International Journal of Industrial Ergonomics 57 (2017) 88–102

Contents lists available at ScienceDirect

International Journal of Industrial Ergonomics

journal homepage: www.elsevier.com/locate/ergon

Human-oriented design of collaborative robots

Pauline Maurice [a, *], Vincent Padois [a], Yvan Measson [b], Philippe Bidaud [a, c]

[a] Sorbonne Universités, UPMC Univ Paris 06, CNRS UMR 7222, Institut des Systèmes Intelligents et de Robotique, F-75005, Paris, France
[b] CEA, LIST, Interactive Robotics Laboratory, Gif-sur-Yvette, F-91191, France
[c] ONERA, 91123 Palaiseau, France

ARTICLE INFO

Article history:
Received 29 October 2015
Received in revised form
8 September 2016
Accepted 18 November 2016
Available online 31 December 2016

Keywords:
Digital human model
Dynamic simulation
Collaborative robot design
Sensitivity analysis

ABSTRACT

Collaborative robotics is a possible solution to the problem of musculoskeletal disorders (MSDs) in industry, but efficiently designing such robots remains an issue because ergonomic assessment tools are ill-adapted to such devices. This paper presents a generic method for performing detailed ergonomic assessments of co-manipulation activities and its application to the optimal design of collaborative robots. Multiple ergonomic indicators are defined to estimate the different biomechanical demands which occur during manual activities. For any given activity, these indicators are measured through dynamic virtual human simulations, for varying human and robot features. Sensitivity indices are thereby computed to quantify the influence of each parameter of the robot and identify those which should mainly be modified to enhance the ergonomic performance. The sensitivity analysis also allows to extract the indicators which best summarize the overall ergonomic performance of the activity. An evolutionary algorithm is then used to optimize the influential parameters of the robot with respect to the most informative ergonomic indicators, in order to generate an efficient robot design. The whole method is applied to the optimization of a robot morphology for assisting a drilling activity. The performances of the resulting robots confirm the relevance of the proposed approach.

1. Introduction

Work-related musculoskeletal disorders (MSDs) represent a major health problem in developed countries. They account for the majority of reported occupational diseases and affect almost 50% of industrial workers (Schneider and Irastorza, 2010). Since MSDs result from strenuous biomechanical solicitations (Luttmann et al., 2003), assisting workers with collaborative robots can be a solution when a task is physically demanding yet too complex to be fully automatized (Fig. 1); a collaborative robot enables the joint manipulation of objects with the worker (co-manipulation) and thereby provides a variety of benefits, such as strength amplification, inertia masking and guidance via virtual surfaces and paths (Colgate et al., 2003).

In order to design a robot which decreases at best the risk of developing MSDs, an ergonomic assessment of the robot-worker system must be performed throughout the design process. Though standard ergonomic assessments are based on the observation of a worker performing the task (Li and Buckle, 1999; David, 2005), digital evaluations now tend to replace physical evaluations in the design process of workstations; digital evaluations – in which a digital human model (DHM) is used to simulate the worker – indeed present several major advantages (Chaffin, 2007). Firstly, the simulation enables easy access to detailed biomechanical quantities, which otherwise can only be measured on real humans through complex instrumentation, if at all (*e.g.* muscle or joint forces). Secondly, different morphologies of workers can easily be tested without the need for a wide variety of real workers. And thirdly, a virtual – instead of a physical – mock-up of the robot is used for digital assessments, thus removing the need to build a new prototype every time a parameter of the robot is tuned. The overall development time and cost is thereby decreased.

To perform digital ergonomic evaluations, several commercial DHM software for workplace design provide ergonomic analysis tools (*e.g.* Delmia, Jack (Raschke, 2004), Ramsis (Seidl, 2004), Sammie (Porter et al., 2004)). These software – based on simple rigid-body models of the human body – include standard assessment methods which estimate an absolute level of risk depending on the main MSDs factors (Luttmann et al., 2003) (posture, effort, duration and frequency of the task) and possibly additional factors (*e.g.* RULA (McAtamney and Corlett, 1993), REBA (Hignett and

* Corresponding author.
E-mail address: pauline.maurice@polytechnique.org (P. Maurice).

http://dx.doi.org/10.1016/j.ergon.2016.11.011
0169-8141/

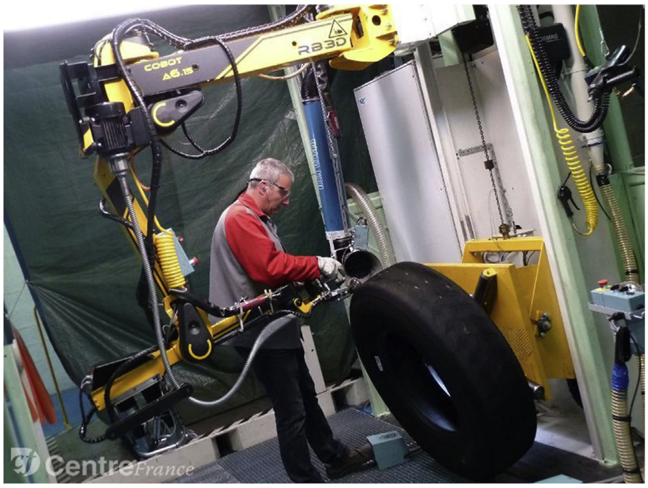

Fig. 1. A collaborative robot providing strength amplification for tire retreading (developed by RB3D, CEA-LIST, CETIM).

