Effects of a passive back assistance exoskeleton for load carrying and trunk bending tasks

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ABSTRACT

Low back pain affects millions of workers every year. From a preventive perspective, the use of passive exoskeletons is growing in the industrial field. The present study aims to evaluate the effects of a passive trunk exoskeleton on muscle activity and kinematics of the trunk and legs, displacement of the center of pressure, and perceived discomfort. 14 participants performed two tasks with and without exoskeleton. The first one was a lifting and lowering task and the second one was a static trunk flexion task at 40°. The results showed a significant reduction of approximately 18% in myoelectric activity of the erector spinae longissimus as well as a reduction in perceived discomfort in the thoracolumbar area on both tasks. The use of the exoskeleton increased external oblique activity by 28.6% during the load-bearing task, while leg muscles were not significantly impacted. The exoskeleton slightly impacted the kinematics of the trunk but leg kinematics were not, nor was postural balance. Given the study's results, this device therefore seems to have the ability to reduce the risk of onset of low back pain at work.

Key words: Low-back pain, Exoskeleton, Back assistance, EMG, Postural balance, Kinematics, Perceived Discomfort

INTRODUCTION

Low back pain is one of the major global public health problems. Globally, the number of years lived with disability caused by low back pain increased by 54% between 1990 and 2015 (Hartvigsen et al., 2018). Low back and neck pain are the leading cause of disability in 2015 in most countries (Vos et al., 2016).

Gourmelen et al (2007) studied the frequency of low back pain in the French population aged from 30 to 64 years old. The prevalence of low back pain lasting at least one day in the last 12 months is estimated at 55%, that of low back pain lasting more than 30 days at 17% and that of limiting low back pain at 8%. The lifetime prevalence of low back pain is estimated to be 75-84% (Thiese et al., 2014).

According to the French National Research and Safety Institute for the Prevention of Occupational Accidents and Diseases (INRS), low back pain accounts for 20% of occupational accidents and 7% of occupational diseases, corresponding to nearly 11.5 million lost working days each year (*Lombalgie. Statistique - Risques - INRS*, s. d.).

The development of low back pain is associated with several work-related factors, including lifting and carrying loads as well as awkward postures such as trunk flexion and rotation. Nearly half of work accidents due to low back pain occurred while carrying loads (Bosch et al., 2016; da Costa & Vieira, 2010).

According to Eurofound (2012), more than 30% of the working population in the EU is exposed to physical workloads due to handling, while 63% of workers are exposed to repetitive movements and 46% to awkward body postures. Automation of manufacturing workshopes would solve these problems, but many tasks require high levels of flexibility and require strong observation and decision-making skills. In such cases, full automation is either impossible or unaffordable. As a result, many workers are still exposed to various activities that generate musculoskeletal disorders (MSDs) (Looze et al., 2016).

One of the preventive strategies to deal with it, among the emerging research avenues, is the use of exoskeletons. The main objective of lumbar exoskeletons is to prevent injuries, while preserving the versatility of workers during tasks involving

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forward bending of the trunk (Koopman et al., 2019). Existing devices are mainly based on storing elastic energy during forward bending, which then helps the user to extend their forward bent work posture or straighten their body when carrying an object (Bosch et al., 2016).

According to Looze et al. (2016), exoskeletons have the potential to significantly reduce the underlying factors associated with the development of work-related MSDs. Several models of passive exoskeletons have already been studied and have, among other things, shown a 10-50% reduction in spinal erector activity (Abdoli-E et al., 2006; Alemi et al., 2020; Bosch et al., 2016; Koopman et al., 2019; Looze et al., 2016; Madinei et al., 2020). Benefits have also been reported in terms of endurance and perceived discomfort (Baltrusch et al., 2019; Bosch et al., 2016).

In some cases, an exoskeleton can also have negative impacts due to its structure and/or to the modified distribution of efforts. This can lead to discomfort and contribute to the development of new biomechanical and/or physiological constraints. For example, we can expect an overuse of antagonist muscles to those assisted, a disturbance of postural balance or changes in the user's kinematics. Therefore, it is important to quantify the effectiveness and impact of exoskeletons before using them in work situations.

The present study aims to evaluate the passive exoskeleton Hapo, from the company ErgoSanté, which mainly aims to reduce the activation of erector spinae during flexion/extension of the trunk. This evaluation is based on objective (myoelectric activity, velocity of displacement of the center of pressure (CoP) and kinematics) and subjective criteria (perceived discomfort).

EXPERIMENTAL PROTOCOL

Participants

14 adult volunteers, 6 women (32 ± 10 years, 163.8 ± 4.6 cm, 57.2 ± 10.1 kg) and 8 men (32 ± 13 years, 183.5 ± 6.5 cm, 86.5 ± 11.4 kg), with no medical history of neuromuscular disorders of lower limbs and back, have participated in this study. Each participant gave written and oral informed consent. They were selected among ErgoSanté workers who are not involved in the design of exoskeletons. Participants were asked not to perform strenuous activities for at least two days before the experiment to avoid the risk of muscle fatigue.

