Sensor-Based Task Ergonomics Feedback for a Passive Low-Back Exoskeleton

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Abstract. Low-back exoskeletons are a wide-spreading technology tackling low-back pain, the leading work-related musculoskeletal disorder in many work sectors. Currently, spring-based (i.e., passive) exoskeletons are the mostly adopted in the industry, being cheaper and generally less complex and more intuitive to use. We introduce a system of interconnected wireless sensing units to provide online ergonomics feedback to the wearer. We integrate the system into our passive low-back exoskeleton and evaluate its usability with healthy volunteers and potential end users. In this way, we provide the exoskeleton with a tool aimed both at monitoring the interaction of the system with the user, providing them with an ergonomics feedback during task execution. The sensor system can also be integrated with a custom-developed Unity3D application which can be used to interface with Augmented- or Virtual-Reality applications with higher potential for improved user feedback, ergonomics training, and offline ergonomics evaluation of the workplace. We believe that providing ergonomics feedback to exoskeleton users in the industrial sector could help further reduce the drastic impact of low-back pain and prevent its onset.

Keywords: Low-back pain · Exoskeleton · Industrial sector · Ergonomics · User feedback · Usability

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1 Introduction

Exoskeletons are among the mostly widespread assistive technologies since the last two decades. Robotic exoskeletons are more and more used for rehabilitation and neuro-rehabilitation. Exoskeletons are also used to provide assistance to disabled or impaired people with daily-life activities. In this context, industrial exoskeletons are an emerging topic [2]. Their aim is to support workers with either tiring or non-ergonomic tasks, preventing or mitigating the impact of low-back pain [5,9]. Indeed, low-back pain and other work-related musculoskeletal disorders are among the most common causes of disability for workers in the field of automotive, logistics, aerospace, and other industrial sectors [20].

Passive exoskeletons are currently the most adopted in the industrial context. While research on active exoskeletons is ongoing, their higher potential is not yet fully exploitable, and comes with higher cost and complexity [15]. Passive exoskeletons are typically actuated by means of springs or elastic elements and thus provide assistance in a repeatable and intuitive way. With this in mind, we designed a system of interconnected Wireless Sensing Units. We opted for the integration of such sensors in a passive low-back exoskeleton. Of course, the same technology could be integrated in active exoskeletons as well. Being wearable, the system could be easily worn as a standalone system, either for ergonomics training or when exoskeleton assistance may be not necessary.

State of the Art. Work-related musculoskeletal disorders (WRMD) are a significant issue that spans many work sectors. Poor ergonomics is well know to cause musculoskeletal disorders. This phenomenon is recently being studied not only in the industrial sector, but also in constructions [18], agriculture [4], clinical laboratories [7], healthcare [8], dental practice [6], surgery [17], and many more. Here, we focus on the industrial sector, in which the dominant WRMD is low-back pain.

Several strategies have been recently proposed to mitigate and prevent low-back pain and ergonomics-related musculoskeletal disorders for workers. Worker feedback and workplace improvements have been suggested to improve task ergonomics with the aim of reducing the spread of low-back pain and other disorders [13]. Participatory ergonomic interventions is often a common and cost-effective strategy. Specifically, ergonomic training by an expert ergonomist was found to be the most common intervention [19]. On the other hand, novel sensor-based assessment and feedback tools are being developed. The ErgoTac [11] is a wearable device that embeds a reduced-complexity biomechanical model aimed at giving online tactile feedback to the wearer. It was recently evaluated in a simulated industrial setting to provide ergonomic postural adjustments [10]. Similarly, the Smart Workwear System [12] is a wearable sensor system that provides haptic feedbacks for ergonomics interventions. The *ErgoTac* requires external inertial sensors (IMU) and ground reaction force measurements. Sensor data is fed to the human biomechanical model that provides online estimates of joint overloading, then used to provide ergonomic feedback. On the other hand, the *Smart Workwear System* is focused on the upper limbs and exploits only postural data and ergonomic-derived thresholds to provide user feedback.

In the literature, there is no record of a sensor-based ergonomic feedback device embedded in an exoskeleton.

Aim of the Work. Our aim is to exploit the higher level of technological readiness of passive exoskeletons and improve their end-user acceptability embedding some *intelligence* in a simple yet effective mechanical design. Specifically, in this work we present a sensor-based system for a passive low-back exoskeleton aimed at providing online feedback on task ergonomics to the wearer. We exploit wireless inertial measurement units with sensor fusion and Unity3D for virtual/augmented-reality-ready kinematic reconstruction and task ergonomics.

2 The Low-Back Exoskeleton

Currently available low-back exoskeletons are designed in order to reduce the stress on the musculoskeletal system, and in particular on the lumbo-sacral (L5-S1) joint. A trade-off among several requirements is often to be solved, with particular attention to output power (i.e., provided assistance), freedom of motion and user ergonomics, and manufacturing cost. As a result, the most widely adopted low-back exoskeletons rely on passive actuation, as discussed above.

