Abstract

In the manufacturing environment, wearable robotics is one of the innovative solutions to support the execution of tasks that cannot be fully automated. Trunk exoskeletons fall into this category, designed to alleviate the physical effort exerted by workers during bend-over tasks for material handling, thereby preventing work-related injuries. Various exoskeletons have been proposed in recent years, ranging from passive devices, that favor lightness, to active devices, that can provide tailored and flexible assistance. However, current applications lack a device with an embedded sensor system in order to differentiate bend-over techniques and customize the assistance provided based on the kinematics adopted by the user.

Given these considerations, this Ph.D. thesis aimed to implement an active trunk exoskeleton and develop high-level control logics to modulate assistance based on the bending technique performed and the user's preferences. The prototype, designed in a previous study, includes two smart active joints with electric servomotors, placed at pelvic level. These motors generate torque transferred to the chest and thighs through rigid supports integrated into the structure. Its significant structural novelty regards the integrated angular sensor system, which measures user kinematics while bending. Specifically, a sensor within the servomotor measures the angle between the thighs and trunk, while an additional encoder measures the angle between the thighs and the pelvis, allowing for configuration tracking of the human segments primarily involved in bending.

The prototype was assembled, and after conducting preliminary bench tests and fitting trials, several structural modifications were introduced. In particular, the transmission system of the additional encoder embedded into the joint was enhanced. The device control adopts a two-level strategy where the high level imposes torque based on kinematics and the detected bending strategy in open-loop control, while the low level involves direct actuation management by the motor driver. Given the open-loop control, a joint model, that encompasses the disturbances introduced by the Harmonic Drive reducer within the actuation system, was introduced allowing to achieve the desired support torque or driving the exoskeleton in transparency mode.

The bend-over kinematics of five subjects wearing the exoskeleton were experimentally collected, revealing subjective movement patterns within the spectrum of bending strategies due to

individual mobility and behaviors. A movement recognition algorithm was developed to assess in real-time the performed bending techniques and to generate specific support. This early user-specific recognition algorithm achieved excellent performance, detecting the technique within 200 ms from the motion onset, enabling real-time identification.

To customize support based on the selected movement technique, human joint kinematics was investigated through a multibody model. The torque demand during bend-overs was estimated based on the identified gesture and movement phase along with the measured human segment configuration. Biomechanical effects were evaluated through simulations, covering the entire range of bending motions. The support strategy of the prototype overcomes the limitations of current passive and active devices by exploiting the flexibility of active support, considering the user's segment configuration, and avoiding issues related to bio-signal and external sensor integration.

In conclusion, this research highlights the importance of considering varying torque demands on the joints during different bend-over strategies, taking into account the user’s subjective preferences. This approach supports users smartly during manual handling tasks, thereby preventing work-related musculoskeletal disorders.