Exoskeleton

The studied device is the 2022 version of the Hapo (ErgoSanté, Anduze, France), a passive trunk exoskeleton (Figure 1). It weighs 1.1 kg and is available in 3 sizes (depending on the morphology of the user). It is composed of two cylindrical springs made of composite materials, fixed to shoulder straps and to interfaces at the thighs. The springs are also attached to a belt (with a lumbar support) *via* straps that allow the adjustment of pre-tension of the springs.

As the trunk bends forward, the exoskeleton springs generate an extension moment in the lower back by transferring some of the forces applied to the lumbar area to the torso and thighs.

Figure 1: Isometric view of the HAPO. Elastic springs are represented in yellow

Experimental design

After a short warm-up, participants performed two tasks with and without an exoskeleton. Subjects began with a lifting/lowering task and then performed an isometric trunk-flexion task. The order of the conditions (“with exo” and “without exo”) varied systematically from one subject to another.

Task 1: load lifting

Subjects had to stand on a force platform, facing the load (6 kg box) placed on the ground 20 cm in front of the platform. Subjects had then to grasp this load from the ground, stand up, put it back down to the same place and finally to stand up again without the load. It has been asked to subjects to bend the knees while performing the task. This exercise was performed 10 times in a row in each condition.

Task 2: static trunk flexion

Subjects had to maintain the following posture during 1 minute on the force platform: legs straight but knees unlocked, trunk bended at approximately 40° (defined as the Vertical-T8 angle), arms relaxed vertically (hands were about knee level).

To ensure the trunk-flexion angle was maintained at 40° during the task, the experimenter referred to the measurement displayed by the motion capture software. Subjects were immediately corrected verbally in the event of deviations observed with respect to the angular target.

Data processing and analysis

Data processing have been done with customized scripts in MATLAB (The MathWorks Inc. Natrick, MA, USA).

EMG

Electromyographic (EMG) activity of the latissimus dorsi, erector spinae longissimus, rectus abdominis, external oblique, rectus femoris, biceps femoris, tibialis anterior, and gastrocnemius medialis was recorded on the right side of the body during both tasks according to the SENIAM recommendations (Hermens & Freriks, 1997). EMG signals were recorded at 2000 Hz and filtered with a 4 Hz low-pass filter. Prior to the experimental tasks, a Maximal Voluntary isometric Contraction (MVC), performed against manual resistance by the experimenter, was performed successively for all muscles (exercises inspired of Pitcher and al., 2007 and Silvers & Dolny, 2011). All contractions were held 5 seconds and separated by at least 45 seconds of recovery. For each acquisition, a 100 ms sliding window was used to determine the maximum rectified and averaged value. This value was used as a reference value (Burden, 2010).

For both experimental tasks, RMS (Root Mean Square) value was calculated for each subject in both conditions. This value was normalised to the corresponding reference value. The normalised values of the 14 subjects were then averaged for each condition.

Force plateform

During both experimental tasks, an AMTI® force platform was placed under the participants' feet to assess the displacements of the centre of pressure (CoP) with and without the exoskeleton. The signal was recorded at 150 Hz. The average velocity of the centre of pressure (CoPv), averaged over the 14 participants, was chosen as the parameter of interest to study CoP displacement.

Motion capture

Kinematics analysis was performed using motion capture software (MVN, Xsens Technologies, Enschede, The Netherlands). 17 inertial units were placed on the whole body.

For both tasks, average angles (in flexion/extension) of the hips, knees, ankles and Vertical-T8 were calculated. The range of motion (ROM) of the above-mentioned joints was also calculated for the dynamic task. For this task, the 10 load-bearing repetitions were segmented and averaged. The segmentation was performed using the Vertical-T8 angle pattern. For each angle studied, an average pattern of the 14 subjects was plotted in both conditions.

Perceived discomfort

Perceived discomfort (PDR) of the lower limbs, torso and dorsolumbar area was assessed using a Borg scale (CR10 scale – Figure 2). Participants were asked to rate these 3 parameters after each task, in both conditions.

0	None
0,5	Very, very light
1	Very light
2	Light
3	Moderate
4	
5	Intense
6	
7	Very intense
8	
9	Very, very intense
10	Maximum

Figure 2: CR10 scale

Statistiques

Statistical analyses were carried out with JASP software (version 0.16.1.0). As the sample was relatively small (N = 14), the *a priori* assumption of the Student's paired samples *t*-test (normality of the distribution of differences) is not always respected. Its non-parametric equivalent, the Wilcoxon test, was therefore used. The significance level was set at 5 % ($p < 0.05$). The values presented are the means of the 14 participants ± standard deviations.

RESULTS

EMG

Task 1: load lifting

EMG results of the load-bearing task presented in Figure 3 showed a significant effect of wearing the exoskeleton on two muscles: there was an 18.3 % reduction in longissimus activation (p = 0.006) and a 28.6 % increase in external oblique activation (p = 0.007). No statistically significant differences in EMG activity were reported for the other muscles in this task.

