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The effects of a passive exoskeleton on muscle activity, discomfort and endurance time in forward bending work

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A B S T R A C T

Exoskeletons may form a new strategy to reduce the risk of developing low back pain in stressful jobs. In the present study we examined the potential of a so-called passive exoskeleton on muscle activity, discomfort and endurance time in prolonged forward-bended working postures.

Eighteen subjects performed two tasks: a simulated assembly task with the trunk in a forward-bended position and static holding of the same trunk position without further activity. We measured the electromyography for muscles in the back, abdomen and legs. We also measured the perceived local discomfort. In the static holding task we determined the endurance, defined as the time that people could continue without passing a specified discomfort threshold.

In the assembly task we found lower muscle activity (by 35–38%) and lower discomfort in the low back when wearing the exoskeleton. Additionally, the hip extensor activity was reduced. The exoskeleton led to more discomfort in the chest region. In the task of static holding, we observed that exoskeleton use led to an increase in endurance time from 3.2 to 9.7 min, on average.

The results illustrate the good potential of this passive exoskeleton to reduce the internal muscle forces and (reactive) spinal forces in the lumbar region. However, the adoption of an over-extended knee position might be, among others, one of the concerns when using the exoskeleton.

1. Introduction

Work-related musculoskeletal disorders (WMSDs) affect a considerable proportion of the working population. Of all WMSDs 30% are located in the low back region (Eurostat, 2010). Low back pain (LBP) frequently results in sick leave and disability, and thus, puts a large burden on individuals and the society (Goetzel et al., 2003). The development of work-related LBP has been associated with several work factors, among others lifting and carrying of loads and awkward body postures like trunk flexion and rotation (Griffith et al., 2012; Da Costa and Vieira, 2010). Hereto, various preventive measures have been proposed, e.g. the training of workers, the adjustment of work stations, the re-organization of work processes, and the use of mechanical aids like cranes or balancers (Lavender et al., 2013). From the developments of new technologies, other potentially preventive strategies emerge. One of these could be the use of exoskeletons.

An exoskeleton is a wearable device supporting the human to generate the physical power required for manual tasks. Exoskeletons could be useful, when (i) other preventive measures are not feasible, usable or effective, and (ii) where the automation of tasks is not feasible when tasks constantly change (e.g. the job of movers, unloading loose loads from containers, patient handling). Exoskeletons could be classified as 'active' or 'passive' (Lee et al., 2012). An active exoskeleton is comprised of one or more actuators (e.g., electrical motors) that actively augments power to the human body. A passive system does not use an external power source, but uses materials, springs or dampers with the ability to store energy from human movements and release it when required.

Active exoskeletons have been particularly developed for the purpose of rehabilitating injured or disabled people. Active exoskeletons with an occupation or industrial purpose are being developed, but these are mainly in a laboratory stage now (e.g., Kadota et al., 2009; Lee et al., 2012; Luo and Yu, 2013; Looze de et al., 2015).

On the other hand, several passive systems ready to be used in work situations, have been described in the literature. These

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include the Personal Lifting Assistive Device (PLAD) and the Bending Non-Demand Return (BNDR). Both devices consist of a frame that stores elastic energy when bending forward, which then helps a person to prolong bent-forward working postures or to erect the body again when lifting an object. The BNDR frame covers the trunk and pelvis and is supported by the upper legs and chest (Ulrey and Fathallah, 2013a). The final version of PLAD frame supports sharing of the load between the spine, shoulders, pelvis and feet (Whitfield et al., 2014).

For the PLAD, significant reductions of the back muscle activity during lifting have been reported (Abdoli-Eramaki et al., 2008; Lotz et al., 2009; Whitfield et al., 2014) and during static bending (Graham et al., 2009). For the BNDR, the back muscle activity was studied in a constrained isometric posture by Ulrey and Fathallah (2013a). They found a reduction of muscle activation in a subselection of their study population (namely only in those subjects not experiencing the flexion-relaxation phenomenon when adopting isometric torso flexion postures).

In the current study, the effect of a passive exoskeleton was studied on the activity of the back muscles during a simulated assembly task with the trunk in bent forward position. We additionally measured the muscle activity of the abdominal muscles and the hip extensor to study the occurrence of any potential negative side effects. We also measured local perceived discomfort. In a separate task, namely in static holding of the upper body in forward flexion, we studied the effect of the exoskeleton on endurance time.