Here, we exploit our low-back exoskeleton – shown in Fig. 1-(a). Its design consists of three main elements: the backbone-tracking kinematics, the wearable suit, and the passive actuation system. The goal of the backbone-tracking kinematic structure is to follow the motion of the human spine, and in particular of the second thoracic vertebra (T2), allowing the wearer to move as naturally and unconstrained as possible. In order to achieve this, its elements are obtained from a user-centric optimization process. A subject-specific structure can be designed and manufactured to achieve optimal tracking of the backbone, adapting the exoskeleton to the wearer. The kinematic structure presented in [16] was equipped with a passive actuation system, shown in Fig. 1-(b).

3 Sensor-Based Ergonomics Feedback

The passive exoskeleton for the low-back described above (cf. Fig. 1) has been equipped with a set of wireless Inertial Measurement Units (IMU). Each sensing unit is made of a low-power micro-controller with built-in Wi-Fi connectivity (WeMos D1 Mini), a 9-axis IMU (InvenSense MPU-9250), a buzzer for user feedback, and a 3.7 V Lithium polymer (LiPo) battery. Each Wireless Sensing Unit (WSU) is rigidly attached to each of the four links of the exoskeleton, thus tracking the motion of the wearer. Specifically, we are interested in monitoring position and motion of the two legs, the hips, and the trunk.

Fig. 1. Our low-back exoskeleton featuring the backbone-tracking kinematic structure (a) and passive actuation (b). WSU's are shown with blue arrows.

The WSU's can work in two modalities. In the *stand-alone mode*, each sensing unit is calibrated while the wearer is standing in upright position, and can track user motion with respect to the gravity vector. This means that while the wearer is standing still, the relative angle measured by each WSU is zero. In the *inter-connected mode*, all four WSU's can be connected to a computer and provide data to a custom application developed in Unity3D. In this case, data from all sensors is used for the kinematic reconstruction of the pose of the human wearing the exoskeleton.

In the stand-alone mode, each WSU measures the orientation of its reference body segment. 9-axis IMU data (3-axis accelerometer, 3-axis gyroscope, and 3-axis magnetometer) is sampled at 50 Hz. The internal Digital Motion Processor is then exploited to compute quaternion data online by means of sensor fusion. The unit then compares the computed orientation with a reference value that sets the ergonomics threshold for each task. We set the *safe* range of motion for each monitored joint according to state-of-the-art ergonomics. For load lifting from the ground, for example, we set the threshold of trunk forward bending to 45°. Un-assisted forward trunk bending between 20° and 60° is beyond the acceptability threshold accoring to RULA [14] (RULA score +3), and bending past 60° further increases the risk score (RULA score +4). If the measured orientation overcomes the threshold, the buzzer is used to provide localized feedback to the user. The quaternions of each sensor are also converted to Euler angles for easier visualization of the orientation. Specifically, Euler angles can be streamed

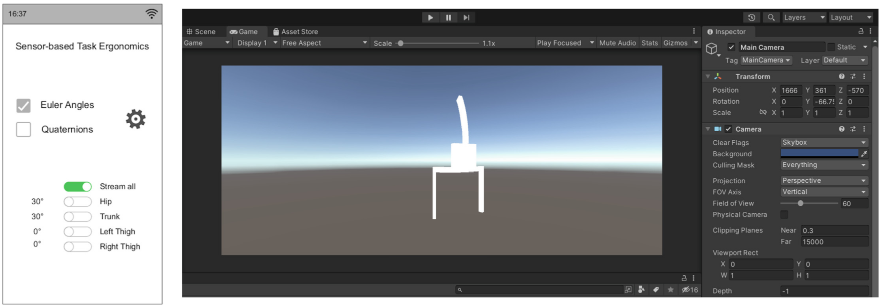

Fig. 2. Smartphone application (left) and Unity3D framework for kinematic reconstruction and task ergonomics (right).

over Wi-Fi either to a computer or to a custom-made smartphone application. This application can be used for online visual feedback, or to save and store data for later analysis. The smartphone application (app) is shown in Fig. 2-(a).

In the inter-connected mode, all the WSU's are connected to a computer and stream quaternion data to a custom-developed Unity3D application. The application – shown in Fig. 2-(b) – is used for kinematic reconstruction from sensor data. This allows to visualize online the motion of the wearer while they are using the exoskeleton. In this way, the task can be monitored considering the overall posture, thus providing a higher-level ergonomics feedback to the user. Unity3D allows to integrate data from the sensing units and could be exploited to deploy augmented/virtual-reality tools for operator training and task ergonomics feedback. Moreover, this data could also be exploited for operator monitoring in the developing context of smart factories.

4 Usability Evaluation

The overall system, that consists of the exoskeleton and the wireless sensing units, has been tested with healthy volunteers. In particular, we recruited 2 healthy subjects and 4 healthy workers of the logistic sector, for a total of 6 healthy male subjects (age: 37 ± 18.10 years; height: 1.79 ± 0.07 m, weight: 76.67 ± 9.43 kg).