Task 2: static trunk flexion

During the trunk flexion task, there was a significant reduction in the activation of the longissimus (p < 0.001), as well as the latissimus dorsi (p = 0.004), by 18.2 and 18.8 % respectively. The activation of the rectus femoris was also significantly reduced by 19 % during this task (p = 0.002). The activity of the other muscles was not significantly affected by wearing the exoskeleton.

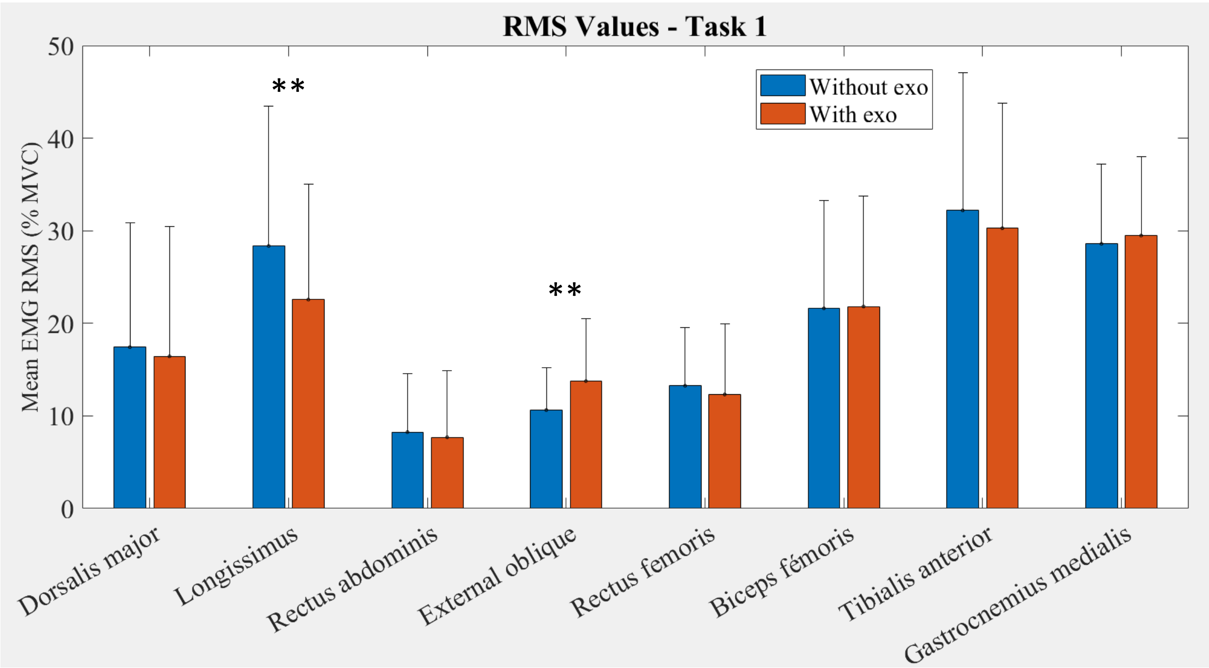

Figure 3: mean EMG values normalized by MVC, with and without exoskeleton for the load lifting task. Asterisks define a significant differance (= p < 0,05 ; ** = p < 0,01 and *** = p < 0,001) compared to the reference condition (without exoskeleton)*

