Human-Robot Collaboration (HRC) Technologies for Reducing Work-Related Musculoskeletal Diseases in Industry 4.0

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Abstract. The paper describes the activities of the European project SOPHIA, Socio-Physical Interaction Skills for Cooperative Human-Robot Systems in Agile Production. The project has been funded by European Union program Horizon 2020 under Grant Agreement No. 871237. The consortium involves European partners from academia, research organizations and industry. The main goal of the project is to develop a new generation of CoBots and Wearbots and advanced instrumental-based biomechanical risk assessment tools in industrial scenarios to reduce work-related musculoskeletal disorders and to improve productivity in industry 4.0.
Further aim of the project is to create the basis for new ergonomic international Standards for manual handling activities.

Keywords: First Keyword, Second Keyword, Third Keyword, Forth Keyword, Sixth Keyword.

1 Introduction

The new scenarios of a connected and digital world provide opportunities for the integration of new tools into everyday life and workplaces, the so-called Industry 4.0.
In the workplace, the use of sensor networks and human–robot collaboration (HRC) technologies are coming more and more to the fore as an opportunity for both biomechanical overload risk mitigation and for the adoption of new return-to-work strategies. On these grounds, the European Union's Horizon 2020 research and innovation program funded the Socio-physical Interaction Skills for Cooperative Human-Robot Systems in Agile Production (SOPHIA) project with the aim to develop a new generation of HRC technologies and sensors networks.
Sensor networks, through the continuous and real-time monitoring of worker's physiological and biomechanical parameters (by measuring kinematic, kinetic and muscular activity, etc.), can be used to control the robots through specific interfaces, evaluate the efficacy of ergonomic interventions and provide vibro-tactile/acoustic/visual

stimuli to the workers to execute the task in a less overloading way to reduce the risk of developing work-related musculoskeletal disorders (WMSDs).
HRC technologies include wearable assistive robots (WearBots, Exoskeletons) and collaborative robots (CoBots) able to act on the base of the real needs of the worker, support him during the working activity with the aim of minimize the biomechanical load and reduce the probability of WMSDs insurgence.

2 Wearable sensors and robotic technologies: state of the art

2.1 Wearable sensors

Recently, commercial and research miniaturized wearable wireless sensors were introduced in the workplace to monitor workers during their activities.
These sensors include Inertial Measurement Units (IMUs) to measure bodies' kinematics, dynamometers to evaluate subjects' force and surface electromyography (sEMG) sensors to analyze the muscle behaviors.
Commonly used IMUs can be accelerometers (uni-/bi- or tri-axial), gyroscopes and magnetic sensors. Typically, the probes are equipped with three orthogonal accelerometers and three orthogonal gyroscopes to measure linear acceleration and angular velocity, respectively, along three orthogonal axes. These devices are particularly suitable for use in the workplace since they are portable, easy to wear for the users, monitored remotely and able to provide a direct feedback to the end-users [1-5].
The forces exchanged by workers with the environment can be measured by highly reliable [6], easy to use, portable and low-priced hand-held dynamometers. These devices are placed between a fixed point and the subject's body part to assess the isometric muscle (or muscle group) strength to investigate changes in the functional status of trunk, lower and upper limbs [7-11]. For a given hand size, forces are also recorded by superior grip dynamometers, by instrumented gloves (i.e., equipped by force sensitive resistors) or by force sensor mats applied to handles [12-18]. To adapt to a wide variety of handle sizes and geometries multi-dimensional grip dynamometers are a valid alternative. In the end, we can also mention the use of the byhaptic tools, physical bendable strips that enable the users to manipulate and apply deformations to digital surfaces and to move and rotate virtual objects [1].
sEMG sensors are used to investigate the muscle activity during the execution of manual handling activities. Single- or double differential bipolar recordings using wet electrodes are the most widely used sEMG measurement methods in the workplace, since in this case the probes do not interfere with the typical movements performed by workers thanks to the miniaturization process and wireless communication protocols.

