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Active back-support exo-skeletons: how assistive strategies determine effectiveness

The potential versatility of active exoskeletons is achieved by appropriately modulating their actuation forces. This is done by assistive strategies that interpret user's movements and assistance needs during operation. This article shows how different strategies determine the effectiveness of an active back-support exoskeleton designed to assist manual material handling.

Stefano Toxiri, Axel S. Koopman, Maria Lazzaroni, Jesús Ortiz, Valeria Power, Michiel P. de Looze, Leonard O'Sullivan, Darwin G. Caldwell

Exoskeletons are wearable devices that assist physical activities by generating assistive forces to the user's body. There has been increasing interest in using exoskeletons in industrial environments to improve ergonomic conditions. Manual material handling is a common activity in different industrial sectors consisting of repeatedly lifting and moving objects, e.g. baggage handling in airports. It is typically associated with large compressive forces on the lumbar spine, leading to high risk of physical injury (Norman, et al., 1998), (OHSA (European Agency for Safety and Health at Work), 2000). To mitigate this challenge, a few exoskeletons have been developed internationally (within research studies and as commercial products) to support and assist the lower back.

Figure 1. Side view of the back-support exoskeleton prototype (DoF stands for Degree of Freedom).

An important distinction should be made between passive and active devices, based on whether the forces are generated by mechanical elements (e.g. springs) or by powered actuators (e.g. electric motors). While the forces in a passive device are determined at the design stage, the assistive function of an active exoskeleton is automatically adjusted during use by a computer, which controls the actuators based on data from sensors as input and according to what is known as the *assistive strategy*. Although sensors, computers and actuators certainly make the design of active exoskeletons more challenging compared to passive ones, it is generally considered that active devices hold the potential for superior versatility, within which assistive strategies are the key to exploiting it (Young & Ferris, 2017).

This study describes an experiment that assessed and compared two alternative assistive strategies for an active back-support exoskeleton prototype. A more detailed description of the methods and results can be found in (Toxiri, et al., 2018).

Methods

Platform: exoskeleton prototype

An active back-support exoskeleton was developed in the context of the Robo-Mate EU project (Stadler, et al., 2017) and developed further via national Italian funding by an INAIL project (the Italian Workers' Compensation Authority). The prototype (Figure 1) spans the torso and upper legs. Two actuators are located lateral to both hips and aligned approximately with its centre of rotation when putting on the exoskeleton. The rigid structures transmit actuator torques between the torso and the thigh frames. The assistive torques are approximately restricted to the sagittal plane, while passive degrees of freedom allow unhindered movements outside of that plane.

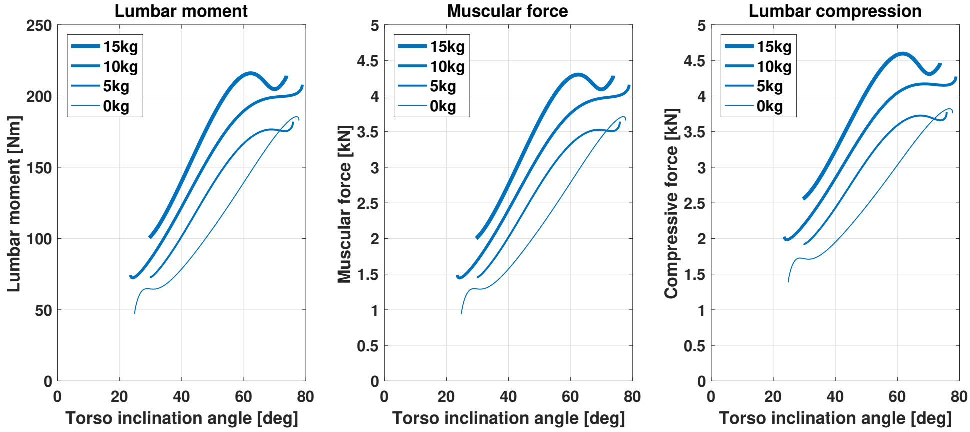

Figure 2. Computed lumbar moment, muscular force and lumbar compression as depending on (a) torso inclination angle, and (b) mass of the object lifted.

Each actuator consists of a commercial brushless DC motor, a reduction gear and a joint torque sensor. The electronics to drive the actuators implements a closed-loop torque control scheme that tracks, on both sides, the reference signal generated by the assistive strategy.