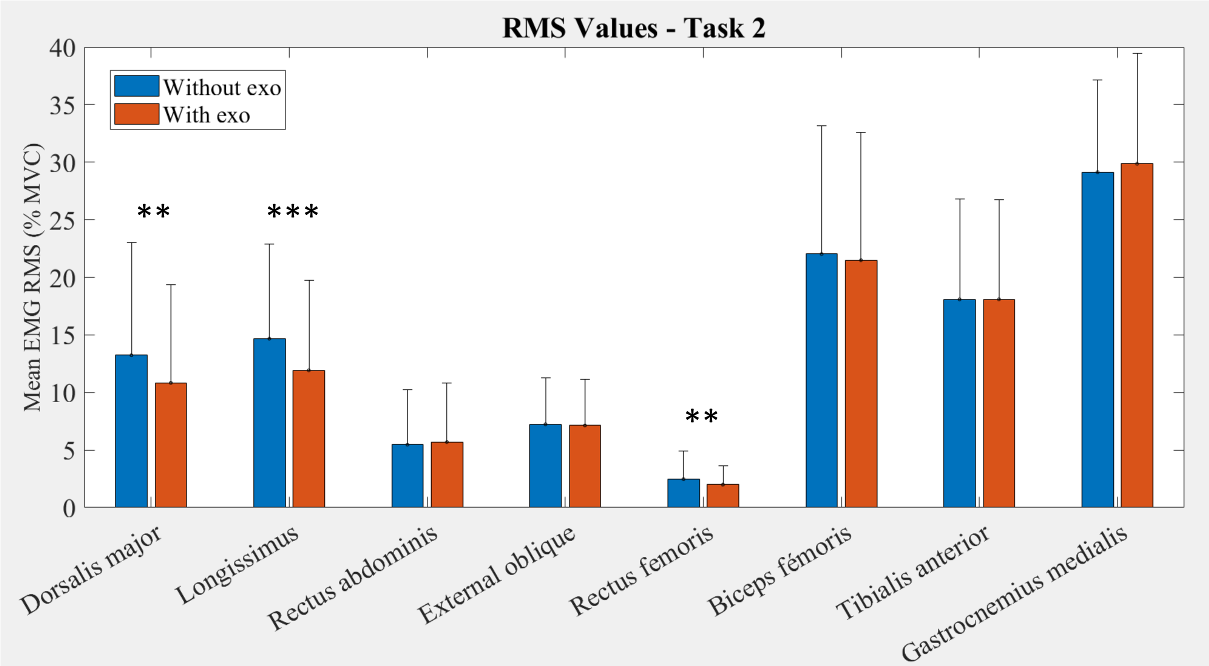

Figure 4: mean EMG values normalized by MVC, with and without exoskeleton for the static trunk flexion task. Asterisks define a significant differance (= p < 0,05 ; ** = p < 0,01 and *** = p < 0,001) compared to the reference condition (without exoskeleton)*

Kinematics

Task 1: load lifting

Hip ROM presented in XXX Figure 5 was significantly lower "With exo"; a reduction of approximately 6.5 % (p = 0.025 for the left hip and p = 0.005 for the right hip). The mean hip angles were not significantly different between both conditions.

The mean Vertical-T8 angle (Figure 6) corresponding to trunk flexion was significantly higher in the "With exo" condition (39.5° instead of 36.5°) (p = 0.035). The ROM was also higher in this condition but not significantly. ROM and mean angles of the knee and ankle didn't show significant differences between the two conditions.

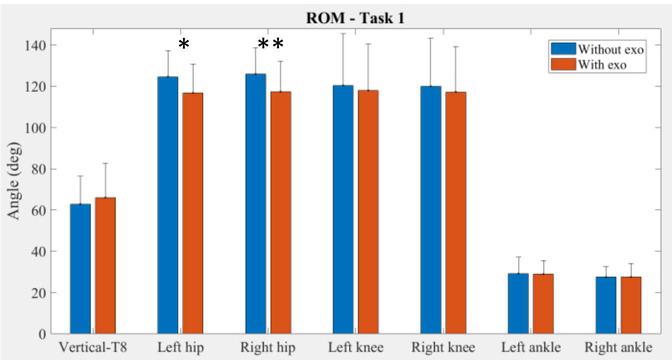

Figure 5: Mean values of joints range of motion, with and without exoskeleton for the load lifting task. Asterisks define a significant differance (= p < 0,05 ; ** = p < 0,01 and *** = p < 0,001) compared to the reference condition (without exoskeleton)*

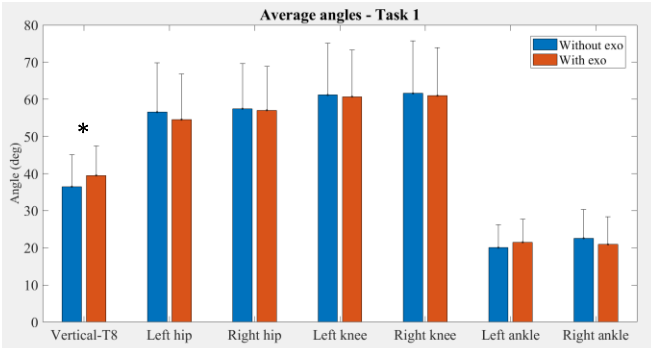

Figure 6: Mean values of joints angles, with and without exoskeleton for the load lifting task

Task 2: static trunk flexion

During the trunk flexion task, the mean Vertical-T8 angle was 42.4° (± 4.1°) without exo and 40.9° (± 6.6°) with exo. The reduction of the mean angle from one condition to the other was not statistically significant.

The mean hip angle was lower with exoskeleton (significantly for the left hip; p = 0.035). The average knee and ankle angles were not significantly different between both conditions.

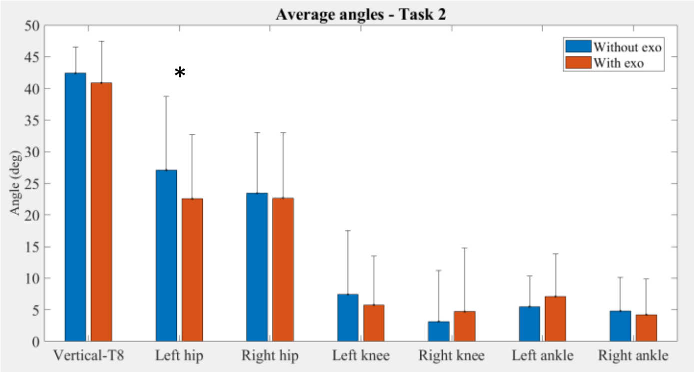

Figure 7: Mean values of joints angles, with and without exoskeleton for the static trunk flexion task. Asterisks define a significant differance (= p < 0,05 ; ** = p < 0,01 and *** = p < 0,001) compared to the reference condition (without exoskeleton)*

Force plateform

Due to technical issues, subjects 4 and 14 were excluded from the platform results for task 1 and subject 8 was excluded for task 2. The center of pressure displacement velocity (CoPv) was not statistically different between conditions in both tasks.