2. Methods

2.1. Participants

In this study eighteen healthy participants (nine male, nine female, mean age was 25 (SD 8) years, mean body mass was 71 (SD 12.4) kg and mean height 1.76 (SD 0.1) m), volunteered to participate in the study. None of the participants reported low back pain in the previous three months. Subjects signed an informed consent, after being informed about procedures of the experiment. The study was approved by the Ethics Committee of VU University Amsterdam.

2.2. Passive exoskeleton

In the study, a passive exoskeleton (Laevo, Delft, The Netherlands) was used as presented in Fig. 1. This exoskeleton consists of three types of pads: two chest pads, one back pad and two (upper) leg pads. On both sides of the body, the pads were connected through a circular tube with spring like characteristics. The exoskeleton is intended to transfer forces from the lower back to the chest and leg pads.

2.3. Procedure

Participants performed two different tasks, i.e. assembly work and a static holding task, with and without wearing the exoskeleton. All subjects started with the assembly task, followed by the holding task. The order of the two conditions (with and without exoskeleton) within the tasks was systematically varied across subjects. To familiarize the participants with the experimental equipment and procedure, a training session was performed prior to the first condition. All sessions were performed in a laboratory at a constant ambient temperature of 22 °C.

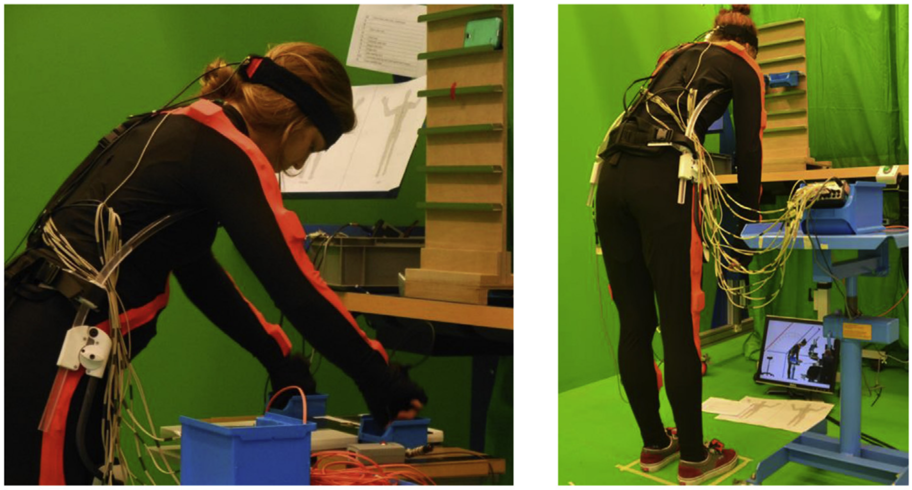
Fig. 1. The passive Laevo exoskeleton used in the current study.

2.4. Tasks

2.4.1. Task 1 – simulated assembly

The first task involved repetitive pick and place actions so as to simulate industrial assembly work as described by Bosch et al. (2011). The task was performed using a Perdue pegboard (Purdue Pegboard Model 32020; Lafayette Instrument Company, Lafayette, IN, USA) centrally positioned in front of the participant. Participants had to pick, place and remove 10 pairs of pins in a fixed order with the left and right hand simultaneously on the beat of a metronome (2/3 Hz). Bins with these components were placed to the left and the right of the participant (Fig. 2). Working height was standardized placing the table surface 15 cm below the participants Trochanter Major. At the start and end of each work cycle, participants had to move the two bins to a fixed position at shoulder height in front of them and push a red button at the right side of the Pegboard. When performing the pick and place actions participants adopted a 40° trunk flexion (defined as the angle between the line from L5-C7 with the vertical, Fig. 2A). In between pick and place work cycles participants had to adopt an upright neutral posture, with the hands hanging alongside the body for 30 s. In total ten work cycles were performed.