Rationale for strategies: biomechanics of lifting

Based on the simplified two-dimensional musculoskeletal model of the spine introduced previously (Toxiri, et al., 2015), two key factors appear to affect the lumbar moment, the muscular force of the *erector spinae* and the resulting compression force (Figure 2) are: (a) the *orientation of the upper body* and (b) the *mass of the object* being handled. Lower back biomechanical loading increases with increased flexion in the sagittal plane, reflecting a corresponding increase in muscular activity. Indeed, greater forces at the back-flexion musculature (*notably the erector spinae muscle*) are necessary to counteract the moment generated by gravity acting on the user's upper body and external mass. Consequently, increased lower back biomechanical loading is directly associated with increased object mass. In order to appropriately time and assist modulated physical assistance in the exoskeleton, these two factors were considered for the design of the assistive strategies, as described below.

Proposed assistive strategies

Three strategies are proposed. The first (*imu*) and second (*myo*) strategies each reflect the two factors described above (i.e. torso inclination angle and external mass). The third strategy (*hyb*) is a combination of the first two strategies, accounting for both factors at the same time. Figure 3 illustrates their working principle in terms of the reference torque signal that each strategy generates during the task.

The *imu* strategy uses a measurement of the inclination of the torso to assist the user. This is based on the estimated weight of the upper body itself. Rather than using a precise estimate, the sine of the inclination angle is multiplied by a scaling factor . Increasing this scaling factor increases the physical assistance generated, which can be thus adjusted to user preference. The angle is measured via an integrated onboard Inertial Measurement Unit (IMU).

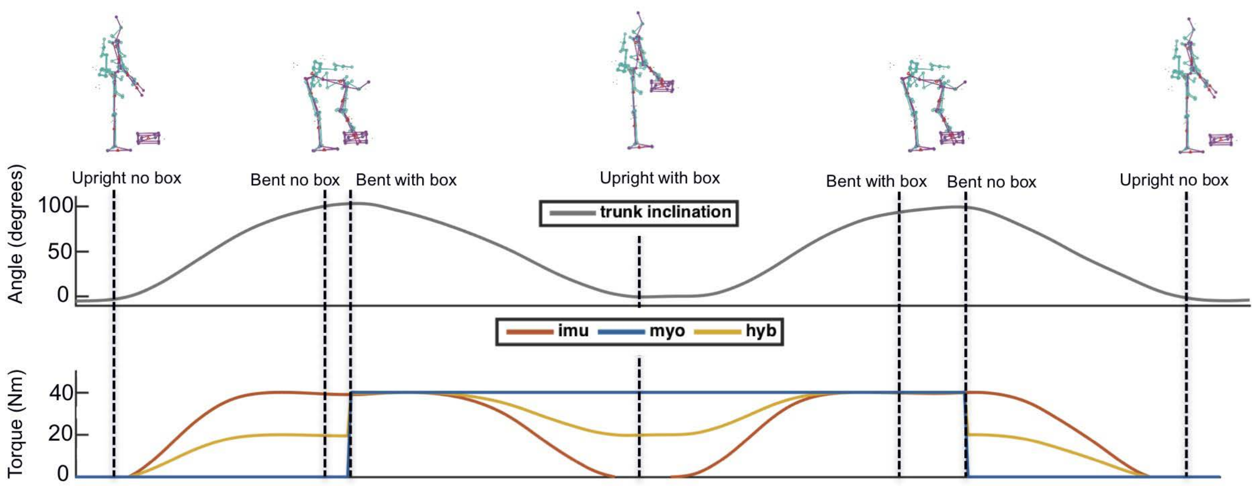

Figure 3. This simplified illustration describes the idea behind the implemented control strategies. The top plot displays the inclination angle of the torso over time. The bottom plot displays the torque reference signals generated by three different strategies., i.e. "imu" (orange), "myo" (blue), and "hyb" (yellow).

The *myo* strategy is based on the concept that the overall muscular activity at the forearm carries information about the weight of the object lifted. A commercial armband (Myo – www.myo.com) records forearm muscle activity by means of eight pairs of dry sEMG electrodes and sends the data to an integrated computer via Low-Energy Bluetooth. The sum of the eight values is normalized (using a maximum value recorded during a preliminary calibration procedure) and multiplied by a scaling factor that may also be adjusted to user preference. As with the previous strategy, increasing the scaling factor results in stronger physical assistance.