Task 1: load lifting

The CoPv measurements for the first task were:

- CoPv without exo = 0,091 m.s^{-1}
- CoPv with exo = 0,086 m.s^{-1}

Task 2: static trunk flexion

For the second task, the speed of movement of the center of pressure was:

- CoPv without exo = 0,0059 m.s^{-1}
- CoPv with exo = 0,0058 m.s^{-1}

Perceived discomfort

Task 1: load lifting

Subjective results when carrying a load presented in Figure 8 showed a reduction in the average perceived discomfort score for lower limbs (from 3.7 to 3.1/10) and in the thoracolumbar area (from 3.5 to 2.2/10; p = 0.027). When wearing the Hapo, the discomfort score was the same for the torso in both conditions (2.0 and 2.1/10).

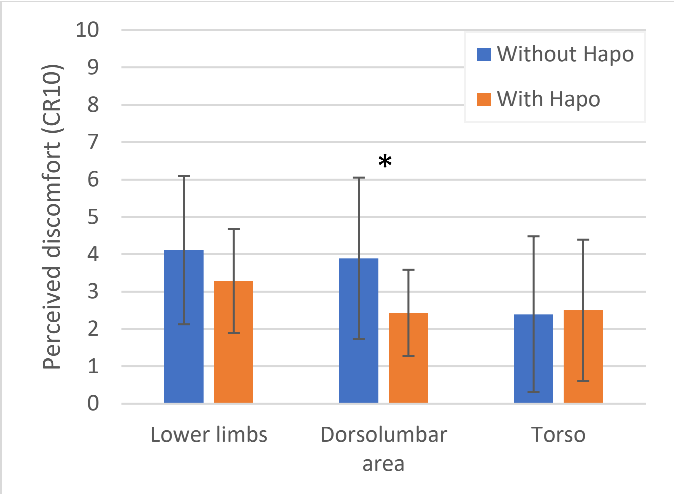

Figure 8: Subjective results for the load lifting task: perceived discomfort with and without the exoskeleton. Asterisks define a significant differance (= p < 0,05 ; ** = p < 0,01 and *** = p < 0,001) compared to the reference condition (without exoskeleton)*

Task 2: static trunk flexion

Perceived discomfort results for task 2 (Figure 9) showed similar trends to task 1: reduction in perceived discomfort on the lower limbs (from 3.0 to 2.5/10) and back (from 3.5 to 1.9/10; p = 0.004) when wearing the exoskeleton, and almost identical score for the torso (1.2 and 1.3/10).

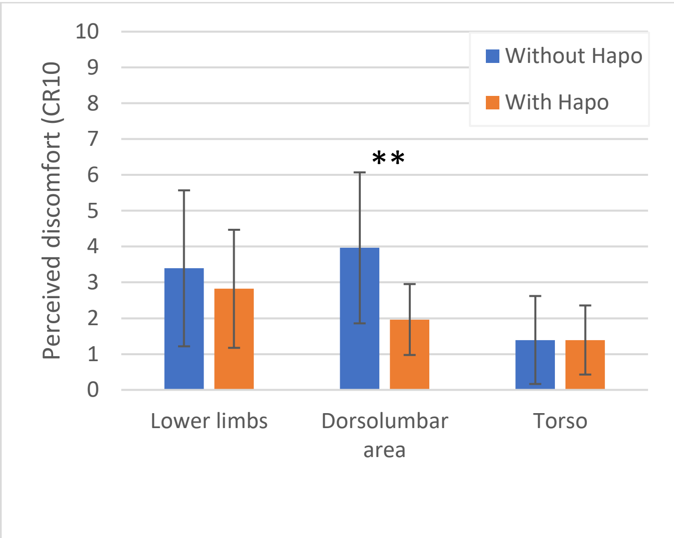

Figure 9: Subjective results for the static trunk flexion task: perceived discomfort with and without the exoskeleton. Asterisks define a significant differance (= p < 0,05 ; ** = p < 0,01 and *** = p < 0,001) compared to the reference condition (without exoskeleton*

DISCUSSION

The goal of the present study was to evaluate the effects of the passive trunk exoskeleton Hapo on the operator's muscle activity, kinematics, postural balance and perceived discomfort during both lifting/lowering and trunk flexion tasks.

Task 1: load lifting

It was seen that the ROM and mean hip angles were lower with the Hapo. These results, studied in conjunction with the mean hip movement curves (Figure 10) have shown that the Hapo slightly reduces the range of motion of the hip (less extension and less flexion).

