Toward an Adaptive Human-Robot Collaboration Framework for Ergonomic Risk Assessment

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Abstract— **Among the numerous risk factors associated to work related musculoskeletal disorders (WMSD), the most frequently cited in literature are excessive mechanical loading and repetitive movements. The first is commonly associated with manipulating heavy objects while the latter can result in fatigue accumulation when using light weight tools over a protracted period of time. In a previous work, we developed an algorithm for the real time monitoring of joint overload induced by an external force. By exploiting this estimation method and considering joint torque capacity, an overloading fatigue model has also been proposed to account for the cumulative effect of joint overload throughout time. The overloading joint torque and the overloading fatigue estimation can be combined and integrated in an adaptive human robot collaboration (HRC) framework to improve workers' ergonomics while performing tasks with both heavy and light weight objects, addressing the correspondent risk factors, i.e. the excessive loading or the fatigue accumulation on body joints, respectively.**

I. INTRODUCTION

Work related musculoskeletal disorders (WMSDs) are well know to be a widespread issue in many industrial countries, with substantial costs and impact on quality of life [1]. Even though numerous studies in this field have identified physical, psychosocial/organizational, and individual occupational determinants for the development of WMSDs [2], our work is focused on the assessment of physical work load and on the monitoring and mitigation of the risk factors associated to it, with mechanical overexertion and repetitive and monotonous movements among the most frequently cited in literature [3]. Overexertion is commonly generated by the manipulation of heavy objects. Repetitive movements, on the contrary, even if they are performed with light weight tools, can result in the accumulation of local muscle fatigue when protracted over time. Both of these activities can cause injuries in the human joints but with different modalities, thus different parameters must be taken into account in evaluating of the ergonomic risks associated with them. Specifically, the instantaneous overload of the joints induced by an external force has to be considered for assessing mechanical overexertion, while the building up of said overload effect on the joint in time can be indicative for estimating the level of fatigue. Consequently, an integrated system able to monitor concurrently both these quantities is needed for the prevention of WMSDs.

To assess the human physical workload associated with manipulating weights in different postures [4] or for protracted periods of time [5], several methods have been proposed in literature, but only off line procedures or static conditions are considered. Other studies developed accurate biomechanical models to evaluate the human dynamic behaviour. However, these models are the product of computationally onerous identification processes or they can be obtained with anthropometric tables thus they are not subject specific and can introduce a large level of uncertainty. The real time applicability of such approaches in industrial use cases is therefore questionable.

For this reason, we recently proposed a reduced complexity approach to the whole body estimation of human joint overload induced by external forces [6]. In that work, a reduced number of subject parameters is used to avoid the use of standard average anthropometric data and address real time compatibility. This algorithm was built to monitor the instantaneous overload on the joints while manipulating heavy objects. However, considering fatigue as the cumulative effect of the joint overload throughout time, it can be extended to enable even the assessment of repetitive tasks performed with light weight tools. In fact, a direct estimation of fatigue can be obtained from the measurement of the reduction of muscular strength or force output when exerting against an external load for a period of time and such reduction can be estimated by fitting a certain function, with exponential models among the most common [7], [8]. Applying this concept to the joint level, similarly as in [9], we develop a whole body and subject specific model to evaluate the human fatigue progression, induced by the building up over time of the moderate joint overload due to light payloads.

Nevertheless, to avoid joint injuries which can result in WMSDs, methods and indexes for assessing risks associated to physical work load have to be combined with practical strategies to reduce their effects. For this reason, the joint overload estimation approach we proposed in [6] was integrated in a human robot collaboration (HRC) control framework [10], by which a collaborative robot continuously adjusted the human counterpart's body configuration to perform a heavy manipulation task in an ergonomic way. In the same way, the overloading fatigue model can be integrated in the HRC framework to cope with repetitive task involving

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light weight tools. Our objective is to develop an adaptive HRC framework to improve worker's ergonomics while performing tasks with both light weight and heavy tools, taking into account the corresponding risk factor, i.e. the fatigue accumulation or the excessive mechanical overload on the body joints, respectively.

II. Overloading Joint Torque and Fatigue monitoring

We recently proposed an algorithm to monitor the human overloading joint torque variations induced by an external force in real time [6]. The method is based on the displacements of the centre of pressure (CoP) in the support plane (*x*-*y*), defined as the difference between an estimated one (using an off line calibrated model) and a measured one (using external sensors). If no external interactions of the human with the environment (or object) are taking place, the estimated CoP computed by the human body model corresponds to the measured CoP. If an external force is applied to the human, the estimated and the measured CoP differ. Accordingly, the overloading joint torque vector can be estimated in any arbitrary body configuration from the CoP displacement along with the ground reaction forces (GRF) exchanged between the human and the support plane. A detailed explanation of the method can be found in [6] and will not be repeated here due to page limits.

Taking advantage of this estimation method, we developed an overloading fatigue model which reflects such variations of joint overload and takes into account joint torque capacity. Similarly to [9], the fatigue model can be represented by an RC circuit with zero initial charge state, which is mathematically modelled by a differential equation. The overloading joint *fatigue model* of the *i*-th joint τ_i^F at a time instant *t* can be defined as:

$$\tau_i^F(t) = \tau_i^{\max}\left(1 - e^{\int -K\frac{\tau_i^{\Delta}(t)}{\tau_i^{\max}}\mathrm{d}t}\right), \tag{1}$$

where $\tau_i^{\max}$ is the maximum allowable joint overload for the *i*-th joint and can be chosen from the biomechanical data [11], K is the fatigue ratio (set to 1), and $\tau_i^{\Delta}(t)$ is the overloading torque for the *i*-th joint at a time instant *t*, which is obtained by the generalised coordinates $\mathbf{q}$ of a floating base human model: $\mathbf{q} = \begin{bmatrix}\mathbf{x}_0^T & \boldsymbol{\theta}_0^T & \mathbf{q}_h^T\end{bmatrix}^T \in \mathbb{R}^{6+n}$. $\mathbf{x}_0^T$, $\boldsymbol{\theta}_0^T$ and $\mathbf{q}_h \in \mathbb{R}^n$ represent the position, the orientation of the base frame w.r.t the inertial frame and the angular position of n human joints, respectively.

