Towards Design Guidelines for Physical Interfaces on Industrial Exoskeletons: Overview on Evaluation Metrics

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Abstract— **Physical interfaces with the body are one of the key enabling component to promote user acceptance, comfort and force transmission efficiency. A structured design workflow is needed for any application-driven product, such as industrial exoskeleton. In this paper, we review objective and subjective evaluation metrics that can be applied to physical interfaces. These indexes are analyzed to create an ordered list of requirements to guide future body attachment design. Pressure magnitude, duration, distribution, direction and time to don and doff are relevant objective indexes related to interfaces. While pain, comfort and ease of operation are subjective indexes. We propose that collecting a suitable set of metrics will lay the foundation for an effective design guideline for industrial exoskeletons.**

I. INTRODUCTION

Force augmenting exoskeletons are useful device in factories. There is growing evidence of their effectiveness on lowering risk of work-related musculoskeletal disorders (WMSDs) and increasing comfort of operation in certain physically demanding tasks characterized by poor ergonomics (e.g. manual material handling, overhead assembly) [1]. Therefore, several companies in conjuction with research institutes put their efforts to develop exoskeletons. There are some models commercially available such as Model Y (Atoun, Nara City, Japan), HAL for Labour Support (Cyberdyne, Tsukuba, Japan), Ekso Works (Ekso Bionics, Richmond, CA, U.S.A.) and Laevo Back Support (Laevo, Delft, The Netherlands) [2].

For widespread adoption of exoskeletons in industrial environments, several aspects need to be optimized. Here we focus on exoskeleton's physical interfaces. With physical interfaces we refer to braces, cuffs or any other attachment to the wearer's boyd. An interface is responsible for the transmission of assistive forces from the actuators and the overall wearing comfort. In [3], up to 50% of exoskeleton power was reportedly lost due to the physical interface dynamics, dissipating the force in shear stresses, compression and misalignment over the body. Moreover, this inefficiency generates discomfort to the end user, compromising acceptance of the device. Therefore, design criteria for exoskeleton interfaces are desiderable. However, listing mechanical and comfort requirements for an exoskeleton interface is challenging. Will the mechanical requirements for an optimal force transmission agree with user comfort? What are the key factors affecting comfort? What metrics should be used for subjective evaluations? This paper is divided in: state of the art on attachment design and evaluation methodologies, list of objective and subjective evaluation metrics and conclusions.

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II. STATE OF THE ART

A. Design

Interface design for industrial exoskeletons does not typically differ from attachments design for medical exoskeletons, even if the two devices address different users. In fact, people in need of a medical exoskeleton typically have muscular impairments, while industrial exoskeletons are worn by healthy subjects. In the first case, it is important to have it secured to the limb, as the robot applies most of the torque that a limb needs to be moved. In the latter case, devices have to deal with healthy muscles that vary shape and stiffness during movements. In fact [4] shows evidence that pressure exerted on tissues varies with different movements, i.e. the back thigh plate recorded up to 9.5 N single-point pressure during squat and leading leg lunge movements. Therefore, a structured set of requirements derived from the indexes that are used to evaluate physical interfaces is desiderable. Indeed technological advancements and research were mainly focused on exoskeleton actuation and mechanical design, with comparatively few advancements in attachments [4]. Having a priority ordered list of requirements based on metrics will help further technical advancements of the interfaces and ultimately promote the adoption of industrial exoskeletons.

B. Evaluation Methodologies

Interfaces to the human body, as a part of the exoskeleton itself, are tested and assessed with the whole device. Static (donning and doffing) and dynamic tests are run. In [4] and [5] wearing comfort is assessed through pressure acquisition at the interfaces with the body. To record pressures, in [4], a custom sensing system is used at every attachment point. In [5], an external commercial pressure mat is used. [6] presents a viable methodology to acquire crucial information on mutual influence of kinematic constraints, reaction forces, attachment pressure and subjective exoskeleton performances. Pressure on the limb is obtained from pressure fed to air cushions mounted on the inside of the attachments. Evaluation of exoskeletons also needs to take into account comfort related to wearability, that is another challenging task. In [7], the authors present a framework to evaluate lower limb exoskeleton, focusing on wearing comfort and interfaces indexes, i.e. ease of donning/doffing, aestethic design or attachment types (straps or velcro bands).