Results presented in Figure 11 also show a higher trunk flexion for the "With exo" condition. Moreover, according to the curves representing this average angle during the movement, the value for the "With exo" condition is always higher than the "Without exo" condition. This is even more true when subjects grasp and put down the load. In general, while subjects are wearing the exoskeleton, they are more likely to bend the trunk when they are going to the ground whereas they straightened less when extending their trunk. This can probably explain by the fact they want to take full advantage of the assistance. This slight difference in kinematics is the only notable one since the ROM and average angles of the knees and ankles showed no significant difference between the two conditions.

EMG results of the lifting task show assistance from the Hapo on the back muscles: activation of the longissimus is significantly reduced by 18.3% while latissimus dorsi muscular activity is reduced, but not statistically significant. Baltrusch and al. (2019) who evaluated a comparable physical assistance device during a lifting task, have also observed a tendency of the exoskeleton to reduce the activity of the spinal erectors. Authors specified the effort exerted by the trunk extensor muscles is partly supported by the torque generated by the exoskeleton.

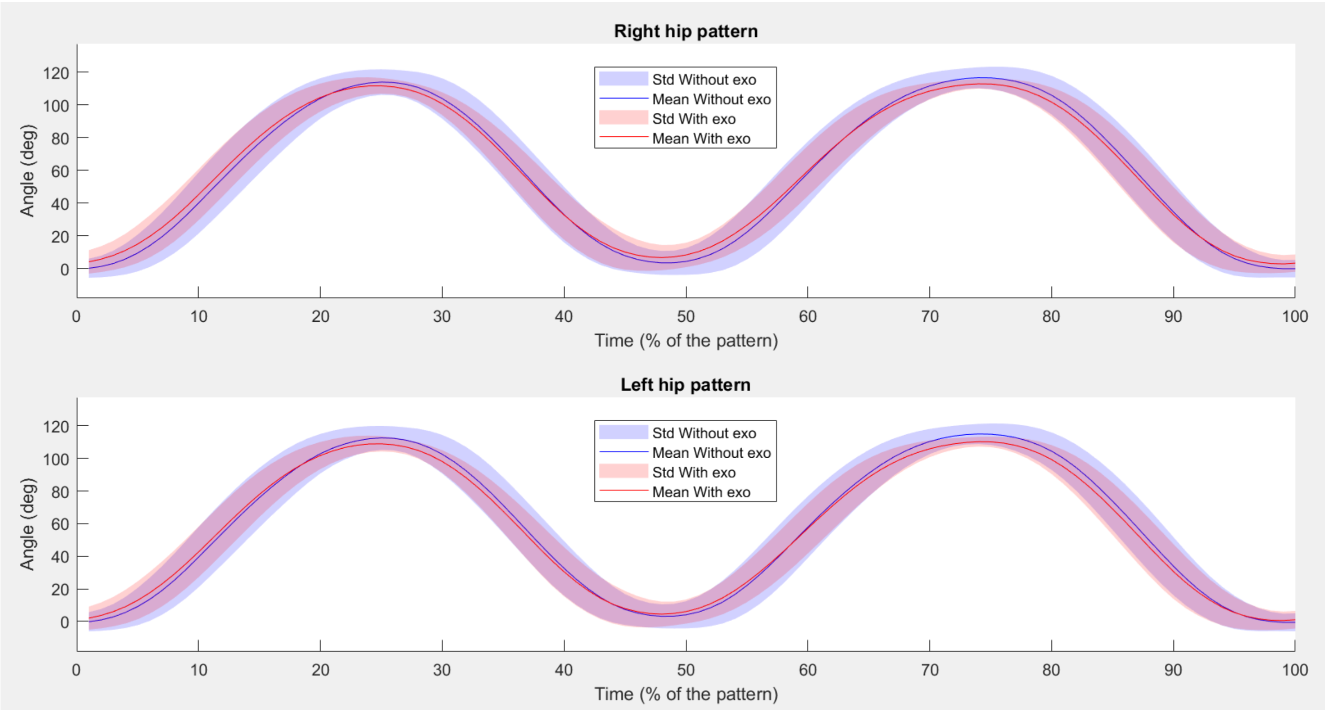

Figure 10: Mean values of hips flexion angles during the averaged flexion/extension movement, with (red curve) and without exoskeleton (blue curve) for the load lifting task.

