Towards methodology and metrics for assessing lumbar exoskeletons in industrial applications

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***Abstract* — Lumbar exoskeletons have the potential to reduce work-related musculoskeletal disorders and injuries in workers performing repetitive manual handling tasks. For a wide adoption of exoskeletons in industrial workplaces the definition of methodologies and metrics is crucial. In this paper, we present an overview of evaluation methods and metrics from state-of-the-art studies and propose a set of suitable evaluation tests and metrics to evaluate lumbar exoskeletons.**

Keywords* — *Exoskeletons, benchmarking, industry 4.0, metrics

I. INTRODUCTION

Work-related musculoskeletal disorders (WMSDs) in the low-back still affect a considerable number of workers in modern factories. Indeed, although automation is widespread in industrial workplaces, workers are still required to perform physically demanding tasks, such as manual handling of heavy goods in manufacturing and logistics [1]. In this case, workers are typically exposed to physical risks for prolonged periods within a shift of repetitive lifting, trunk bending and twisting [2]. Consequently, occurrence prevention and incidence reduction of low-back WMSDs (e.g. low-back pain) have been widely investigated [3]–[6]. Different strategies have shown positive effects to reduce low-back pain in manual handling tasks, such as training of workers about the correct techniques to handle heavy loads [5], fostering the use of weight-relief mechanical devices [2] or wearable such as lumbar supports [7] and insoles [8] or optimizing the workplace by adopting job rotations [9]. Despite the huge effort of majority of factories in the implementation of these measures towards the improvement of workplaces, the incidence of low-back pain is still considerably high, as it affects a considerable percentage of the workforce in western countries [1], [10], [11].

In the last decade, many researchers have been considering exoskeletons as a new technological tool for tackling the occurrence of WMSDs by assisting workers in performing repetitive and even strenuous jobs [12]. An exoskeleton is a wearable device that augments, restores or empowers human movement functions and performance. Exoskeletons can be categorized into passive and active devices, depending on whether they have powered actuators or not. Despite the huge potential of this technology, a consensus on the methods and metrics for the evaluation of exoskeletons for worker assistance has not been reached yet and it would be important to compare different prototypes and foster the diffusion of this technology in manufacturing plants.

In this paper, we present an overview of the methodologies used in previous experiments carried out with healthy participants performing repetitive lifting tasks with an active lower-limb exoskeleton [13]–[16]. Moreover, we propose a set of suitable metrics that can be used to evaluate and compare lumbar exoskeletons.

The goal of this work is to foster the discussion on the need for common evaluation methodologies and metrics that can serve as guidelines for lumbar industrial exoskeletons evaluation.

II. STATE OF ART

Table I and Table II provide an overview of the methods and metrics from studies carried out with exoskeletons assisting the load lifting task. Reported examples include studies with active [13], [17], [18] and passive [19], [20] exoskeletons.

III. PROPOSED METHOD AND METRICS

A. Experimental conditions

In state-of-the-art experiments, the lifting trials have been designed to replicate a scenario of repetitive load lifting, similar to the one presented in [13]. In our previous studies, we used the APO, a powered robotic hip exoskeleton, designed to assist the hip flexion-extension movement [13]–[16]. Recruited subjects were asked to repetitively perform lifting and lowering of a 5-kg box between two locations at different heights.

A prototypical experiment with an exoskeleton for lumbar support is composed of three trials, each corresponding to a different tested condition (randomized across subjects):

- NO EXO: subjects are asked to lift a pre-defined load without wearing the exoskeleton;

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TABLE I. OVERVIEW OF EXPERIMENTAL DESIGNS FOR A SAMPLE OF REPRESENTATIVE STUDIES