2.2 Wearable robotic technologies

Exoskeletons are wearable devices that help people during the execution of specific tasks by applying forces and/or torques on one or more joints. They were first developed in the clinical setting for motor rehabilitation [19] and to support people with motor disabilities [20–21], in military [22] and sport [23] fields.
More recently, the use of exoskeletons has also been extended to the industrial sector, as they can be an additional tool for reducing biomechanical risk in the workplace. The exoskeletons essentially differ based on how the torques / forces applied to the

human joints are generated and therefore the first distinction is between active and passive exoskeletons.

Active exoskeletons are those that generate forces/torques with powered actuators, such as electric motors, pneumatic or battery-operated exoskeletons. The action of the exoskeleton is controlled by a computer program based on information acquired through a series of sensors applied to the body of the subject who uses it (e.g.: sEMG, accelerations, angular velocities). Since the functioning of these exoskeletons is based on the online processing of biomechanical parameters, these exoskeletons are considered more versatile than the passive ones for the tasks in which they can contribute. In addition, those with battery are also easier to move, and therefore more comfortable to use at workplace, than the tethered ones. On the other hand, however, these exoskeletons are heavier and less manageable than the passive ones [24].

Passive exoskeletons use elastic elements such as coil springs, compact rotational springs, integrated gas springs or elastic bands [24] for the generation of joint forces/torques. .

Within each of these two macro categories, the exoskeletons are then divided into soft, rigid, or mixed.

2.3 Collaborative Robots (Cobots)

Collaborative robots, also called cobots [25] are robots based on HRC systems and represent a natural evolution of industrial robot, because they can solve existing challenges in industry, i.e., they can help workers to perform physically heavy tasks, thanks to the ability to physically interact with humans in a shared workspace; moreover, they are designed to be easily reprogrammed even by non-experts to be used for different roles [26]. Furthermore, the greater convenience of collaborative systems is their flexibility [27].

HRC systems were introduced primarily for occupational health (ergonomics and human factors) reasons [27]. The use of cobots can contribute to economic growth and the creation of better, healthier, and more attractive working environments for the future workforce since cobots can simultaneously increase productivity and reduce WMSDs, which represent the single largest category of work-related disease in industrial countries.

Anyhow, several technologies must be in place to enable humans and robots to work together to achieve shared goals.

So, it is important to distinguish the different ways of interaction. Müller et al. [28] proposed a classification for the different methodologies in which humans and robots can work together. They distinguish among: i) coexistence, when human and robot are in the same environment, but they do not interact, ii) synchronized if human and robot work in the same space at different time, iii) cooperation, when human and robot work in the same workspace at the same time, but they perform different tasks and iv) collaboration, when human and robot perform the task together.

Regardless of the type of the human-robot interaction, to make it effective, it is fundamental to ensure a correct information exchange between the operator and the cobot. This requires suitable interfaces that monitor human behavior—to properly plan the execution of the collaborative task—and strategies that increase the mutual awareness of the human–robot couple [29]. To this scope, as mentioned above, kinematic, kinetic and sEMG sensors networks are available. In addition, other devices are also available that can enhance the sensory experience when using a cobot, such as wearable haptic systems to provide the user with the sense of touch [30], or augmented reality systems, in which components of the digital world may be superimposed upon or composed with the real world and used in teleoperation [31].

3 The SOPHIA project activities

3.1 Standardization

To provide definitions and guidelines for the safe and practical use of cobots in industry, several standards are already available [32-35]. Moreover, none of the ergonomics standards [36–41], neither the traditional methods listed within them cover the biomechanical risk detection when collaborative technologies are used. This gap, together with the need to strengthen the scientific basis upon which the standards are based [42], represents the reasons that existing standards should be supplemented or revised or, if necessary, that new standards should be developed [29].