To control the predefined trunk flexion angle during the assembly task, feedback on the body posture was given to the subjects by the experimenter using the Ergomix (Hallbeck et al., 2010). Two parallel lines with a 40° angle were projected and presented to the subject. The subjects had to keep their trunk between these two



(A) (B)

Fig. 2. A participant wearing the Laevo exoskeleton and performing (A) the simulated assembly work and (B) the static holding task.

parallel lines. One of the experimenters constantly checked whether the participant still stood in the correct position. When the trunk posture deviated from the predefined posture, the experimenter verbally corrected the participant.

2.4.2. Task 2 – static holding

Participants were instructed to maintain a forward flexed trunk posture (40°) while both hands were hanging down vertically (Fig. 2B). Trunk posture was controlled in the same way as in the assembly task. Every 30 s subjects were asked to rate their discomfort score. When the subjects rated 2 on the Borg scale (i.e. "slight discomfort") in any of the back regions, the experimenter stopped the measurement and noted the endurance time. The subjects were not informed about the reason the experimenter stopped the task, to avoid bias during the other condition.

2.5. Measurements

2.5.1. Electromyography

Electromyographic (EMG) activity of the left and right m. Trapezius pars Ascendens (TA), m. Erector Spinae Longissimus (ESL), m. Erector Spinae Illiocostalis (ESI), m. Obliquus External Abdominis. (OA), m. Rectus Abdominis (RA) and m. Biceps Femoris (BF) were recorded using a porti 16/ASD system (TMS, Enschede, The Netherlands). Bipolar Ag/AgCl (Medicotest; Ambu A/S, Ballerup, Denmark) surface electrodes were positioned according to Hermens et al. (2000) with inter electrode distance of 20 mm. A reference electrode was placed on the C7 spinous process. Before the electrodes were applied, the skin was shaved, scrubbed and cleaned with alcohol. EMG signals were sampled at a sampling rate of 2000 samples/s and band-pass filtered (10–400 Hz) in both tasks. For both tasks the EMG recordings during the forward bending phase were used for analysis. The forward bending phase during the assembly task was determined by the signal of the button pushed by the participant at the start and end of each work cycle. The mean EMG amplitude was determined by averaging the band-pass filtered (10–400 Hz) and rectified signal, obtained by taking the absolute value of the each sample using a custom script in MATLAB (The MathWorks Inc., Natrick, MA, USA). EMG amplitudes were normalized for all muscles using three 3-s maximum voluntary contractions (MVCs) performed against manual resistance at the start of the experiment. Each MVC was followed by a rest period of at least 1 min. MVC data were band-pass filtered (10–400 Hz). A 0.5-s moving window was used to determine the maximum rectified and averaged value for each muscle across both MVCs.

2.5.2. Kinematics

The trunk posture of the participants was recorded by a full body inertial motion capture system (MVN, Xsens Technologies, Enschede, The Netherlands). This system comprises a suit, equipped with 17MTx sensors. Prior to the experiment, participants' body dimensions and calibration poses were measured according to Xsens calibration protocol with the MVN software (MVN Biomech 3.1), to fit and scale the MVN Biomech model to the participant. Positions of anatomical landmarks were not measured directly, but derived from sensor orientations in combination with the biomechanical model. The anatomical landmarks were collected at a sample rate of 120 Hz and exported in a C3D format. A custom script in MATLAB (The MathWorks Inc., Natrick, MA, USA) was used to calculate the trunk angle, defined as the angle between a vector from the C7 spinous process to the L5 spinous process and a vertical downward vector (Könemann et al., 2015). For both tasks the kinematic recordings during the forward bending posture were used for analysis. To avoid noise from the XSENS-suit in the EMG signal, foam rings were placed over the EMG electrodes, in such a way that the suit did not touch the electrodes.

2.5.3. Discomfort

Discomfort in the back, legs and chest was measured using the Local Perceived Discomfort Scale (LPD). A body map consisting of eight regions of the posterior side of the body and seven regions of the anterior side of the body, was presented to the subjects (Grinten van der, 1991). Subjects were asked to rate their discomfort in the regions identified on a 10-point scale (ranging from 0 = no discomfort to 10 = extreme discomfort, almost maximum). Every other cycle, the experimenter asked the subject to rate their discomfort in any of the regions during the assembly task. The change in maximum LPD score per region (back, legs and chest) after 10 min of assembly work was used as the measure for discomfort. In the static holding task the subject rated their discomfort every 30 s as mentioned above.