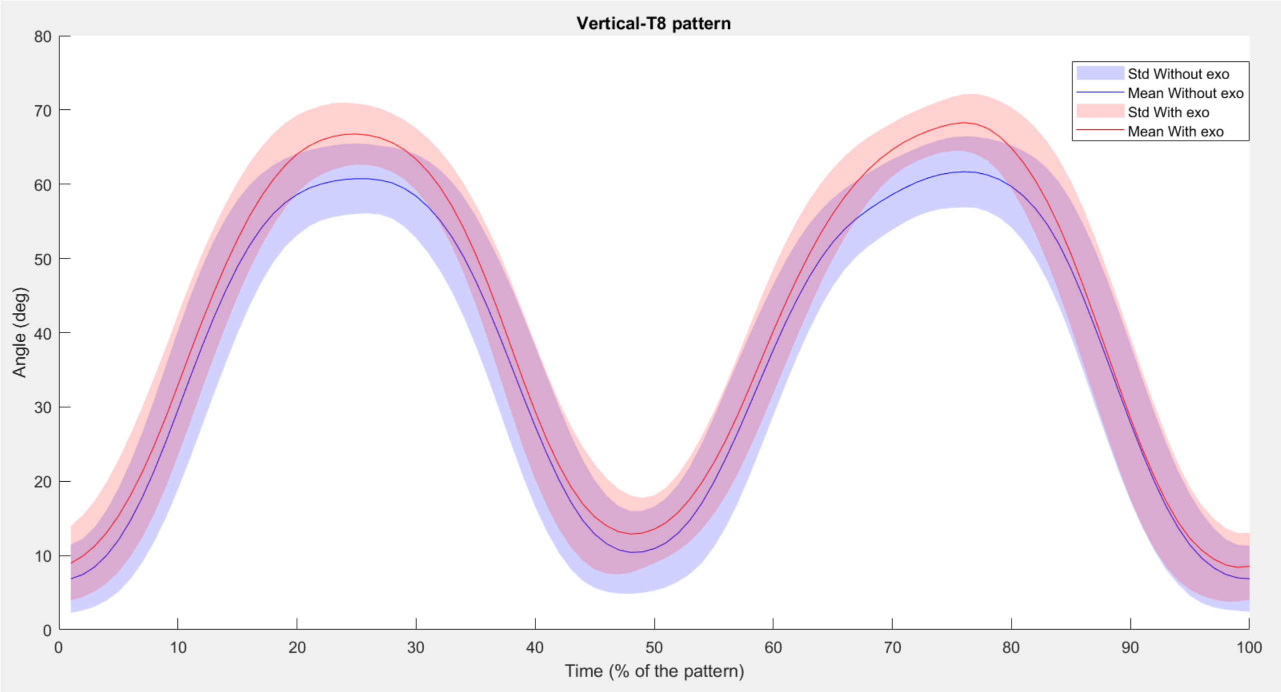

Figure 11: Mean value of the Vertical-T8 angle during the averaged flexion/extension movement, with (red curve) and without exoskeleton (blue curve) for the load lifting task.

The greater trunk flexion with exoskeleton, mentioned above, could induce two opposite effects on the EMG results of the longissimus. On the one hand, increased trunk flexion amplifies the moment on the hip joint, which could attenuate the observed reduction of activation on the longissimus induced by the exoskeleton. On the other hand, Koopman et al. (2019), who evaluated another back-assist exoskeleton for static trunk flexion tasks, point out that the interpretation of EMG activity of back muscles can be complicated due to the flexion-relaxation phenomenon. This phenomenon corresponds to a phase of non-activation of the superficial back extensor muscles commonly observed at the end of the anterior flexion of the trunk starting from an erect standing position (Bourigua, 2014). This implies that a reduction in EMG does not always mean that the back load is reduced. It could also reflect a shift in load from active structures to passive structures. Additionally, flexion-relaxation occurs at different lumbar flexion angles in different individuals. Therefore, lumbar EMG can vary greatly between subjects in a given posture, and subtle variations in posture can mask the effects of an exoskeleton on EMG (Koopman et al., 2019).

External oblique muscle activity increases significantly by 28.6 % when wearing the Hapo, going from 10.7 % MVC to 13.8 % MVC, even though this muscle is relatively little used during the task. One of the functions of the external oblique, in bilateral contraction, is the trunk flexion, which is a necessary movement during the lifting/lowering task. During this movement, the forces developed by the external obliques and the exoskeleton act in opposition. This muscle is therefore more used during the flexion phase to counterbalance the resistance of the springs. Alemi et al. (2019) also observed a 16–39 % increase in the external oblique when wearing a comparable exoskeleton during different lifting tasks. According to them, it is likely due to the fact many of the participants were not fully adapted to wearing the exoskeleton because of too short time for familiarization. This could imply that some individuals were co-contracting abdominal muscles instead of letting the exoskeleton support their torso's weight during lifting. If this augmentation should not be bothersome for healthy users, this type of exoskeleton could be contraindicated for people suffering from pathology of the abdominal muscles.

It seems surprising that the rectus abdominis muscle, also a trunk flexor, was not more used when wearing the exoskeleton. Baltrusch et al. (2019) had found a significant increase in the activation of the external oblique and of the rectus abdominis when wearing another exoskeleton model (on a similar task).

Thigh muscles were not significantly affected by wearing the Hapo. Alemi et al. (2020) also did not observe a significant difference on the thigh muscles with two other exoskeleton models. However, results of the present study show a trend for the rectus femoris muscle with a reduction of 7.4 % when wearing the Hapo. Knowing this muscle is involved in both hip flexion (trunk flexion phase) and knee extension (trunk extension phase), it would have made sense to consider one of the three other quadriceps muscles (which are not involved during the trunk flexion phase). It would have helped to more accurately quantify the possible assistance of the exoskeleton on the thighs. According to Alemi et al. (2019), the use of the exoskeleton studied by the authors reduced the peak activity on the vastus lateralis muscle by approximately 19 % and 17 %, respectively for symmetric and asymmetric lifting tasks.