Device	***Task type***	***Tested conditions***	***Weight***	***Number of movements per condition (cadence)***	***Number of subjects***
APO [13]	Symmetric freestyle	EXO TM, EXO AM (randomized)	10 kg	30 (5 lifts/min)	5 (male)
Robo-Mate [17]	not available	NO EXO (2 times), EXO (2 times) (randomized)	7.5, 15 kg	5 (cadence not available)	12 (male)
HAL for care support [18]	Symmetric freestyle	NO EXO, EXO	17.05 kg	40 (4 lifts/min)	14 (male)
PLAD-1 [19]	Asymmetric freestyle, stoop, squat	NO EXO, EXO (randomized)	5, 15, 25 kg	54 (cadence not available) (one lift per combination of task type and tested condition)	9 (male)
PLAD-2 [20]	Symmetric freestyle	NO EXO, EXO (randomized) (each condition occurred seven days apart)	Weight not available	540 (6 lifts/min)	10 (male)

- EXO TM: subjects are required to lift the load wearing the exoskeleton, which is controlled to provide null output torque;
- EXO AM: subjects are required to lift the load wearing the exoskeleton which provides an assistive action during the trunk extension phase.

These three conditions are designed to allow the following comparisons:

- EXO TM vs NO EXO: to evaluate the effect of wearing the exoskeleton on the user;
- EXO AM vs NO EXO: to evaluate the overall effect of the exoskeleton and the assistive action;
- EXO AM vs EXO TM: it can be useful to evaluate only the effect of the assistance, without taking into consideration the potential loading effect of the exoskeleton.

B. Evaluation metrics

Five categories of metrics have been found useful to evaluate the exoskeleton in the experimental application: human biomechanics, electromyography, physiological parameters, exoskeleton-related parameters and subjective questionnaires.

1) Human biomechanics

Movement analysis is commonly done in human biomechanics research and clinical investigation to compute the joints kinematics and dynamics.

The joint kinematics is usually computed by dedicated software that use the 3D reconstruction of markers placed on anatomic landmarks and tracked by cameras. Moreover, joint torques can be computed by inverse dynamics using the ground reaction force measured by force platforms.

The analysis of human biomechanics can provide useful information for evaluating the effect of an exoskeleton on the human body. Indeed, the result of motion analysis can highlight whether the use of the exoskeleton affects the kinematics of the wearer, for example modifying the range of movement (RoM) while performing the task [21]. Additionally, it is also important to quantify whether wearing the exoskeleton has any loading effects on the human posture: indeed, as a consequence of the mass distribution of the exoskeleton, the wearer may put in place compensatory abnormal muscles activations, which can be reflected by kinematics modifications.

The time to perform the task is also an important metric that can be affected by the assistive action of the exoskeleton and it can be measured through the joint angle profiles.

2) Electromyography

Electromyography (EMG) analysis can be used to investigate superficial muscular activity. Regardless of the application, EMG analysis is a common practice in exoskeleton assessment [13], [17], [21]–[24]. Indeed, thanks to the measurement of EMG signals, the effects of using an exoskeleton on specific muscular groups can be investigated. Typically, the expected outcome of this analysis is the reduction of the muscular activity and fatigue in muscle groups which contribute primarily to perform the working task and that are assisted by the exoskeleton (e.g. back muscles in the case of load lifting, such as Lumbar Erector Spinae and Thoracic Erector Spinae) [12]. On the other hand, the EMG analysis can also highlight potential undesired effects on muscle groups that are not assisted by the exoskeleton (e.g. abnormal/increased muscles activity to counteract the mass of the exoskeleton and its distribution, such as Rectus Femoris or Tibialis Anterior) [12].

EMG analysis can be performed in the time or the frequency domain. Time-domain analysis is computed on the raw acquired signals and typically involves the extraction of the signal linear envelope, activation peak, integral, and root mean square. The frequency-domain metrics refer to the analysis of the changes in the frequency content of raw signals, as mean and median frequency of the power spectrum, whose shift towards low frequency is an index of muscle fatigue occurrence [25].

