operation are predefined in the framework, such as fatigue, posture, discomfort etc. Three main assumptions (Ebaugh et al., 2006) have been formulated as:

- The need of evaluating the contribution of the multiple different risk factors;
- Developing a global index which evaluates the risk for the whole set of tasks;
- Comparing different indexes for eventual work shift re-planning;
- Giving an augmented supply to decision-making instances.

Under these presumptions, muscle fatigue is quantified in order to evaluate the point at which the muscle is no longer able to develop normal activity.

2.2. Fatigue model patterns along with formal methods and governing equations

The actual fatigue model is based on a preliminary partition of the whole set of skeletal muscles which contribute to the cycle during any task m (see Table 1 for nomenclature).

Two main classes are defined:

- Class A: M muscles $a_i|_{i=1,M}$ with very high fatigue resistance due to small force generation capability and low conduction velocity.
- Class B: N muscles $b_i|_{i=1,N}$ with fast fatigability and moderate force capacity.

For each muscle (acting unit) a_i and b_i, three parameters are pre-determined: the maximum voluntary contraction $\tilde{M}_i$ and the maximum joint stress $\tilde{\Gamma}_i$. Parallel to these definitions, $F_i^{(m)}(t)$ and $\Gamma_i^{(m)}(t)$ are defined as t-dependent muscle load and force capacity profiles during a task (m), respectively. For the whole cycle (c), these profiles are juxtaposed as $F_i^{(c)}(t)$ and $\Gamma_i^{(c)}(t)$, respectively.

At this stage, a fatigue index ξ_i is defined for the whole cycle (c). This index verifies, for each unit i, the following system (Liu et al., 2002; Freund and Takala, 2002; Ding et al., 2003):

Table 1
Nomenclature.

Symbols	
i,j,n, m	Indexes
M,N	Integers
$F_i^{(m)}(t)$	t-dependent muscle load during a task (m)
$F_i^{(c)}(t)$	t-dependent muscle load during the whole cycle (c)
M_0	Prefixed integer
$\tilde{M}_i$	Maximum voluntary contraction
B_{4j}	Boubaker polynomials values (dimensionless)
r_j	Boubaker polynomials minimal positive roots (dimensionless)
a_i, b_i	Real coefficients
k,H_n	Real constant
c_j, k'_j,y_j	Real constants
$[C]$	Array
Greek symbols:	
$\alpha_{i,j}$, $\theta_{i,j}$, $\lambda_{i,j}$	Unknown pondering real coefficients
ν	Real constant
Γ	Prefixed integer
$\Gamma_i^{(m)}(t)$	t-dependent muscle force capacity during a task (m)
$\Gamma_i^{(c)}(t)$	t-dependent muscle force capacity during the whole cycle (c)
ξ_i,$\xi_i^{(Sol.)}$	Fatigue index
ξ_G	Global fatigue index
$\tilde{\Gamma}_i$	Maximum joint stress
ϕ_i	Real constant
$[\Theta]$,$[\lambda]$	Arrays

$$\begin{cases} \dfrac{d(\xi_i(t))}{dt} = \dfrac{\tilde{M}_i}{\Gamma_i^{(m)}(t)} \dfrac{F_i^{(m)}(t)}{\Gamma_i^{(m)}(t)} \\ \dfrac{d\left(\Gamma_i^{(m)}(t)\right)}{dt} = -k\dfrac{\Gamma_i^{(m)}(t)}{\tilde{M}_i}F_i^{(m)}(t) \end{cases} \tag{1}$$

with k constant.

2.3. Resolution protocol

The resolution process consists of two main steps. The first step starts with the discretization, over time, of the profile of $F_i^{(c)}(t)$. The total duration of the cycle is divided into M_0 incremental pulses and the second equation in the system (1) is hence reduced, for the cycle (c) to a serial of simple equations of the kind:

$$\frac{d\left(\Gamma_i^{(c)}(t)\right)}{dt} = -\frac{k'_j}{\tilde{M}_i}\Gamma_i^{(c)}(t) \tag{2}$$

with a trivial solution:

$$\begin{cases} \Gamma_i^{(c)}(t) = \sum_{j=1}^{M_0} y_j e^{-\frac{k'_j}{\tilde{M}_i}t} = \sum_{j=1}^{M_0} y_j e^{-\alpha_{i,j}t} \\ \alpha_{i,j} = -\dfrac{k'_j}{\tilde{M}_i} \end{cases} \tag{3}$$

The second step consists of solving the modified equation in the system (1):

$$\frac{d(\xi_i(t))}{dt} = \tilde{M}_i F_i^{(c)}(t)\left(\sum_{j=1}^{M_0} c_j e^{-\alpha_{i,j}t}\right)^{-2} \tag{4}$$

The resolution is carried out using the Boubaker Polynomials Expansion Scheme BPES (Milgram, 2011; Lazzez et al., 2009; Fridjine et al., 2009; Dada et al., 2009; Barry and Hennessy, 2010;