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1. Introduction

Work-related musculoskeletal disorders (WMSDs) are the first cause of occupational diseases in developed countries and represent a major health issue and an important cost for companies (Parent-Thirion *et al.* 2012). WMSDs develop when biomechanical demands at work repeatedly exceed the worker's physical capacity (*e.g.*, extreme postures, high efforts). Overhead work has been identified as a major risk factor for shoulder WMSDs (Grieve and Dickerson 2008). Even without external load or force exertion, supporting the arms' weight imposes prolonged stress on shoulder muscles. Yet overhead work remains very common on assembly lines, especially in the automotive and aerospace industries. One solution to physically relieve workers while keeping them in control of the task execution is to assist them with an exoskeleton (De Looze *et al.* 2016).
Recently, several industrial prototypes providing arm support during overhead tasks have been developed and tested, and some are already commercialized (Bornmann, *et al.* 2016; Butler and Wisner 2017; Gillette and Stephenson 2017; Spada *et al.* 2017; Huysamen *et al.* 2018; Kim *et al.* 2018; Otten, *et al*. 2018; Theurel *et al.* 2018; Van Engelhoven *et al.* 2018). The majority of studies on those exoskeletons showed promising results, reporting reduction in shoulder muscle activity and/or increase in endurance and task productivity. A decrease in physical workload of the targeted limb and/or increased productivity are, however, not sufficient to demonstrate the benefit of an exoskeleton. Several other factors may affect the system's effectiveness. Exoskeleton-induced load transfer and movement modification or restriction may increase biomechanical strain elsewhere in the body (Spada *et al.* 2017; Kim *et al.* 2018; Otten, *et al*. 2018; Theurel *et al.* 2018). In addition, even when a beneficial biomechanical effect is proven, users may perceive otherwise and remain dissatisfied with the system (Kim *et al.* 2018). In this work, we present an exhaustive assessment of the benefit provided by PAEXO, a novel passive exoskeleton for overhead work, and describe on-going field testing.

2. Methods

2.1 Evaluation criteria

In our view, a thorough evaluation should include objective performance measures of local effects and global effects on the user's posture, movement and effort, as well as subjective evaluations of the user's perception and acceptance of the system. We therefore propose the following assessment criteria:

- Impacted limb: Using the exoskeleton should physically relieve the joint or limb it is designed to support.
- Side effects: Using the exoskeleton should not increase physical strain on other body parts.
- Workload: Using the exoskeleton should reduce the global physical and cognitive workload.
- Task performance: The exoskeleton should not degrade task performance or productivity.
- Movement strategy: Potential modifications in users' movements due to the exoskeleton should be investigated to evaluate their consequences.
- Acceptance: Users should feel better, physically and mentally, when using the exoskeleton.

2.2 Exoskeleton

The exoskeleton evaluated in this work is PAEXO developed by Ottobock SE & Co. KGaA together with Volkswagen AG commercialized (Bornmann, *et al.* 2016). PAEXO is a lightweight (1.8 kg) passive exoskeleton that provides a support torque to the user's arms, by transferring an adjustable portion of the arm weight to a hip belt via a passive actuator (Fig. 1).

Figure 1: Description of the PAEXO exoskeleton.

2.3 Lab experiment

Twelve healthy college students performed an overhead pointing task with a portable tool, with and without wearing PAEXO (Fig. 2). The participants' physical and physiological state was monitored with whole-body inertial motion capture (Xsens Awinda system), ground reaction force (Kistler force plates), EMG on shoulder and back muscles (right anterior deltoid and right erector spinae longissimus), oxygen consumption, and heart rate. The tool motion was recorded with optical motion capture

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to evaluate task completion time. The perceived workload was assessed with the NASA Task Load Index. Following the experiment, participants answered a questionnaire and a semi-directed interview was conducted to evaluate technology acceptance.

2.4 Field testing

Following validation with the lab study described above, PAEXO was tested with industrial workers in an automotive assembly factory. Four workers wore PAEXO during 20 consecutive workdays. Data were collected for 15 minutes at the beginning and end of each shift, during one week before starting using PAEXO (baseline), and during the first and last week of use. A simpler set of sensors was used to comply with the work requirements. Movements of workers were recorded with a regular camera, and body pose will be extracted using an image-processing library. Heart rate was also recorded during their shift. At the end of the shift, workers answered a technology acceptance questionnaire.

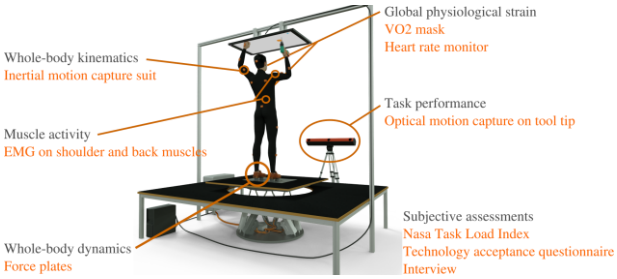

Figure 2: Experimental set-up and sensors used to evaluate the effects of PAEXO in a lab study.

3. Results and discussion

Comparison of the two conditions in the lab study revealed that muscle activation of anterior deltoid, oxygen consumption and heart rate were significantly reduced when using the exoskeleton, respectively by 55%, 33% and 19%. These results suggest that PAEXO efficiently reduces physical strain and fatigue. Conversely, task performance –assessed by movement duration–, activation of erector spinae and center of pressure movements remained unaffected. Hence PAEXO has no negative side effects neither on the user nor on productivity. Importantly, NASA-TLX scores indicate that the reduction in workload observed with objective measurements was perceived as such by participants (21 % reduction in perceived workload with PAEXO). A modification of the arm movement was observed, with the arm being more abducted when using PAEXO. This modified posture however seems to come from a free choice of participants related to not having to sustain the arm weight anymore, rather than being imposed by the exoskeleton. Indeed, participants mentioned that they did not feel constrained in their movements. Eventually, acceptance score was high and participants all said that they would choose to use the exoskeleton again for such a task.

4. Conclusions

Assessment of physical, physiological, and psychological aspects in the lab study suggest that PAEXO is a promising solution to reduce shoulder WMSDs among overhead workers. An inverse dynamics analysis is being conducted to estimate joint torques from whole-body kinematics and ground reaction force to complement the present assessment. Data collected during field-testing with industrial workers are currently analyzed to evaluate the impact of PAEXO on real end-users.

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