2.6. Statistical analysis

Data inspection indicated that neither EMG nor trunk kinematics deviated from normal distributions. Differences in mean EMG amplitude between the two conditions in the assembly task were therefore analyzed using a three-way ANOVA for repeated measures with factors independent factors side (left/right), exoskeleton (with/without) and time (10 work cycles). To evaluate the effects of the exoskeleton in the static holding task, differences in mean EMG amplitude were analyzed using a two-way ANOVA for repeated measures with independent factors side (left/right) and exoskeleton (with/without). Differences in trunk posture were tested using a two-way ANOVA with independent variables time (10 work cycles) and exoskeleton (with/without) for the assembly task and a paired sample t-test for the static holding task.

After carefully inspecting data, it was decided that LPD scores were not normally distributed. Differences between the two conditions (with/without exoskeleton) in LPD scores during the assembly task were analyzed using Wilcoxon signed rank tests, i.e. using participants as their own controls. Differences in endurance time were analyzed using a paired sample t-test. Significance was accepted at $p < 0.05$ and all statistical analyses were performed using SPSS (IBM SPSS Statistics v21.0.0).

3. Results

Due to technical failure, the data analysis could only be done for 17 subjects. No significant differences were found between left and right sided muscle groups. Therefore, the results for the left and right muscles were averaged in the results presented below.

3.1. EMG

The EMG amplitude during the assembly task was significantly lower for the lower back muscles (ESI; $p < 0.001$, $F = 29.66$ and ESL; $p < 0.001$, $F = 27.1$) when wearing the exoskeleton (Fig. 3A). Averaged over all participants and work cycles there was a 38% reduction of muscle activity for the ESI and a 35% reduction for the ESL with the exoskeleton (compared to without). The upper back muscles (TA) also showed a significant reduction of 44% in mean EMG amplitude when wearing the exoskeleton ($p < 0.001$, $F = 30.06$). The mean EMG amplitude of the BF was significantly reduced with almost 20% when subjects used the exoskeleton ($p = 0.006$, $F = 10.25$). For the abdominal muscles (OA and RA), no significant differences in normalized EMG amplitude were found between the two conditions. No significant changes over time were found for all muscles under research.

For the static holding task the mean EMG amplitude was again significantly lower for all back muscles (ESI; $p < 0.001$, $F = 32.24$; ESL; $p < 0.001$, $F = 30.43$ and TA; $p < 0.001$, $F = 29.78$) in the exoskeleton condition (Fig. 3B). Averaged for all subjects there was a 44% reduction of muscle activity for the ESI, 37% reduction for the ESL and 50% reduction for the TA when participants used the exoskeleton. The normalized EMG amplitude of the leg muscles (BF) was significantly reduced ($p < 0.001$, $F = 26.2$) with 24% when the exoskeleton was used. Again no significant differences between the two conditions were found for the OA. However in case of the RA the mean EMG amplitude was significantly lower when the participants used the exoskeleton ($p = 0.015$, $F = 7.48$).

3.2. Discomfort

The ratings of the local perceived discomfort were generally as low as shown in Fig. 4. In case of the back region, significantly lower LPD ratings were found when using the exoskeleton during the assembly task ($p = 0.021$, $Z = -2.31$). In case of the chest region, working with the exoskeleton did evoke significantly higher discomfort ($p = 0.023$, $Z = -2.27$). Finally, in the leg region no significant differences between the two conditions were found ($p = 0.53$, $Z = -0.63$).

