Kinematic and dynamic assessment of trunk exoskeleton

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Abstract	In Industry 4.0, wearable exoskeletons have been proposed as collaborative robotic devices to partially assist workers in heavy and dangerous tasks. Despite the recent researches, proposed prototypes and commercial products, some open issues concerning development, improvements and testing still exist. The current pilot study proposed the assessment of a proper biomechanical investigation of passive trunk exoskeleton effects on the human body. One healthy subject performed walking, stoop and semisquat tasks without, with exoskeleton no support and with exoskeleton with support. 3D Kinematic (angles, translations) and dynamic (interface forces) parameters of both human and exoskeleton were estimated. Some differences were pointed out comparing task motions and exoskeleton conditions. The presented preliminary test revealed interesting results in terms of different human joints coordination, interface forces exchanged at contact points and possible misalignment between human and device. The present study could be considered as a starting point for the investigation of exoskeleton effectiveness and interaction with the user.

Keywords (separated by '-')	Wearable robotics - Trunk-support exoskeleton - Human-robot interface - Biomechanical effects - Industry

Kinematic and Dynamic Assessment of Trunk Exoskeleton

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Abstract. In Industry 4.0, wearable exoskeletons have been proposed as collaborative robotic devices to partially assist workers in heavy and dangerous tasks. Despite the recent researches, proposed prototypes and commercial products, some open issues concerning development, improvements and testing still exist. The current pilot study proposed the assessment of a proper biomechanical investigation of passive trunk exoskeleton effects on the human body. One healthy subject performed walking, stoop and semisquat tasks without, with exoskeleton no support and with exoskeleton with support. 3D Kinematic (angles, translations) and dynamic (interface forces) parameters of both human and exoskeleton were estimated. Some differences were pointed out comparing task motions and exoskeleton conditions. The presented preliminary test revealed interesting results in terms of different human joints coordination, interface forces exchanged at contact points and possible misalignment between human and device. The present study could be considered as a starting point for the investigation of exoskeleton effectiveness and interaction with the user. AQ1

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1 Introduction

In last decades, technological innovations and robotics have radically influenced the industrial environments. Starting from the traditional approach consisting in the replacement of worker's position with robotic systems to automate working processes, collaborative robotics revealed to be a strategic solution to improve industrial procedures, relieving operators from heavy tasks [1]. More recently, wearable technologies have been proposed as collaborative robots in direct contact with the user [2]. Among them, exoskeletons can assist the workers with a partial reduction of the human physical efforts in selected tasks and movements [3].

The introduction of exoskeletons in industrial applications contribute to ergonomic request in order to assure healthy and safe working conditions and to limit the risk of

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injuries and accidents [4]. In particular, low back pain is the most common musculoskeletal disorder affecting the workers due to the involving of human spine in manual, repetitive, and prolonged lifting tasks [5]. Several previous studies dealt with the design [6], the computational multibody model analysis [7, 8], the development [9] and the testing [10] of trunk-support exoskeleton, both passive [11] and active [12]. Despite the numerous investigations on commercial products [11] and research prototypes [13], some challenges in verifying and improving the ergonomics, the encumbrance and the interface with users are still open [14].

One fundamental aspect that requires deeper analysis deals with the evaluation of exoskeleton effectiveness [15]. Experimental tests have been conducted to stress the usability, acceptance and perception of trunk-support exoskeleton both in laboratory [10] and in real applications [16]. However, these studies mainly focused on the user's subjective evaluation. Only a few have tried to quantify the biomechanical effects of the exoskeleton assistance on the human body during working tasks [17, 18]. On this topic, the assessment of human-robot interaction could be crucial for the identification of device advantages and disadvantages and for the description of human adaptation to the wearable system.

The main object of the present pilot study deals with the description and assessment of a suitable biomechanical procedure for the investigation of kinematic and dynamic effects of human-exoskeleton interface. Preliminary experimental tests have been conducted on one subject performing different motion tasks (walking, stoop and semisquat) in different exoskeleton conditions (without exoskeleton, wearing exoskeleton providing no support and wearing exoskeleton providing support). Both human and exoskeleton outcomes are considered for the analysis of interaction.