TABLE II. OVERVIEW OF THE METRICS USED IN THE SELECTED STUDIES

Device	***Human biomechanics***	***Electromyography***	***Physiological parameters***	***Exoskeleton data***	***Questionnaires***	***Others***
APO [13]	not available	Lumbar Erector Spinae, Thoracic Erector Spinae, Erector Spinae Iliocostalis, Rectus Femoris, Biceps Femoris (unilaterally)	not available	Hip joint kinematics, hip joint torque, trunk extension time	not available	not available
Robo-Mate [17]	not available	Lumbar Erector Spinae, Rectus Abdominalis, Biceps Femoris (unilaterally)	not available	not available	Borg CR10, Local Perceived Pressure, SUS	Contact pressure at the physical interface
HAL for care support [18]	not available	Lumbar Erector Spinae, Thoracic Erector Spinae, Quadriceps Femoris (bilaterally)	Heart rate	not available	Borg RPE	not available
PLAD-1 [19]	Trunk moments	Lumbar Erector Spinae, Thoracic Erector Spinae, External Obliques, Rectus Abdominalis	not available	not available	Comfort, effectiveness (ad-hoc)	not available
PLAD-2 [20]	not available	Lumbar Erector Spinae, Thoracic Erector Spinae	Heart rate	not available	Borg RPE	Maximum back extensor muscles strength, endurance time

3) *Physiological parameters*

Physiological parameters, such as heart rate (HR), breath frequency, skin temperature and galvanic skin response, are indicators of global fatigue. Differently from EMG, these parameters reflect systemic changes that arise in the human body and are controlled by the autonomic nervous system. For the assessment of an exoskeleton, they can highlight if its use positively or negatively influences wearer's physiological responses, namely if it reduces or increases the overall fatigue status. For example, the increase of the HR indicates an increased demand for body oxygen, thus giving information on the physical effort done by users. Similarly, the increase of the skin conductance level (i.e. the tonic component of galvanic skin response) also can reflect an increase of the physical exertion [26].

4) *Exoskeleton-related parameters*

Sensors integrated in the exoskeleton can provide data related to the kinematics of the exoskeleton joints and assistance. Kinematics of the exoskeleton can be compared with the kinematics obtained from motion capture, to compute differences between them and possible relative movements between the exoskeleton and the human body, leading to misalignments that can cause undesired forces and overloads to human articulations [27].

Data related to the assistance delivered by the exoskeleton, such as torque and power, can give additional relevant information, such as the similarity between exoskeleton torque and human joint moments, or the ratio between positive and negative mechanical power. This latter information can be very useful in understanding if the designed assistive action of the exoskeleton is compatible with human biomechanics.

5) *Subjective questionnaires*

Administering questionnaires can provide information about the subjective perception of the exoskeleton, in terms of comfort, ease of use and effectiveness. They require little time to be carried out and, in most cases, namely when well-validated questionnaires are used, offer reliable results. Typically used questionnaires are the system usability scale (SUS) [28], the NASA-TLX [29], and the Borg scales [30], but also not-standard and ad-hoc surveys can be administered.

C. Performance indices

Based on the evaluation categories presented, in this section we summarized the performance indices that can be considered more relevant for the assessment of lumbar exoskeletons in industrial applications:

- **RoM**: it allows to assess if the use of an exoskeleton would limit the maximum range of movement allowed to the user. Ideally, an exoskeleton should ensure all physiological movements, without hindering them.
- **Time to extend the trunk**: it allows the evaluation of how the use of an exoskeleton can affect the lifting movement in terms of the time needed to lift an object. In other terms, it is related to the speed of the lifting action.
- **Peak value, root mean square and integral of the EMG linear envelope**: they highlight the level of muscles activation. They can be also reported as percentage of the maximum voluntary contraction to allow inter-subject comparison.
- **Mean and median frequency of the EMG spectrum**: the frequency content of the EMG signal can be used to extract information about the level of muscular fatigue in prolonged tasks.
- **HR**: it provides information about the global fatigue experienced by users. Measuring this parameter and its variability can be useful to understand if, for example, simply wearing an exoskeleton increases the global workload.