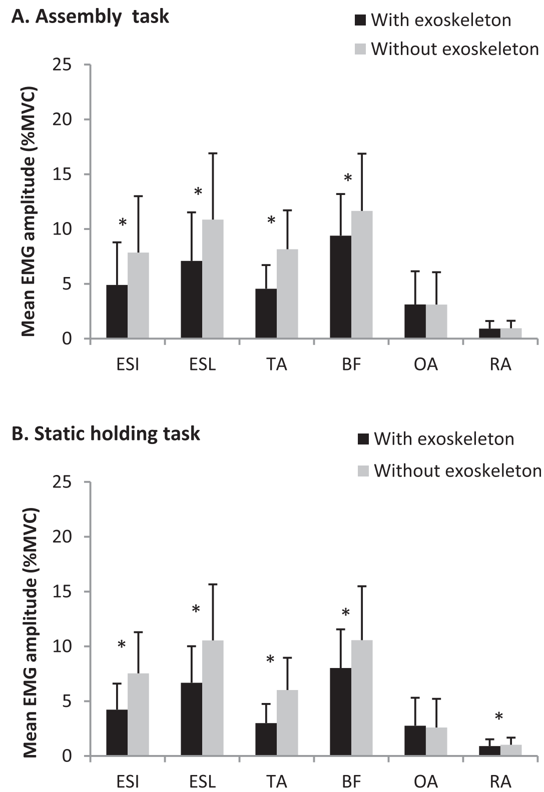


Fig. 3. Mean EMG amplitude (%MVC) values of the. m. Trapezius pars Ascendens (TA), m. Erector Spinae Longissimus (ESL), m. Erector Spinae Illiocostalis (ESI), m. Obliquus Abdominus (OA), m. Rectus Abdominus (RA) and m. Biceps Femoris (BF) with (black) and without (grey) exoskeleton condition for the assembly task (A) and the static holding task (B). Error bars indicate standard deviation. Significant results ($p < 0.05$) are marked with an *.

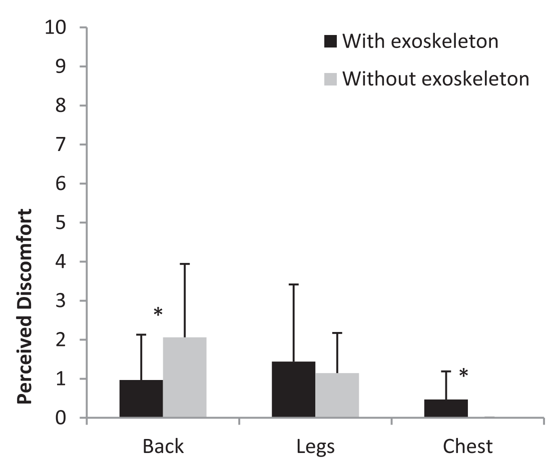


Fig. 4. Mean LPD scores for the back, leg and chest regions during the assembly task for the condition with (black) and without (grey) exoskeleton. Error bars indicate standard deviations. Significant results ($p < 0.05$) are marked with an *.

3.3. Trunk kinematics

For the assembly task the average trunk flexion angle was 5.2° larger in the condition where subjects used the exoskeleton (38.0 ± 7.5°) compared to where they did not (32.8 ± 5.4°). This difference was significant ($p = 0.001$, $F = 15.31$). The trunk flexion angle did not significantly change across time indicating that the trunk posture did not differ across the ten work cycles.

In the static holding task the average trunk flexion angle was 4.6° larger in the condition where subjects wore the exoskeleton (35.2 ± 11°) compared to where they did not (30.6 ± 6.8°). However, in contrast to the assembly task this difference was not significant ($p = 0.063$, $t = 1.99$).

3.4. Endurance time

It appeared that the endurance time for static holding in the forward bended trunk posture, was three times higher ($p < 0.001$, $t = 5.96$) when the exoskeleton was used (9.7 ± 4.9 min) compared to the situation without exoskeleton (3.2 ± 1.8 min).

4. Discussion

We studied the effect of a passive exoskeleton on muscle activity, discomfort and endurance time.

In the simulated assembly task we found lower muscle activity and lower discomfort in the low back region when wearing the exoskeleton. Additionally, the muscle activity of the hip extensor was reduced. The exoskeleton however led to more discomfort in the chest region.

In the task of static holding of the forward-bended position, we observed similar reductions of back and leg muscle activity in the with-exoskeleton condition. As a result, the endurance time was found to be almost three times longer.

4.1. Muscle activity and kinematics

We observed reductions in back muscle activity in the simulated assembly task, in the range of 35–38% when wearing the exoskeleton. Previously, the impact of the PLAD device has been investigated by Graham et al. (2009) during a two hours automotive assembly task: a 37% and 14% reduction in Erector Spinae activity was found at thoracic and lumbar level, respectively. Also for the BNDR positive effects on back muscle activity during static trunk bending were found: reductions ranged from 10.3% to 13.7% at a thoracic and lumbar level (Ulrey and Fathallah (2013a)). In a short conference paper, Barret and Fathallah (2001) describe the effects of the BNDR, HappyBack and Bendezy during static bending while holding loads. These three passive exoskeletons differed with respect to materials and mechanisms, but all showed positive effects, ranging from 21 to 31% reductions in Erector Spinae activity when using these devices. Thus, the reductions in back muscle activity observed in the current study are in line with these earlier observations, although relatively high.