2 Materials and Methods

2.1 Exoskeleton

In the current study, the commercial trunk-exoskeleton Laevo (Laevo, Netherlands) was selected for the analysis. It is a passive device that assists the user during trunk flexion/extension and while holding trunk-flexed posture. It presents three principal parts: i) a torso structure composed by one butterfly pad and two rigid bars, ii) a pelvis belt that allows fixing the exoskeleton to the human pelvis, iii) a thigh structure composed by rigid bars and pads. The torso and thigh structure are connected by two smart joints. Each smart joint presents a cam-spring mechanism (gas spring) to supply torque assistance. This depends on the relative angle between torso and thigh parts. The torque is transmitted to the human body as forces through the pads. The smart joint has to be positioned aligned with the human hip for a suitable assistance transmission. An on/off mechanism allows activating/deactivating the support and action of the spring. It is also possible to adjust the initial device inclination (0–35°), according to the user's request. The pelvis belt is connected to the thigh structure by hinge joints. Figure 1 depicts the last version of the Laevo.

To conduct a biomechanical analysis of human-exoskeleton interaction, a proper kinematic model of the exoskeleton was developed using Vicon ProCalc (Fig. 1). Clusters, consisting each of 3 passive markers, were positioned in correspondence of the

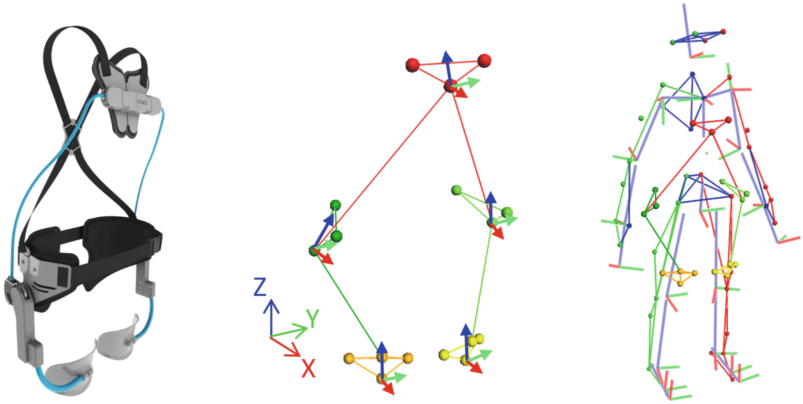

Fig. 1. Graphical representation of the passive exoskeleton Laevo [11], exoskeleton custom kinematic model with local reference systems, biomechanical human-exoskeleton models.

trunk pad and the two pelvis plates; two additional clusters, consisting each 4 markers, were positioned on the two thigh pads. A total of 17 markers were used. For each set, a rigid segment was identified, and a local three-axis coordinate system was reconstructed with z-axis pointing upward (blue axis), x-axis pointing forward (red axis) and y-axis pointing to the left side (green axis). YXZ Euler angles were defined to evaluate relative angles between segments. Figure 1 shows the custom kinematic model and its interaction with human Plug-in-Gait full body model using Vicon Nexus [19].

2.2 Experimental Tests

Subject and Instruments. One healthy female subject (25 age, 1.72 m, 58 kg) participated to the preliminary test. She declared to be not affected by any musculoskeletal disease. For data acquisition, the instrumentations can be resumed as: 2 cameras for video recording (50 Hz), 8 infrared-cameras Vicon Bonita 10 (120 Hz), 17 passive markers (14 mm diameter) for the exoskeleton model, 39 passive markers (14 mm diameter) for the Plug-in-Gait full body human model. Figure 2 depicts several views of the subject wearing the exoskeleton, with applied passive markers.

Motion Tasks. Three motion tasks were performed barefoot: walking, stoop lifting (flexed trunk, extended lower limbs) and semisquat lifting (both flexed trunk and flexed legs). Gait trials were performed with self-selected speed and 5 passages with 3 steps for each foot were registered, for a total of 15 stride cycles. The lifting tasks consisted in descending phase to reach an empty box and ascending phase to go back to the starting standing posture. In both strategies, distance between feet was imposed as the shoulders' width. The box was positioned of a height equal to 20% of the total subject height. A metronome was used to impose the pace (2 s/phase). A total of 10 repetitions were considered for each lifting task. All motions were performed without the exoskeleton, with the exoskeleton and no support, with exoskeleton and support, in a random order.