III. METRICS

Two types of indexes are commonly used to evaluate exoskeleton performances: objective and subjective indexes. The former refer to values that are measured by sensors, the most used are Circumferential and Single-Point Pressure Magnitude, Distribution, Duration, Direction and time to don/doff the attachment. The latter refers to values that are obtained by mean of interviews and convey information about perceived sensation such as Perceived Pain, Pressure Detection Threshold (PDT) and Pressure Tolerance Threshold (PTT), Perceived Comfort, Mental Load, Physical Load and Ease of Use.

As stated before, pressure magnitude is an objective index for interface comfort and it is measured by resistive or capacitive sensors (e.g. Force-Sensing Resistor). However, as found in [4], muscular movements alter the calibrated zero value. Sensors are placed between the skin and the interface itself. Pressure values can be used as a first objective index to guide through design. Although it is not clear what is the limit, 32 mmHg (4.3 kPa) is the blocking pressure for skin capillary flow. However superficial pressure during sitting is well above that threshold (22 kPa) suggesting a compensatory effect [8]. There is distinction between single-point and circumferential pressure. The first is exerted by a force applied on a small area of tissue, the latter is exerted around the whole circumference of a limb. Thresholds over which tissue damages occur are higher for single-point pressure in comparison with circumferential due to limb compression blocking blood flow [8]. Direction, distribution and duration of pression are objective indexes. Distribution and direction are important for both comfort and force transmission. Wrong direction leads to shear stresses and interface movements. Wrong distribution could lead to dissipation of forces in soft tissues [8]. Duration of pression is related to safety (along with pression magnitude) and comfort, since even prolonged low pressures applied to the body are harmful as the body adapts to pain levels. Intermittent pressures at low frequencies (e.g. 0.3 Hz) become quickly unbearable due to accumulation of sensory stimuli (Temporal Summation of Pain) [8]. Finally, another objective metric to assess interfaces is the time of donning and doffing [7].

Subjective indexes are mostly related to perceived wearing comfort. Fabric pattern, breathability or cuff ergonomics are among key factors that enhance or decrease user acceptance of the whole device. Subjective indexes are obtained by mean of structured interviews. We can divide these indexes in usability, pain, and comfort. Usability index quantifies how the system is natural and easy to use. Perceived ease to don and doff the attachments can be evaluated with the System Usability Scale [5]. Since industrial exoskeletons should improve ergonomics of different working tasks, it is central that these devices do not hinder workers in their routine. An indication on how comfortable interfaces are could be alteration of the ability to fulfill a certain task. Nasa Task Load Index (TLX) is used in [6] to quantify how pressure on limbs alters the perception of ease to accomplish a determined movement. In addition, it is proven that a preferred interval of attachment pressure exist, in which users scored higher values in TLX metric [6]. Nevertheless, as the data was collected for an arm exoskeleton, it is not clear whether the findings can be extended to a full or lower body wearable device. Pain and discomfort can be evaluated through Visual Analougue Scale (VAS) metric, thus estimating PDT and PTT for each interface and user.

IV. CONCLUSION

In this overview, we briefly present the state of the art metrics to evaluate performances of attachments for industrial exoskeletons. There is evidence that these devices can lower risk of occupational diseases [1] by physically assisting the worker in different tasks. Exoskeleton mechanical design and actuation were object of technical and technological advancements, however this did not happen for physical interfaces [4]. Evaluation metric are divided into objective and subjective indexes, used to quantify operational capabilities of interfaces. Since a viable ordered guideline for attachments design has not been proposed yet, we can analyze the indexes used for attachment evaluation to extract features to produce a guideline for design. Future works will focus on experimental evaluation of how attachments dimensions, positions, stiffness and materials affect objective and subjective indexes. This will translate objective metrics and feedback from users into design guidelines to improve dynamic and static interaction between human body and exoskeletons, increasing attachments comfort, easy of use, force transmission efficiency and ultimately promoting exoskeletons adoption.

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