TABLE III. RESULTS OF EMG ANALYSIS FROM SELECTED STUDIES

Device	*Measured muscles*	*Performance metric*	*Evaluation method*	*Results*
APO [13]	Lumbar Erector Spinae, Thoracic Erector Spinae, Erector Spinae Iliocostalis, Rectus Femoris, Biceps Femoris (unilaterally)	EMG integral	Comparison between TM and AM, with and without holding the load	Lumbar Erector Spinae: -15.9% (with load), -33% (without load) Thoracic Erector Spinae: -6% (with load), -10.1% (without load) Erector Spinae Iliocostalis: -3.6% (with load), -8.9% (without load) Rectus Femoris: +33.7% (with load), +40.1% (without load) Biceps Femoris: -27.4% (with load), +7.1% (without load)
Robo-Mate [17]	Lumbar Erector Spinae, Rectus Abdominalis, Biceps Femoris (unilaterally)	EMG root mean square	Comparison between without and with the exoskeleton (with different weights)	Lumbar Erector Spinae: -12% (7.5 kg), -15% (15 kg) Biceps Femoris: -5% (7.5 kg), +5% (15 kg)
HAL for care support [18]	Lumbar Erector Spinae[a], Thoracic Erector Spinae, Quadriceps Femoris (bilaterally)	EMG root mean square EMG integral	Comparison between without and with the exoskeleton	Lumbar Erector Spinae: -4.5% (right) Thoracic Erector Spinae: -13% (right), -10% (left) Quadriceps Femoris: +18.7% (right), +13.4% (left)
HAL for care support [18]	Lumbar Erector Spinae[a], Thoracic Erector Spinae, Quadriceps Femoris (bilaterally)	EMG integral	Comparison between without and with the exoskeleton	Lumbar Erector Spinae: -14% (right) Thoracic Erector Spinae: -20.8% (right), -18.3% (left) Quadriceps Femoris: +6.5% (right), -11.3% (left)
PLAD-1 [19]	Lumbar Erector Spinae, Thoracic Erector Spinae, External Obliques, Rectus Abdominalis	EMG integral	Comparison between without and with the exoskeleton	Lumbar Erector Spinae: -23.9% Thoracic Erector Spinae: -24.4% External Obliques: -34.9%
PLAD-2 [20]	Lumbar Erector Spinae, Thoracic Erector Spinae	EMG root mean square	Comparison of metric increase between without and with the exoskeleton	Lumbar Erector Spinae: +88% (without exoskeleton), +26% (with exoskeleton) Thoracic Erector Spinae: +104% (without exoskeleton), +22% (with exoskeleton)

[a] Left Erector Spinae was not collected during HAL usage and results are not reported.

- **Positive/negative power**: it allows to evaluate if the mechanical power delivered to the human joints is well designed, in terms, for example, of being physiologically compatible. Positive mechanical power means that the assistive torque is fully transferred to the user, while negative power means that part of the power is exerted against the user.

IV. DISCUSSION

The five evaluation categories proposed in this work are a first attempt to classify and summarize different evaluation metrics feasible for the assessment of a lumbar exoskeleton for industrial application. The proposed evaluation metrics aimed at gathering enough information, both objective and subjective, to make an effective assessment of the exoskeleton in assisting subjects during the load lifting activity. Well-controlled and structured laboratory experiments are the first and unavoidable step to evaluate the exoskeleton in this application. The use of a standard methodology is also useful to compare the features of different exoskeletons for worker assistance. However, as shown by selected studies, there are neither common methodologies nor uniform metrics to evaluate lumbar exoskeletons for lifting. Indeed, on one hand, as it regards the methods used to evaluate lumbar exoskeletons, there is no uniformity in the weight of the load lifted or the number and frequency of the lifting actions. Moreover, from the point of view of the used evaluation metrics, only electromyography seems to be the metric shared by all studies. However, monitored muscles, evaluation methods and performance metrics used change among studies, as shown in Table III. Therefore, even in the case of EMG analysis, the lack of standardization makes it difficult to compare the performance of different exoskeletons used as load lifting assist devices. Finally, it is worth to note that any of the selected studies used all the evaluation metrics proposed in this work.

V. CONCLUSIONS

Although industrial exoskeletons are one of the most emerging technologies to reduce the risk of developing WMSDs among manual handling workers, there is still the problem of benchmarking their efficacy. In this paper we proposed a list of possible metrics to perform the evaluation of an exoskeleton used to assist the load lifting task that can be comprehensive. The proposed work is not intended as an exhaustive list of methodology and metrics but aimed at fostering the discussion about the problem of lacking methodology for industrial exoskeletons evaluation.

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