Fig. 2. Frontal, lateral, back views of female subject wearing the Laevo with passive markers.

Parameters and Data Analysis. The following kinematic and dynamic objective parameters were estimated:

- gait spatio-temporal parameters during walking trials;
- range of motions (ROMs) of human joints (spine, hip, knee);
- interface forces exchanged at exoskeleton pads with support;
- distance of the exoskeleton smart joint with respect to the human hip joint;
- exoskeleton pads slippage with respect to selected human markers.

Markers positions were registered and post-processed using Vicon Nexus with standard and custom operations for human and exoskeleton kinematics. Customized Matlab routines were implemented to calculate the outcomes. Due to the symmetry of lifting tasks and the verified symmetry during gait (limp index 1.00), human left and right sides were averaged. Data among repetitions was averaged and time was normalized to the percentage of task cycle.

3 Results and Discussion

Table 1 shows mean and standard deviation (SD) values of the spatio-temporal parameters calculated during walking. Some differences can be highlighted among exo conditions. Without exoskeleton, the walking speed was 1.24 m/s, stride length 1.34 m and stride time 1.09 s. These parameters resulted lower (1.15 m/s, 1.22 m, 1.07 s, respectively) when wearing the exoskeleton without support. An additional reduction was registered in case of exoskeleton with support (1.10 m/s, 1.19 m, 1.07 s, respectively), accordingly to previous studies with Laevo [20]. On the contrary, the normal step width (0.05 m) increased when wearing the device (0.06 m). A different distribution of gait phases can be stressed, with higher stance duration (62% exoskeleton without support and 63% exoskeleton with support) and lower swing duration (38% exoskeleton without support and 36% exoskeleton with support). Important differences between exoskeleton conditions can be also pointed out from the evaluation of human joint ROMs, as reported in Fig. 3. In detail, the figure shows the relative ROMs of spine, hip and knee joints in all three planes.

Table 1. Mean (SD) of spatio-temporal parameters during self-selected walking

STPs	No exo	Exo no support	Exo with support
Walking speed (m/s)	1.24 (0.03)	1.15 (0.05)	1.10 (0.02)
Stride length (m)	1.34 (0.01)	1.22 (0.02)	1.19 (0.01)
Step width (m)	0.05 (0.02)	0.06 (0.01)	0.06 (0.01)
Stride time (s)	1.09 (0.02)	1.07 (0.03)	1.07 (0.02)
Stance duration (%Gait cycle)	60.84 (1.03)	62.30 (1.22)	63.73 (0.47)
Swing duration (%Gait cycle)	40.04 (0.78)	38.49 (1.03)	36.86 (0.40)

