Towards standards for the evaluation of active back-support exoskeletons to assist lifting task

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***Abstract*—Back-support exoskeletons have been recently proposed to reduce the risk of injuries for workers performing repetitive lifting tasks. Appropriate standards for their evaluation do not exist, but their definition would promote large-scale adoption in workplaces. This paper presents relevant standards and evaluation metrics as applied to similar devices and discusses their applicability to back-support exoskeletons, with the final goal to propose a reference methodology.**

***Keywords*—exoskeletons, back-support, evaluation, standards.**

I. INTRODUCTION

In industrial manufacturing processes, various manual work tasks are still difficult to automate due to their complexity. These activities can significantly load workers musculoskeletal system, causing injuries and occupational diseases. Among them, musculoskeletal disorders (MSDs) represent the 68% of the total and are the main cause of absence from work [1]. High risk of developing MSDs is associated with heavy physical work, twisting and bending, frequent lifting, awkward postures and manual handling activities [2] due to the overloading of body joints. Seeing more in detail MSD cases, back and shoulders are the body areas more affected, with a 39% and 27% respectively [1]. Spinal and abdominal muscles, associated with repetitive and prolonged trunk flexion, generate compression on lumbar discs.

In order to assist workers to prevent these problems, wearable technologies, as exoskeletons, have been proposed in recent years [3]. Important technical challenges and a lack of specific safety standards delay their large-scale use in workplaces [3]. To date, international safety standards and legislations for industrial application of exoskeletons do not yet exist. Some progress has been made recently by the industrial community. In October 2017, a new standard was published by the Japanese Standards Association [4] that prescribe safety, performance and labelling criteria of wearable robots for lumbar support. Other problems deal with the subjects' perception of exoskeleton comfort and assistance. From the user point of view, the most critical issues are:

- freedom of movements without any constraints or undesirable interaction forces between the skin and the mechanisms;
- intuitive use (related to control aspects, specifically for the task);
- comfort in use;
- ease of donning and doffing.

Passive exoskeletons are suited for very specific tasks and provide moderate amounts of assistance by means of elastic elements only. Active ones employ actuators that can modulate their assistance during operation, adapting to a wider range of tasks and users. Moreover, greater levels of assistance are possible with adequate powerful motors. However, several open challenges specifically related to active exoskeletons have to be considered. Actuators for each active joint and power supply increase the total system weight, risk and cost, and complicate the design and control process. Moreover, different sensors and signal processing are often required to detect the user's movement intention, resulting in additional control problems. From the user's point of view, it has to be considered workers' inexperience with the technology, that may introduce perceived unsafety.

To solve these practical and technical issues it could be useful to involve the end users (the workers who will use it and the employers who will buy) in the exoskeleton design, to remain more focused on the objectives and to propose solutions to practical questions. Moreover, in order to provide users with appropriate and honest information about exoskeleton effectiveness, a complete evaluation of the system is mandatory.

II. BACK-SUPPORT EXOSKELETON

An active exoskeleton specifically designed to assist workers while performing repetitive lifting tasks has been developed as part of the Robo-Mate European research consortium [5]. Its aim is to reduce lumbar load and, as a consequence, the risk of developing MSDs, by generating appropriate forces on the user. The prototype is shown in Fig.1. The physical attachments consist of shoulder straps, a waist band and custom Velcro-bands used to fix the leg exoskeleton links to the thighs. Two electrical torque-controlled actuators, one on each side, are placed at the hip joint, approximately aligned with its flexion-extension axis. Reference torques for actuators are generated to allow freedom of movement to the users or to assist the movement addressing users' requirements. Different control strategies to modulate assistance are proposed in [6].

III. SYSTEM EVALUATION

The evaluation of a particular exoskeleton depends on the specific task and the main objectives it has been designed for. While for walking tasks the evaluation procedure takes as a reference clinical gait analysis standards [7], for lifting

Fig. 1: Side view of the back-support exoskeleton prototype

tasks a clear standard evaluation does not exist. As regards the objectives of the system, it is very important to identify, along with the main objective, all the other requirements the device has to fulfil. Considering back exoskeletons, for which the main objective is to reduce the lumbar compression, additional important goals could be:

1) increase the endurance time of executing the task, i.e. decrease the overall fatigue perceived by the user;
2) not overload other muscles or joints, by focusing only on reducing lumbar compression.

Starting from the literature of exoskeletons evaluation, both passive and active, common methodologies and metrics have to be identified to define a standard. In the following, the most relevant metrics are analysed in order to present their advantages and disadvantages with the final goal to propose a reference methodology to evaluate the effectiveness of a back-support exoskeleton. To this end, the PLAD passive exoskeleton (Personal Lift Assistive Device) [8], specifically designed for lifting task, will be taken as a reference, since many evaluation studies have already been conducted.