McAtamney, 2000) and OWAS (Karhu et al., 1981) methods, OCRA index (Occhipinti, 1998), NIOSH equation (Waters et al., 1993)). The resulting ergonomic indicators are, however, either very rough (*e.g.* effect of external load in RULA) and/or task-specific (*e.g.* NIOSH equation for lifting loads), so they do not accurately cover all kinds of manual activities which may be addressed by collaborative robots. Besides, these assessment methods are static, *i.e.* dynamic phenomena are not taken into account; yet fast motions do increase the risk of developing MSDs (Marras et al., 1993). In collaborative robotics, evaluating the dynamic phases of an activity is even more important because the robot is never perfectly backdrivable and some phenomena cannot be compensated even with a dedicated control law (*e.g.* additional inertia); manipulating the robot might then require extra efforts and cause new MSDs.

Concurrently to DHM software for workplace design, other DHM software provide more accurate musculoskeletal models of the human body, including muscles, tendons, and bones (*e.g.* OpenSim (Delp et al., 2007), AnyBody (Damsgaard et al., 2006), LifeMOD). Beyond classic macroscopic measurements (joint angles, joint forces and moments), these software also provide dynamic measurements (joint velocities and accelerations) and quantities that more accurately account for the biomechanical demands on the human body (muscle force, tendon deformation, muscle fiber length …). The high number of outputs (one for each muscle/tendon/joint) is, however, difficult to interpret without specific biomechanical knowledge, especially when the purpose is to summarize the global ergonomic level of the activity.

The second criticism which can be addressed to both kinds of DHM software concerns the animation of the DHM. The DHM motion is generated through forward or inverse kinematics, predefined postures and behaviors (*e.g. walk towards*, *reach towards*), or from motion capture data. Apart from motion capture, none of these animation techniques enables to come up with a truly realistic human motion. Kinematic techniques do not take into account the inertial properties of the human body or external load, so the simulated motion is rarely human-like (Chaffin, 2007). Pre-defined behaviors result in more realistic motions since they rely on a prerecorded motions database, but only a limited number of behaviors can be simulated and they become unrealistic when external conditions are modified (*e.g.* adding a load in a reaching motion). In general, the obtained motion is not even dynamically consistent. For instance, the DHM balance is never considered though it affects the relevance of the evaluation (Lämkull et al., 2009). As for motion capture, the human subject and the avatar must experience a similar environment to obtain a realistic simulation. In particular, the interaction forces with the environment are crucial, so the subject must either be provided with a physical mock-up (Fig. 2) or be equipped with complex instrumentation (digital mock-up through virtual reality and force feedback devices). Motion capture is therefore highly time and resource consuming. In order to circumvent the above-mentioned issues, De Magistris et al. developed an optimization-based DHM controller to automatically simulate dynamically consistent motions (De Magistris et al., 2013). The dynamic controller computes DHM joint torques from a combination of anticipatory feedforward and feedback control. It has many advantages over kinematics techniques, such as ensuring DHM balance and generating hand trajectories that are in accordance with some psychophysical principles of voluntary movements. However, though this controller has been successfully used for a virtual ergonomic assessment, the Jacobian-transpose method used in the feedback control does not guarantee the optimality of the solution, because joint torques limits cannot be explicitly included in the optimization.

Eventually, evaluating the ergonomic benefit provided by a collaborative robot requires that the robot be included in the DHM simulation. Though most DHM software can simulate a DHM within a static environment, they cannot simulate the motion of a collaborative robot which depends on its physical interaction with the DHM, both through its control law and through physical interferences.

Thus, despite many available tools for performing virtual ergonomic assessments, none of them is suitable to evaluate comanipulation activities. This work therefore presents a novel approach for quantitatively comparing the ergonomic benefit provided by different collaborative robots when performing a given activity, and its application to the optimal design of such robots. The proposed method consists in four components (Fig. 3):

1 A list of ergonomic indicators defined to accurately account for the different biomechanical demands which occur during manual activities. They cover all kinds of manual activities, without requiring any *a priori* hypotheses on the activity that is performed.
2 A dynamic simulation framework in which a DHM can interact with a controlled collaborative robot. The simulation is used to measure the ergonomic indicators. The DHM is animated through an optimization-based whole-body controller to ensure the dynamic consistency of the motion. The controller can be used either with high level tasks descriptions (autonomous DHM, 2a), or with motion capture data (2b). 2a enables the evaluation of robots under development without the need for a

Fig. 2. Animation of a DHM using motion capture data, with the Jack software (picture from Jack documentation). The human subject is placed in a physical mock-up of the environment in order to obtain realistic motions.