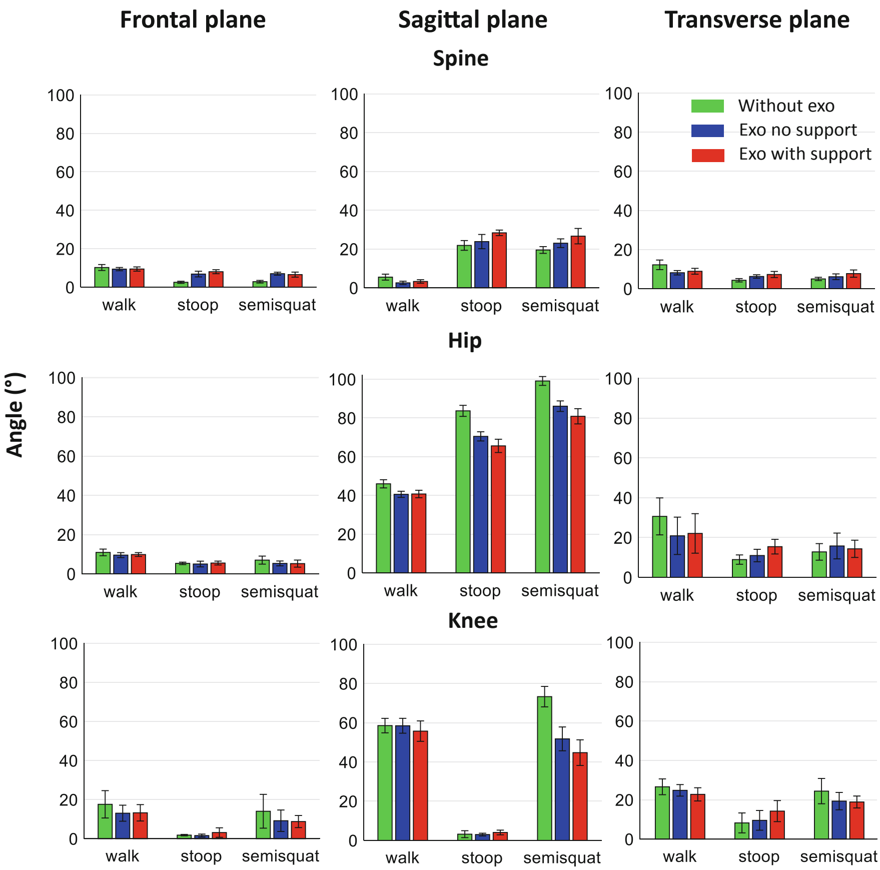

Fig. 3. Mean and SD ROMs of human joints in different planes, tasks, exoskeleton conditions.

During walk, smaller ROMs were registered for all joints and planes when wearing the exoskeleton, especially with support. For lifting tasks, in the sagittal plane the exoskeleton caused a reduction of the contribution of knee and hip joints to the range of movement, with the increase of spine flexion-extension. Moreover, despite the symmetry, additional rotations for all joints were registered with exoskeleton. These results underline a different human joints coordination when wearing the device, accordingly to previous studies on Laevo [10, 20].

Possible reasons can be identified in the assistance forces and ROMs restrictions caused by the exoskeleton. The torque-angle relation characterizing the Laevo assistance (Fig. 4) was measured with a dynamometer in previous experimental bench test and it confirmed results proposed by Koopman and colleagues [10]. Considering this relation and the geometrical dimensions of Laevo, interface forces in case of exoskeleton with support were estimated at pad contacts (Fig. 4). Comparable resultant forces were estimated at trunk and thigh pads, while some differences were pointed out between motions. Indeed, during walking, interface forces were lower (maximum value of 50 N). Comparing stoop and semisquat lifting, interface forces resulted different due to the greater relative angle between trunk-thigh structures in semisquat. Nevertheless, in both tasks, peaks of 90 N and 75 N were reached at trunk and thigh pads respectively.

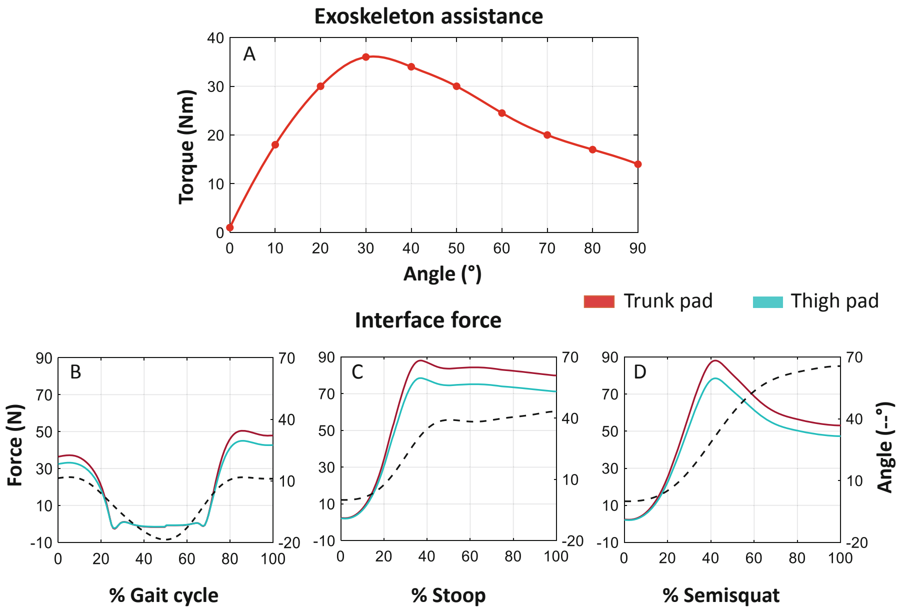

Fig. 4. A) Torque-angle characteristics of the exoskeleton assistance (red line), the interface forces exchanged at trunk (dark red) and left thigh pad (light green) during B) walk, C) stoop, D) semisquat. Forces are related to the exoskeleton angle (black dashed line).