Along with the overloading joint fatigue model, a *recovery model* has also to be modelled to describe how the force generation capacity is recovered during rest periods. The recovery model can be defined as:

$$\tau_i^F(t) = \tau_i^{\max} - (\tau_i^{\max} - \tau_i^{F_0})e^{-Rt}, \tag{2}$$

where $\tau_i^{F_0}$ is the initial value of the overloading fatigue and R is the recovery ratio for the *i*-th joint, which is set to 2.4 in accordance with other works on recovery models found in literature [7], [12].

In the new proposed overloading joint fatigue and recovery models, we assume that the relationship between the models is represented by the threshold $\tau_i^{\mathrm{th}} = 0.33\tau_i^{\max}$. The model can then be defined as:

$$\tau_i^F(t) = \begin{cases}\text{Fatigue model} & \text{if } \tau_i^{\Delta}(t) > \tau_i^{\mathrm{th}} \\ \text{Recovery model} & \text{otherwise}\end{cases}.$$

III. Verification of the method

This section presents the proposed overload fatigue model evaluation results. We have selected a real life scenario in the manufacturing industry which consists in a high rate of repetitive work with a short cycle time and light weight tool that can result in fatigue accumulation: manual spray painting. One healthy adult subject, (age: 31 years old; mass: 76.8 kg; height: 178 cm) was recruited in the experimental session. A written informative consent was obtained after explaining the experimental procedure. The aim of this experiment was to demonstrate the capability of the overloading fatigue model to monitor the progression of fatigue for different body configurations and thus to show how its trend varies for different joint overload. Accordingly, the subject, wearing a MVN Biomech suit (Xsens Tech) equipped with seventeen inter connected inertial measurement unit (IMU) sensors to measure the whole body motion, was asked to hold a 1.5 kg spray gun with the dominant hand and to simulate the painting action changing periodically the body configuration and thus the overload on the joints induced by the tool weight. The overloading fatigue in the main human joints was estimated throughout the experiment and its values was normalised between 0 and 1. We focused on the body motion on the sagittal plane because it is the mainly involved in the activity we have analysed. Additionally, we assumed the overloading torque on the lower body joints to be equal since the movements of the legs were almost symmetric.

In Fig. 1 we present the normalised overloading torque $||\tau^{\Delta}||$ (red line) and the normalised overloading fatigue $||\tau^F||$ (blue line) in the main human joints: hip (H), knee (K), ankle (A), shoulder (S) and elbow (E). These plots show how the trend of the overloading fatigue varied depending on the value of the overloading torque: if $||\tau^{\Delta}||$ was over the threshold, $||\tau^F||$ increased while it decreased under the threshold when the recovery mode was activated. In the lower body the torque was lower in average than in the upper body throughout the task and thus the fatigue accumulated less. In the shoulder and in the elbow fatigue accumulation was more significant and this is consistent with the fact that they are the joints more at risk specifically for the painting task [13]. It is worth noticing here that the overloading fatigue model is able to account for the building up of the overloading torque throughout time. Considering, for example, the elbow joint, the overloading torque value remained moderate and almost constant over the whole duration of the task thus it did

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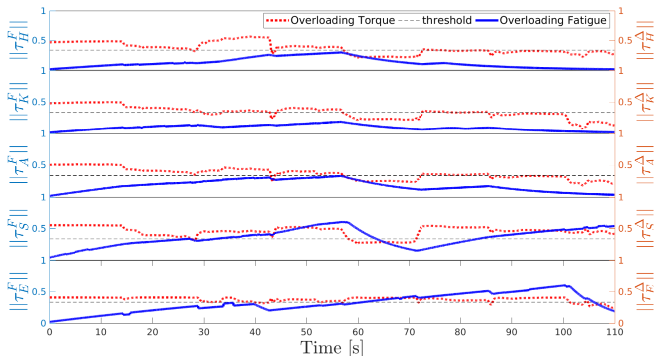

Fig. 1: Overloading joint torque (red line) and overloading joint fatigue (blue line) estimated in the main human joints - hip (H), knee (K), ankle (A), shoulder (S) and elbow (E) - while performing a painting task with a light weight tool changing periodically body configuration for one subject;

not represent a potential source of risk. On the other hand, the overloading fatigue addressed its cumulative contribution and, after some time, its value grown significantly.

IV. Conclusions

In this work we presented a new overloading fatigue model to account for the cumulative effect of the overload induced on human body joints by a light payloads throughout time. Overloading fatigue can be considered as an index to the risk assessment of repetitive and monotonous tasks performed using light weight tools. Along with the instantaneous overloading joint torque, this index can be integrated in HRC frameworks to develop an adaptive system to prevent work related injuries. Future works will focus on the implementation of a HRC framework, which will be able to handle tasks performed with both light weight and heavy tools, accounting for the corresponding risk factor, i.e. the fatigue accumulation or the excessive mechanical overload on the body joints, respectively. To prove the effectiveness of the proposed framework, experiments with multiple subjects performing various different tasks will be conducted.

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