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

Mattia Pesenti[1][0000-0002-0505-4361], Marta Gandolla[1,2][0000-0001-5237-714X], Carlo Folcio[3], Sha Ouyang[3], Luigi Rovelli[3], Mario Covarrubias Rodriguez[3][0000-0003-4195-9333], and Loris Roveda[4][0000-0002-4427-536X]

[1] NearLab, Department of Electronics, Information and Bioengineering, Politecnico di Milano, 20133 Milano, Italy
[2] Department of Mechanical Engineering, Politecnico di Milano, 20156 Milan, Italy
`mattia.pesenti,marta.gandolla@polimi.it`
[3] Virtual Prototyping and Augmented Reality Lab, Department of Mechanical Engineering, Lecco Campus, Politecnico di Milano, Italy `mario.covarrubias@polimi.it`
[4] Istituto Dalle Molle di studi sull'Intelligenza Artificiale (IDSIA), Scuola Universitaria Professionale della Svizzera Italiana (SUPSI), Università della Svizzera Italiana (USI), 6962 Lugano-Viganello, Switzerland `loris.roveda@supsi.ch`

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 [1]. Their aim is to support workers with either tiring or non-ergonomic tasks, preventing or mitigating the impact of low-back pain [3],[4]. 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 [6].

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. 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 opted for the integration of smart sensors in a passive low-back exoskeleton. Of course, the same technology could be easily integrated in active exoskeletons as well. 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 that is shown in Figure 1-(a). Its design consists in 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. The kinematic structure presented in [5] has been equipped with a passive actuation system, visible in Figure 1-(b).

3 Sensor-Based Task Ergonomics

The passive exoskeleton for the low-back described above 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. The structure of the exoskeleton is shown in Figure 1. 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 the motion of the two legs, the hips, and the trunk.

Each sensing unit is calibrated while the wearer is standing in upright position, and can track user motion with respect to the gravity vector (stand-alone mode). This means that while the wearer is standing still, the

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

relative angle measured by each WSU is zero. Moreover, 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 human wearing the exoskeleton (inter-connected mode).

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 arbitrarily set the *safe* range of motion for each monitored joint. For load lifting from ground, for example, we set the threshold of trunk forward bending to 45°. 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 over Wi-Fi either to a computer or to a custom-made smartphone application. This application can be used for online visual feedback. The smartphone application (app) is shown in Figure 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 Figure 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 context of smart factories, as suggested by Industry 4.0.

4 System Usability and User Feedback

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 ± 9.43kg). We submitted to each subject the System Usability Scale (SUS) [2] to evaluate the overall usability of the system, and to have an idea of end-user's acceptability. The average score of the SUS was found to be 70.83, as shown in Figure 3.

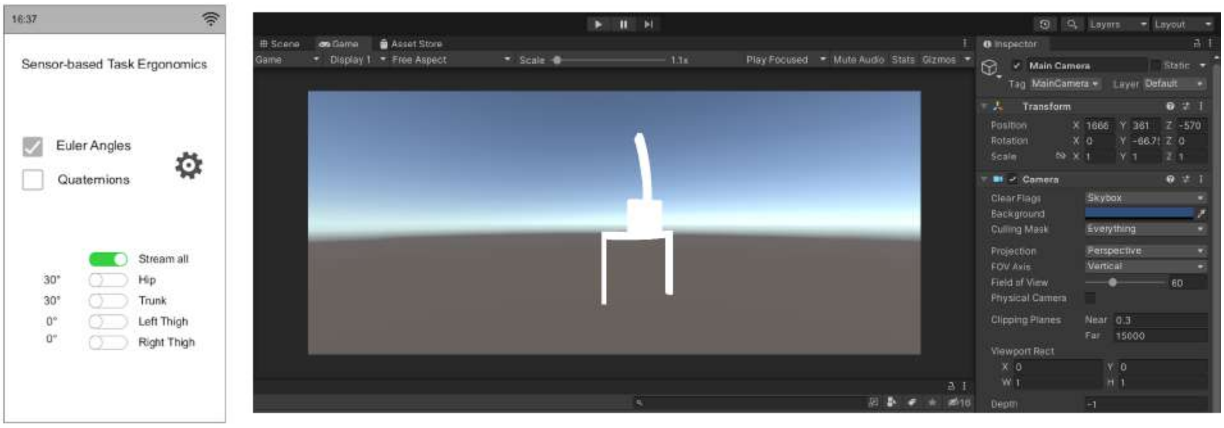

Fig. 2: Smartphone application (left) and Unity3D framework for kinematic reconstruction and task ergonomics (right).

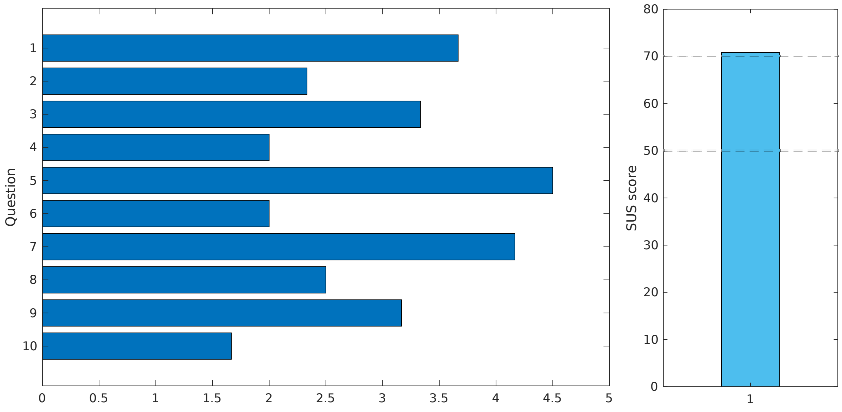

Fig. 3: SUS questionnaire: average score for each answer (left panel) and average SUS score (right panel).

5 Conclusion

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 lumbo-sacral 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 inter-task corrective action – and offline task analysis – to improve long-term ergonomics for the users of the exoskeleton. Finally, we showed the results of a SUS questionnaire submitted to 6 healthy subjects who evaluated rather positively the system.

With this work, we have shown and tested a proof-of-concept of a sensor-based system for online task ergonomics. 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.

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 assistance it provides.

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