Furthermore, another crucial aspect that needs investigation is the relative slippage of exoskeleton joints and interface contacts with respect to the human body. In all tasks, a relative movement of the exoskeleton smart joint in the sagittal plane was pointed out, with respect to the human hip joint, as reported in Fig. 5. Greater translations were registered during walking, while they were lower during stoop. Considering the exoskeleton without support (blue line), the range of distance resulted higher. In all tasks, the smart joint resulted positioned posterior to the human hip joint. This misalignment could cause undesired or lower assistance forces, movements limitations and perceived discomfort. Therefore it is crucial to correctly align the smart joint with the hip joint.

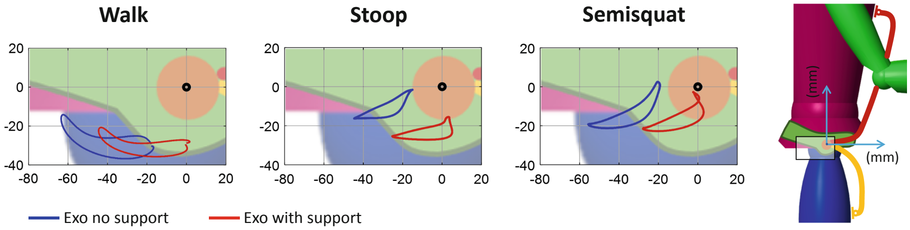

Fig. 5. Maps of the relative distance between human hip joint and exo joint in sagittal plane

Trunk and leg pads slippages were measured with respect to the trunk and legs local reference frames (Fig. 6). Longitudinal distance (Z axis) resulted the greater contribution of slippage (maximum value of 75 mm during stoop with support), while medio-lateral one (Y axis) resulted negligible. During walk, as expected, were registered higher slippages of thigh pads with respect to trunk pad for all directions, with an increase in case of support. Different results were assessed during lifting, with higher slippages at trunk pads along longitudinal direction. In the medio-lateral direction, slippages are comparable between trunk and legs pads. The slippage along forward (X axis) was due to the inclination of pads with respect to the human segment. It caused a smaller contact surface and higher undesired perceived forces.

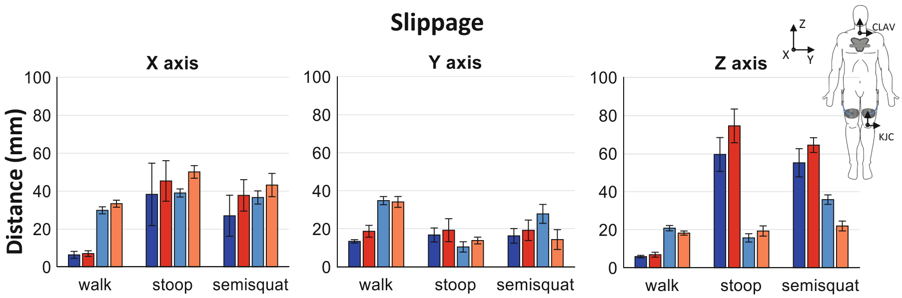

Fig. 6. Slippage of trunk (blue for exoskeleton no support, red for exoskeleton with support) and thigh (light blue for exoskeleton no support, orange for exoskeleton with support).

4 Conclusion

The current study focused on the biomechanical evaluation of human-exoskeleton interaction and the quantification of exoskeleton effects on human body. The preliminary experimental test demonstrated the importance of investigating and quantifying the efficacy of wearable device in terms of kinematic and dynamic effects. Some limits could be identified: a) single participant, b) the execution of only symmetrical movements, c) the absence of external load during lifting, d) the reconstructed interface forces instead of direct measurement. Future tests with a larger population, additional symmetrical and asymmetrical tasks will be conducted, and further biomechanical parameters will be investigated in order to define a standardized and systematic experimental testing procedure. Moreover, the validation of experimental results with a proper computational model might reveal important considerations.

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