A. EMG measurements

Electromyography (EMG) signals measure the muscles activity. Evaluating muscles activity provides an indirect evidence of an exoskeleton effectiveness, as EMG signals are direct measures of muscular efforts. As regards the biomechanics of lifting task, spinal muscles, responsible for back extension, are the ones that generate most of the lumbar compressive loads, which the exoskeleton aims to reduce [9]. Abdominal muscles are activated to stabilise the spine and, as a consequence, they also contribute to spinal compression [10]. Studying muscles activity to obtain an estimation of muscles fatigue is also important if the exoskeleton is interested also in improving the endurance of the task. In [11], the authors underline two major phenomena often noticeable in the EMG signals, when investigating the reduction of general and local muscle fatigue:

1) the median power frequency decreases;
2) the root mean square amplitude increases [11].

In the literature, analysis of EMG activity has been frequently employed in the exoskeleton evaluation domain. In the review [3], for 13 of the 26 different industrial exoskeletons, evaluations of the physical load reduction were performed, analysing their effect on muscles activation. For exoskeletons specially designed for walking task EMG electrodes are placed symmetrically on the lower limbs of the subjects. In [12] the effects of an active exoskeleton on muscles activity was discussed taking into account the differences between the average and the peak of the EMG activity.

For exoskeletons that have to assist lifting, the electrodes are located to record the spinal and abdominal muscles, that were proved to be responsible for lumbar compression [9] [10]. A research conducted on a passive exoskeleton [13], shows that the exoskeleton use did not change abdominal muscle activation, but decreased back and leg extensor muscle activity. Leg muscle activity reduction is considered as an additional advantage of the exoskeleton. In experiments conducted to evaluate PLAD exoskeleton [14], EMG erector spinal activity has shown a significant reduction when wearing it.

In a laboratory setting, EMG analysis is a standard metrics to evaluate exoskeletons effectiveness on muscle activity. A possible guideline regarding electrodes placement and signals post-processing may be the European project ”Surface EMG for non-invasive assessment of muscles (SENIAM)”. It is important to underline that EMG signals are associated with some evaluation problems due to their non-stationary characteristics and subject dependency. Moreover, many factors affect EMG signals acquisition such as noise due to other biological signals and the environment, motion artefacts, electrode shift, and muscles fatigue.

For lifting task execution, a reduction of spinal [9] and abdominal [10] muscles EMG can be significantly associated to a reduction in the lumbar compressive loads. As a consequence, the evaluation of an exoskeleton for this specific task has to include the analysis of these muscles activity. Frequency information of EMG signals has to be investigated in order to evaluate fatigue. An observed decrease in the median power frequency and an increase in the root mean square amplitude are considered as an objective measure of the fatiguing process. Indications about the endurance of the task can be retrieved from fatigue level of all active muscles. Furthermore, secondary muscles that are involved in the execution of the task or affected by the exoskeleton employment have to be studied to provide a complete characterisation of the device.

B. Biomechanical measurements

The analysis of human biomechanical data includes kinematic and kinetic measurements. Trajectories and angles are recorded using 3D motion capture system or sensors as rotary potentiometers and encoders. Joints moments are estimated with inverse dynamic methods. Using simplified human models, compression forces may be derived from muscle forces.

Kinematic quantities may be used to identify the difference in the movement path and range of motion when wearing an exoskeleton, underlining the constraints introduced for the task execution. Joints moments are used to evaluate the effectiveness of the system in evaluating whether the load on the joints of interest is reduced while using it or not. Other joints load is studied if an evaluation is needed on how the exoskeleton affects the whole body.

In exoskeleton evaluation literature, biomechanical data recording is frequent for walking, lifting, bending and load carrying tasks [3]. Experiments conducted on the quasi-passive MIT exoskeleton for walking [15] was done recording joints trajectories and moments. Differences in results with respect to the walking condition without the exoskeleton were explained by authors as a consequence of the increased mass attached to the human leg, which limited maximum hip flexion. The research conducted on an active exoskeleton for walking [12], compared kinematic and kinetics results across different conditions i.e. with and without the exoskeleton and different control strategies. Walking profiles at the hip, knee, and ankle were found to be largely similar, while internal joint moments were slightly lower in conditions with the exoskeleton, proving the exoskeleton effectiveness in assisting walking.

Biomechanics evaluation for PLAD was conducted in [14]. In terms of moments, a reduction of L4/L5 lumbar discs moments was observed about all the three axes. With a mathematical proof of principle it was attested that the PLAD reduces also compressive and shear forces at the L4/L5 [16]. Another example of biomechanical analysis for an exoskeleton designed for lifting is provided in [13] for trunk flexion angle.

The specific goal of biomechanics research is to analyse the mechanics of the musculoskeletal system during the execution of tasks. In clinical and experimental settings, motion capture systems (optical-based and inertial-based) have been widely used in synergy with musculoskeletal models for measuring 3D kinematics. Traditionally, the musculoskeletal system has been modelled as a multi-link system with individualised body segment parameters. This simplification affects precise joints kinematics and thus the estimated internal moments. Inverse dynamic solutions are mainly influenced by musculoskeletal models but also by input inaccuracies as errors in body segment parameters, ground reaction forces (GRF) measurements, joints centre of rotation locations and segment angle calculations (the latter two mainly due to skin movement artefacts). Knowledge of accurate kinematics of human joints is essential for the understanding of their function. As a consequence, their study is fundamental for the iterative process of exoskeleton design and evaluation. Internal moments, on the other hand, provides information about joints load in the physiological execution of a task and with exoskeleton assistance.