The *hyb* strategy generates a torque assistance based on the sum of the two previous strategies. This represents a more general case, and it is possible to adjust the two scaling factors independently based on user preference and task conditions.

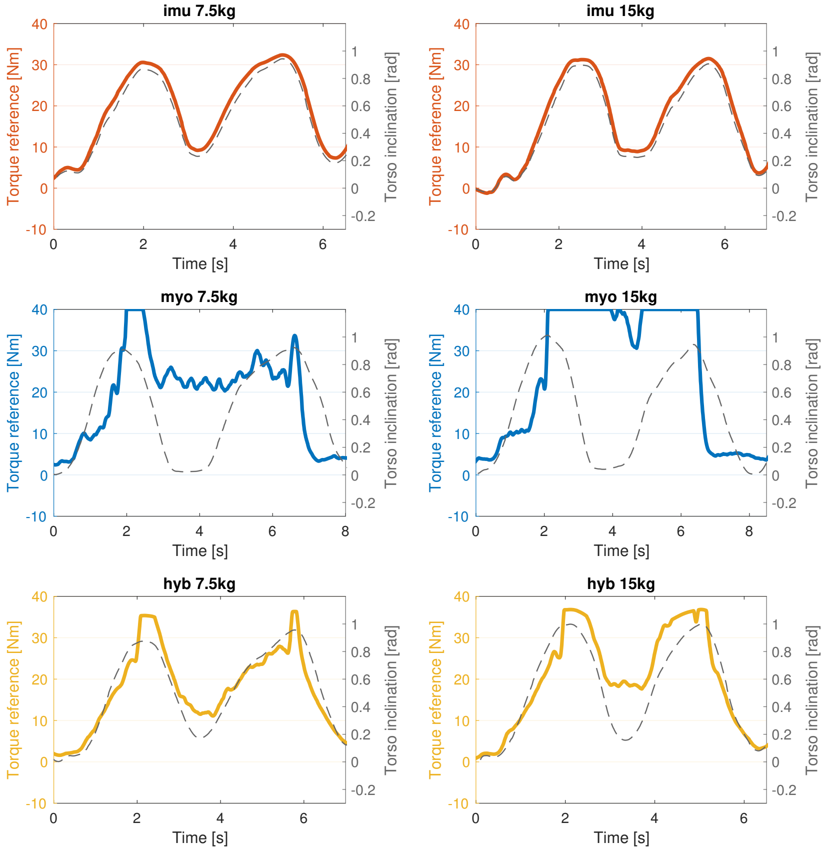

Figure 4. The solid lines represent the torque reference profiles (sum of the two actuators) generated by the different strategies, while the dashed lines show the corresponding torso inclination angle. The imu is invariant to the external object, while the myo increases the assistance for the heavier object. The hyb results in an intermediate behavior.

Evaluation

The effectiveness of the three strategies is evaluated by considering the resulting muscular activity at the lower back (de Looze, Bosch, Krause, Stadler, & O'Sullivan, 2016) during an experimental campaign aimed at recreating the key biomechanical conditions of a lifting task. A significant reduction in muscular activity is, in most cases, associated with a reduction in the corresponding compressive loads.

Protocol

The lifting and lowering task consisted of the sequence in Figure 3, i.e. bending over to reach a box placed at mid-shin height, taking it to an upright position, and taking it back down. This sequence was repeated three times and executed with a 7.5-kg and then with a 15-kg box. The task was performed in four different conditions:

- *no exo*: no exoskeleton is worn;
- *imu*: the exoskeleton is commanded via the *imu* strategy;
- *myo*: the exoskeleton is commanded via the *myo* strategy;
- *hyb*: the exoskeleton is commanded via the *hyb* strategy;

with the *no exo* condition being first in all cases, and the other three in a randomized order. The torque reference signals generated by the *imu*, *myo* and *hyb* conditions are shown in Figure 4, as averaged across all executions and subjects. No instructions on a specific lifting technique (i.e. stoop or squat) or speed were given. Eleven healthy, young males (average age 25.0 [SD 6.9] years, weight 70.9 [SD 8.8] kg, height 1.77 [SD 0.06] m) participated in the experiment, of which none had any history of low-back pain.