To each subject, we submitted the System Usability Scale (SUS) [3] to evaluate the overall usability of the system. The SUS is a commonly used tool that measures the usability of a new technology. It is a ten-question survey that investigates usability, effectiveness, and perceived complexity. It was introduced as a *quick and dirty* survey to have an idea of end-user's acceptability. Each item of the SUS is evaluated with a 5-point Likert scale (i.e., ranging from *Strongly Disagree* to *Strongly Agree*). The global score – computed from the question scores q as shown in Eq. 1 – is obtained in a 0–100 scale. Then, we interpreted the results according to Bangor's guidelines [1]. Specifically, these set a threshold

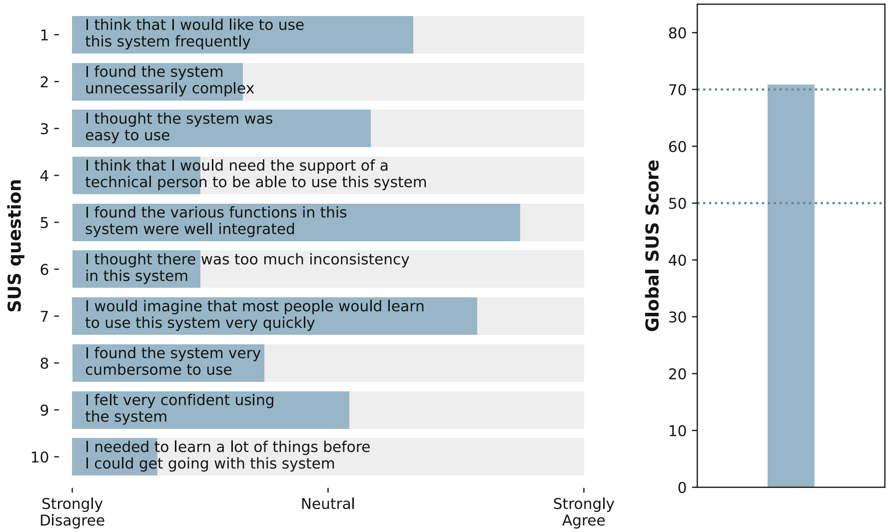

Fig. 3. SUS questionnaire: average score for each question (left panel) and average global SUS score (right panel).

for end-user acceptability at 70/100, also suggesting that scores below 50 should raise major concerns, while scores of 85 or higher indicate exceptional usability.

$$\mathrm{SUS} = 2.5 \cdot \left(\sum_{i=1,3,5,7,9} (q_i - 1) \; + \sum_{j=2,4,6,8,10} (5 - q_j) \right) \tag{1}$$

For our system, the average score of the SUS was found to be 70.83, as shown in Fig. 3. In the plot, we also show the average of each of the 10 questions of the survey.

5 Discussion

We have introduced a sensor-based, task-aware ergonomics feedback for a passive low-back exoskeleton. We described the wireless sensing units that were designed and attached to the exoskeleton in order to monitor the body segments of interest for industrial workers. Each sensor can provide online feedback to the wearer while they are executing tasks that require assistance at the level of the lumbosacral joint. The overall architecture described above also features a smartphone application and a custom-developed Unity3D application for kinematic reconstruction. With this framework, we can achieve both online user feedback for task ergonomics – aimed as an intra-task corrective action – and offline task analysis – to improve long-term ergonomics for the users of the exoskeleton.

We showed the results of a SUS questionnaire submitted to 6 healthy subjects who evaluated rather positively the system. Indeed, the average score of 70.83

is just above the recommended acceptability threshold according to Bangor's interpretation of the SUS. Being a scale to evaluate products to be commercialized, we are rather satisfied of the score obtained by our prototype. Evaluating a prototype with a usability scale allows to involve end users in the design process. User feedback will be exploited to improve the re-design of the device, aiming at higher overall usability for the final device.

5.1 Conclusion

With this work, we have shown and tested a proof-of-concept of a sensor-based system for online task ergonomics. Although few similar systems exist, our is the first to be featured on a (passive) exoskeleton for the industrial sector. A similar framework could be used to measure and investigate several other kinematic and non-kinematic features, including other non-invasive human-monitoring sensors. Augmented- or virtual-reality could be integrated aiming at achieving either online operator feedback or operator training, respectively. Depending on the context, several technological solutions could be exploited to provide online user feedback limiting the invasiveness of the device and maximizing its efficacy.

The development of the system will continue treasuring the user feedback obtained with the SUS questionnaire. User testing will also continue throughout the process, extending also the evaluation to female subjects. The major limitation of this study is indeed the study population, consisting of 6 male subjects.

In conclusion, we believe that featuring a passive exoskeleton with smart, wireless sensing units could increase the end-user acceptability of exoskeletons in the industrial field and further improve task ergonomics and thus the efficacy of the exoskeleton and the assistance it provides.

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