Results from the force platform do not show a significant difference in CoPv. Therefore, the Hapo does not seem to have an effect on the subjects' postural balance. Furthermore, based on the results of the anterior tibial and medial gastrocnemius postural muscles (no significant difference), it appears that there are no additional anticipatory postural adjustments with the Hapo.

Regarding subjective results during the lifting task, the average perceived discomfort in the thoracolumbar area reflects the EMG results of the erector spinae muscles. There was a significant reduction in perceived discomfort from moderate (3.5/10) to low (2.2/10). Reduction in perceived discomfort on the lower limbs (not significant) could be related to the possible assistance on the rectus femoris mentioned above. It could also be caused by a placebo effect. The average perceived discomfort score for the torso was similar in both conditions, indicating good comfort with the exoskeleton straps.

Task 2: static trunk flexion

During this task, subjects had to remain in a static trunk flexion posture, with a 40° angle between the vertical and the trunk. The measured angle was on average 42.4° without exo and 40.9° with exo, with standard deviations of 4.1° and 6.6° respectively. The reduction in mean angle from one condition to the other condition is not statistically significant.

On a similar task, Bosch et al. (2016) who have evaluated the effects of another exoskeleton, have observed a higher trunk flexion angle with the exoskeleton compared to the condition without (38.0 ± 7.5 versus 32.8 ± 5.4). According to the authors, this was explained by the fact that flexing the trunk requires much less muscular effort when wearing the exoskeleton (37 % reduction on the longissimus). Based on their kinematics and EMG data, they concluded muscle activity in the lower back was significantly and substantially lower with the exoskeleton, even though the flexion angle was higher in this condition.

Since the instructions for their task were the same as in the present study (40° flexion, corrected during the task by the experimenter), it is possible that the difference observed in the two studies is rather the consequence of experimental biases or random facts.

EMG results of the present study for the second task show a significant reduction in the muscle activity of the latissimus dorsi and the longissimus, of 18.2 and 18.8 % respectively. It can be concluded the Hapo also help to reduce the activation of back muscles during a static task.

The rectus femoris muscle was also significantly less solicited with the Hapo (19.3 %) compared to the condition without the exoskeleton, but this should be put into perspective given the low level of use of this muscle in both conditions (2.5 and 2.0 % of the MVC). The other muscles were not significantly affected by wearing the exoskeleton.

Bosch et al. point out that the exoskeleton they have studied is attached to the front of the thighs (this is the same for the Hapo), are leading to a rearward force on the lower limbs. They hypothesised this force might induce hyperextension of the knees, causing a higher activity of the biceps femoris in compensation. This hypothesis was neither confirmed by the authors, nor in the present study. However, Bosch et al. Bosch et al. observed greater knee extension with exoskeletons and feared a risk for the health of the users' backs and/or knees. The kinematic results of the present study do not seem to support these observations, as the Hapo had little impact on the position of the lower limbs. The average angles of the knees and ankles are not significantly impacted by the condition. The left hip mean angle was the only one to be significantly lower (4.5° difference) with the exoskeleton, which was not the case on the other body side.

Postural balance of the subjects was also not impacted during this task: neither the CoPv nor the RMS of the gastrocnemius and the tibialis anterior were significantly different from one condition to another.

Regarding subjective results, the same trends were observed as for task 1: reduction of the perceived discomfort on the lower limbs even though they are not significant (from 3.0 to 2.5/10), the back (from 3.5 to 1.9/10), and almost the same score for the torso. These results are consistent with the EMG results.

LIMITS

Limitations of the study are mainly related to the sample. As for most of lab evaluations, participants did not cover the entire working population, being relatively young and in good health. Caution should therefore be exercised in generalizing the current results for older, injured and/or overweight workers. In addition, participants are almost all employees from ErgoSanté. Even though they are not involved in the design of the exoskeleton, this could represent a bias of the study, especially with regard to subjective results.

Another limitation to consider is the short duration of experimental tasks. Some discomforts could, for example, be revealed over longer periods of use. It would be very interesting to evaluate the impact of the exoskeleton in a longer-term use and in real work situation.

CONCLUSION

Reductions in EMG signal amplitude observed on spinae erectors, as well as the reductions in perceived discomfort on the thoraco-lumbar area, help to conclude the Hapo reduces muscular efforts. This passive exoskeleton could therefore constitute an effective strategy to reduce the risk to develop low back pain during work requiring trunk flexion, whether dynamic or isometric, complete or not.

Results of this study made it possible to ensure that the device did not create harmful constraints on users. Except the increased activation of the external oblique during the dynamic task, the exoskeleton did not significantly overstress neither antagonistic nor postural muscles studied. It also did not disturb users' balance.

Finally, kinematics analysis showed small changes from one condition to another, which could slightly vary the reduction in erector spinae activation. No modification of the operator's kinematics potentially hazardous for him was observed.

DISCLOSURE OF INTEREST

The authors are affiliated to the company that develop and sell the exoskeleton.

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