Muscular activity

Standard laboratory equipment for surface electromyography (sEMG; Porti-17TM, TMS, Enschede, The Netherlands) was fitted to measure the activity of left and right spinal muscles (*iliocostalis*) following SENIAM guidelines (Hermens, et al., 1999).

The recorded activity is shown in Figure 5. With respect to the *no exo* condition (green), reduced activation of the spinal muscles is observed in all three strategies. In more detail, the *imu* strategy (orange) led to the lowest activation during both the initial descending phase (before 2.0s) before the box is reached, and the final ascent after the box is released. In contrast, the *myo* strategy (blue) reduced activation the most during the central phase, corresponding to when the box was held by the subject. In line with the average muscular activation profiles, peak muscular activation is also reduced in all three strategies for both the 7.5- and 15-kg loads. With respect to the *no exo* condition, significant relative reductions ($p < 0.05$) in the peaks ranging from 28% to 35% were observed.

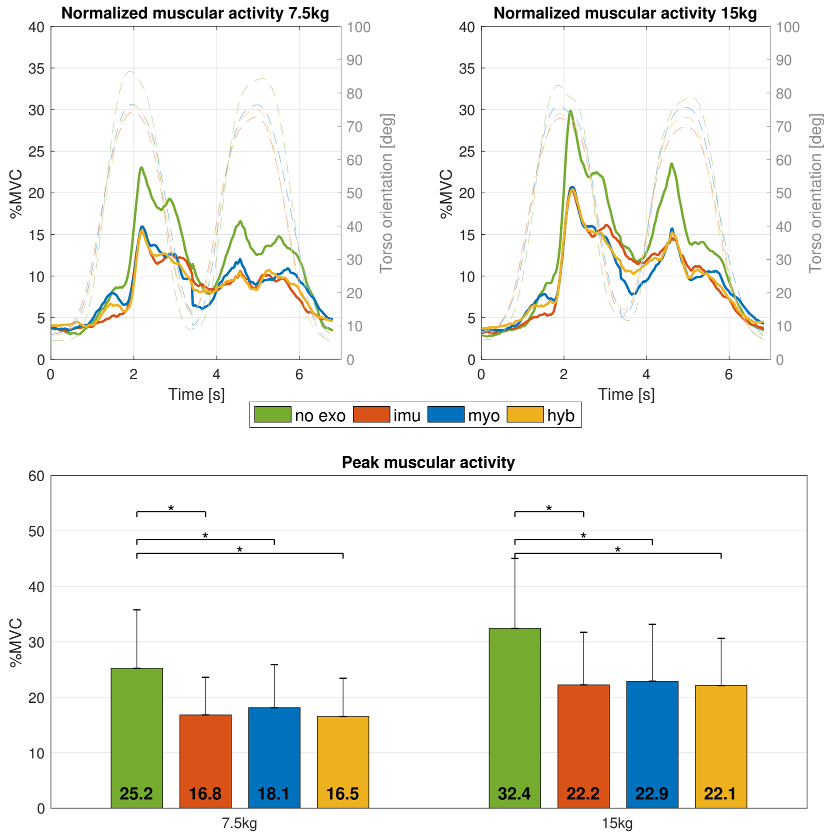

Figure 5. At the top graphs, the solid lines represent averaged EMG profiles (left and right iliocostalis) across all subjects in percentage maximal voluntary contraction (% MVC). The dashed lines show the corresponding torso inclination angle. In all cases, wearing the exoskeleton decreased the activity, with none of the three strategies prevailing. The isolated peak activations, at the bottom, indicate reductions of about 30%.

Discussion

The *imu* and *myo* strategies, each designed to address one of the two key factors determining the need for physical assistance during lifting tasks, should be considered together with their respective advantages and drawbacks, which may impact the practical use. The *imu* strategy is entirely transparent and unobtrusive to the user as it uses signals acquired by onboard sensors. However, as it cannot adjust to the variability of the external load, it may be a good solution to support against known loads, as is the case in static postures. In contrast, the *myo* strategy captures the additional load caused by the external object and therefore may be suitable for tasks involving repeated handling of unknown loads. Additionally, the wireless armband does not appear to be cumbersome to wear, nor distracting the wearer from the task at hand.