Literature [43] already evidenced some critical issues such as: their observational nature, subjectivity, susceptibility to the restrictions of the equations and parameters, insufficient accuracy, precision and resolution, unclear choices of the preferred methods of risk assessment over others.

New sensor-based tools for biomechanical risk assessment will be used for quantitative “direct instrumental evaluations” to obtain the rating in standard methods, when applicable, to measure some parameters otherwise measured with poor precision and accuracy, necessary to obtain the level of risk.

In this light, SOPHIA is going to work on the need of a revision of current ergonomics standards to also include the use of these tools for biomechanical risk assessment.

3.2 Reduction of biomechanical risk

Bio-electrical activity, skeletal joint kinematics and kinetics data will be used to assess the worker motor capacity and how it varies over time thus providing a musculoskeletal model that can predict muscle fatigue and injury based on worker movements. Next step will be the investigation of the interaction between worker and external systems (wearable and robots) and to analyze how these impact on biomechanical load. These data could also be used to develop an online instrumental-based tool for monitoring and classifying the biomechanical risk in manual handling activities when standardized protocols cannot be used or for a confirmation of the rating of observational data with standard protocols. One more target is to develop wearable devices to monitor human-motor variables and to render haptic stimuli to specific areas of the worker’s body (e.g. shoulder, lower back, ankle, knee, etc.) to inform the users about the inappropriateness of the posture adopted guiding them towards ergonomic postures and a safe action execution.

3.3 HRC in work environment

The European Union (EU) recognizes to HRC technologies a high relevance for the economic growth and for population health care. EU has planned a Strategic Research Agenda to provide a strategic overview and a technical guide aimed to identify medium term research and innovation goals [44-45] and promotes standardization activities for a better market adoption and to develop a single digital market [46].

In this light, the SOPHIA project aims to achieve successful and robust HRC through the process of data from different sensors and to publish a software library and an open access dataset for benchmarking HRC solutions in collaborative scenarios. It will be also developed the overall cognitive decision frameworks allowing the human and robot to collaborate considering human and environment constraints, to guarantee health (ergonomics) and safety (collision avoidance). In this light it is critical to develop the social interaction principles (human-centered) to ensure a fluent communication between workers and HRC technologies.

To improve the flexibility of Fellow-Assistant robots, SOPHIA project includes activitiesfocused on the development of stable hierarchical interaction controllers. This will enable CoBots to reconfigure the collaborative task frame, to simultaneously ensure human ergonomics and safety requirements and adapt task parameters by optimizing the required multi-task criteria. Multi-task and multi-person optimization will be central to the development of CoBot control framework in real environmental scenario.

3.4 HRC and work rehabilitation

SOPHIA project aimsto validate the HRC technologies also in the healthcare sector and in return-to-work rehabilitation of neurological patients with motor disorders and to develop miniaturized wearable devices to monitor human-motor parameters and treat specific areas of the worker's body with tactile stimuli. To achieve these outcomes the European consortium is developing myoelectric HRC interfaces to study the interaction among hybrid work environments and workers with the aim to highlight their specific residual abilities and unfulfilled potential. Furthermore, the project aims to design training plans on sEMG based technique for broaden the audience of experienced professionals in multifactorial movement analysis.

Neurological disease patients can receive remarkable rehabilitation results from the use of HRC technologies. Ongoing monitoring of sEMG parameters such as muscle activation timing, amplitude and fatigue play a significant role in the design of innovative active exoskeleton controller systems. The main issue with using sEMG to control collaborative wearable trunk and upper limb devices designed to assist neurological patients, concerns the algorithms applied in human-robot interfaces. Just few years ago the application of these algorithms was limited due to their inaccuracy in recognizing the high subjective movement variability of neurological patients. But now, thanks to machine learning algorithms, these limits have been overcome and HRC technologies are enhanced and optimized also for people with severe upper and lower limb disabilities [53].

Hence, SOPHIA project will develop algorithms for the HRC to recognize specific movement pattern to predict patient's movement intention.

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