C. Metabolic measurements

Metabolic cost can be derived from oxygen consumption and carbon dioxide production measured by a metabolic analysis system [17].

Studying the metabolic cost of a task provides information about the total energy demand asked to the user [8], which is an indication of the total muscles activity. In a repetitive task, energy consumption has a direct consequence on the endurance of the work [11].

In the literature, metabolic study is a standard evaluation method for gait analysis and, as a consequence, it has been used to examine the performance of exoskeletons designed specifically for walking assistance. As regards passive exoskeletons for walking, a research conducted on quasi-passive MIT exoskeleton [18] shows the increase of the metabolic cost by 10% compared to the condition without the exoskeleton. The researcher proposed the added mass and kinematic constraints imposed on the wearer as the main causes. Correspondingly, in [19] another device was evaluated and the metabolic results reveal significantly higher values of oxygen consumptions using the exoskeleton. It is important to underline that, if the goal of the exoskeleton is to reduce user effort in performing tasks, reducing or, at least, not increasing the metabolic cost represents a key aspect. In [12] different results were obtained by comparing two different control strategies for an active exoskeleton for walking. Both control strategies reveal metabolic cost benefits across subjects.

On the other hand, evaluation of exoskeleton for lifting task from the metabolic cost point of view is not a standard, but may be significant as it was demonstrated that carrying load require a metabolic expenditure [20]. In [8] results show that oxygen consumption is not altered when wearing PLAD exoskeleton, i.e. the total energy demand for the task is unchanged. This outcome shows the possibility that the muscles not assisted by PLAD increase their work when wearing it.

A number of inexpensive, compact systems for measuring metabolic parameters are commercially available [21]. A comparative analysis of metabolic power between the lifting task perform with and without the exoskeleton can be relevant as to whether there is any energetic advantage in the assistance. By subtracting these two quantities, the net metabolic cost can be calculated, indicating the metabolic expenditure associated with using of the exoskeleton.

D. Subjects' preferences measurements

To evaluate subjects' preferences different questions can be verbally asked participants, concerning different aspects of the assistance. First of all, general impressions about comfort, intuitive use and perceived compression are requested, that allowed subjects to provide subjective general feedback. This outputs may be actually relevant to guide exoskeleton re-designed, taking into account users' feedback. Then, benefits in the execution of the task are asked, using the unpowered condition as a reference, as in [14]. In this context, a comparison between different control strategies [12] or different system conditions may be investigated. Subjects' preferences and aspects that they like or dislike about the different conditions may be also demanded.

IV. DISCUSSION

The objective of this paper is to propose standards for the evaluation of active back-support exoskeletons. Indeed, a reference methodology definition, that does not yet exist, would promote large-scale adoption of exoskeletons in workplaces. Relevant standards and evaluation metrics as applied for the evaluation of similar exoskeletons have been analysed in order to present their advantages and disadvantages and discusses their applicability to back-support exoskeletons.

Starting from the consideration mentioned above, we propose an evaluation methodology that combines together the significant metrics analysed in the previous section. In our opinion a meaningful evaluation of a back-support exoskeleton must include: EMG analysis, kinematics recording via a motion capture system to calculate angles, moments and lumbar compression, metabolic cost computation, and a well-defined questionnaire. As regards EMG measurements, the activity of spinal and abdominal muscles has to be evaluated, since for lifting task this reduction is associated with a reduction in the lumbar compressive loads. As explained above, our view is that secondary effects information has to be included in a complete evaluation methodology as well. It is therefore meaningful to examine EMG activity of all the other muscles that can be affected by the exoskeleton employment. When information about the endurance of the task with the exoskeleton is required as an important factor for its effectiveness, fatigue has to be evaluated. In this case, frequency information of EMG signals is a convenient measure of the fatiguing process. Biomechanics study of the musculoskeletal system provides the kinematics of human joints that we suggest in the design process for a better understanding of human joints function. Internal moments and lumbar compression estimated via inverse dynamics, on the other hand, are significant to evaluate the exoskeleton effectiveness in reducing workers' lumbar load. In cases in which we are interested in highlighting whether any energetic advantage is associated with exoskeleton use, a comparative analysis of metabolic power between the task perform with and without the exoskeleton is relevant. Moreover, it is in our opinion that all the analysis just presented have to be integrated with the end users' personal evaluation. Subjects' general impressions of the provided assistance are recommended to evaluate users' acceptability and to re-design the device to address future users' requirements.

Future works will focus on identifying experimentally reference values to indicate substantial improvements in the proposed evaluation metrics. Significant values can be obtained in laboratory experiments, integrating together all the relevant measurements presented, and used as a reference to compare different exoskeletons effectiveness. Additionally, further similar studies will be conducted in a real work environment. In the work filed, different considerations have to be discussed, since EMG, traditional motion capture and metabolic systems employment are largely unsuitable.

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