Interestingly, scaling up the assistance with the *imu* strategy would quickly make the device unusable due to inappropriate and excessive resistance to movements. This strategy may therefore be limited to supporting the user's own upper body. By contrast, *myo* lends itself more naturally to stronger, more powerful devices, capable of assisting manual handling of heavy material.

These experimental data indicate the effectiveness of the proposed prototype as commanded with each of the assistive strategies as tested. The data show reductions of 28% to 35% in peak muscle activation at the lower back across various conditions. Further research is needed to consider other factors, notably lifting speed, which will additionally improve the effectiveness of back-support exoskeletons.

Limitations of this study

Considering muscular activity as an evaluation metric is often a case of convenience, as it can be quite readily measured in a research laboratory with non-invasive technologies. On the other hand, joint loading, more directly connected with the risk of injury, can only be estimated indirectly and requires the use of additional technology (e.g. 3D motion capture and biomechanical analysis) and musculoskeletal models, which results in substantially more time-consuming testing procedures.

This experiment did not study muscular fatigue as it cannot be observed in such short trials. Also, the effect of this prototype on other body areas other than the lumbar spine were not considered. Evidence excluding extra loading on the legs due to the back-support exoskeleton was presented in (Huysamen, et al., 2018).

For an exoskeleton to be successfully adopted in industry as a product, there are many aspects which must be met, many of which are beyond the scope of this study. For instance, the device must have high acceptance by users, so that they feel encouraged to use it and it must be affordable and integrate well with existing infrastructure, so that employers are motivated to purchase it.

Conclusion

The versatility of active exoskeletons lies in their capability to modulate the physical assistance based on relevant task information. Our study shows two important factors of compressive loading during lifting tasks (inclination of the upper body and mass of the object handled) and that an unobtrusive sensor setup can acquire the necessary information to effectively modulate the assistance. The corresponding assistive strategy can be adjusted to user preference and to task variations, making the resulting exoskeleton versatile and intuitive.

Abstract

Active exoskeletons are potentially more effective and versatile than passive ones but designing them poses several additional challenges. An important open

challenge for active exoskeletons is associated with assistive strategies, by which the actuation forces are modulated relative to the user's movements and assistance needs. This paper addresses an element of this challenge for an active exoskeleton prototype aimed at reducing compressive loads on the lumbar spine, which is associated to the risk of musculoskeletal injury during manual material handling (i.e., repeatedly lifting objects). During manual handling tasks, two key factors related to biomechanical loading are posture, e.g. forward inclination of the torso, and external mass lifted. Specific control strategies, accounting for these two factors, were implemented and evaluated experimentally. The results indicate a significant reduction in muscular activity (circa. 30%) at the lower back when using the exoskeleton with the different strategies.

With such strategies, the proposed exoskeleton can quickly adjust to different task conditions (which makes it versatile compared to using multiple, task-specific devices) as well as to individual preference (which promotes user acceptance). Additionally, the strategies explored are potentially applicable to many exoskeleton types for industrial use.

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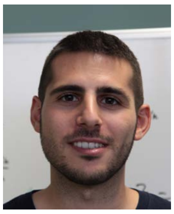
About the author:



Dr. S. Toxiri
Postdoctoral Researcher
Department of of Advanced Robotics – Istituto Italiano di Tecnologia, Genoa (Italy)
stefano.toxiri@iit.it

A.S. Koopman, MSc.
PhD student
Department of Human Movement Sciences, Faculty of Behavioural and Movement Sciences, Vrije Universiteit Amsterdam (the Netherlands)

M. Lazzaroni, MSc.
PhD student
Department of Advanced Robotics – Istituto Italiano di Tecnologia, Genoa (Italy)

Dr. J. Ortiz
Researcher (Team Leader)
Department of Advanced Robotics – Istituto Italiano di Tecnologia, Genoa (Italy)

Dr. V. Power
Postdoctoral Researcher
School of Design, University of Limerick, Limerick (Ireland)

Prof. Dr. M.P. de Looze
Senior Project Manager
TNO, Leiden (the Netherlands)

Prof. Dr. L. O'Sullivan
Associate Professor
Health Research Institute, University of Limerick, Limerick (Ireland)

Prof. Dr. D.G. Caldwell
Department Director
Department of Advanced Robotics – Istituto Italiano di Tecnologia, Genoa (Italy)