We observed no effects on abdominal muscle activation, but we did find a reducing effect of the exoskeleton on the activity of the leg extensor (Biceps Femoris). The latter result is in line with earlier observations for BNDR, also showing slightly lower leg extensor activity (Ulrey and Fathallah, 2013a,b). With respect to the legs, it should be noted that our exoskeleton was attached to the front side of the upper legs and would apply a backward translating force on the upper legs. It could be hypothesized that this force forces the knees in an overstretched position and that the Biceps Femoris would be activated to prevent this. This hypothesis was not confirmed in our experiment. It appeared that the subjects did not withstand, but 'accepted' the overstretched knees. Thus, we did not find the expected increase in Biceps Femoris activity. Instead, we found a decrease, which might be explained by the hip extension function of the same muscle and the fact that in a forward bended posture the exoskeleton takes over part of the hip extensor moment. The decrease in leg muscle activity can be interpreted as another advantage of exoskeleton usage in forward bending work. On the other hand, we observed that the exoskeleton imposed over-extended knees and we do not know the health effect, if such would continue over longer periods of time. Hence we cannot exclude any health-risk shift from the low back to the knees.

During the experiment it was visually checked by one of the experimentators whether the subjects adopted the intended constant 40° trunk flexion in the condition with and without-exoskeleton. Subjects were directly corrected verbally in case of any visually observed deviations. From the measured kinetic data, it appeared that the trunk flexion remained constant across time in both conditions. However, between both conditions a systematic difference in trunk flexion angle occurred: more trunk flexion, by about 5°, was measured in the condition with the exoskeleton. Apparently, the wearing of the exoskeleton elicited the user to adopt more flexion, which can be explained by the fact that trunk flexion requires much less muscular effort when wearing the exoskeleton.

From these kinematic and afore mentioned EMG data, we can conclude that the muscle activity in the low back was significantly and substantially lower in the 'with-exoskeleton-condition', even despite the slightly more trunk flexion in this condition. As the activity of the back muscles is closely related to the spinal compressive forces, we can conclude that this exoskeleton has the potential to significantly reduce the musculoskeletal load in the low back region in workers who have to bend over for longer periods of time.

4.2. Discomfort and performance

The reduced muscular effort in the low back when using the exoskeleton was reflected in the ratings of local perceived discomfort. Significantly lower discomfort values were observed in the with-compared to without-exoskeleton condition. The ratings of discomfort in the upper legs was not affected by the wearing of the exoskeleton.

However the discomfort in the chest increased when using the exoskeleton during assembly work. The participants indicated that this was due to the pressure that they felt at the contact area in between the chest pads of the exoskeleton and the chest. Furthermore, subjects complaint about discomfort in their armpits, where the straps of the exoskeleton gave pressure and friction.

On the basis of these observations, the design of the exoskeletons and particularly the design of the attachment of the exoskeleton to the body, has been re-considered and adapted by the manufacturer. The Laevo now allows more degrees of freedom, allowing twisting and turning. The structures has been improved in resilient structures that bend like the spine and reduce the friction of the chest pad. Also, the obstruction of the armpits has been reduced during bending in plane as well as during twisting. An extra pivot reduces the supportive forces of the Laevo after a certain angle, enabling squatting and reducing the overstretching of the knee. The effectiveness of these design changes has not been investigated until now.

In the static holding task we measured the endurance time, which was defined as the time that workers could continue to hold the forward bent position without perceived back discomfort levels rising above 2 on the 10-point Borg scale (i.e. "somewhat severe"). Previous research showed that workers, reporting low back discomfort as somewhat severe at the end of a normal working day, showed a significant relative risk for developing low back pain of nearly 2.0 (Hamberg-van Reenen et al., 2008). Wearing the exoskeleton in our subject population increased endurance time from 3.2 to 9.7 min, respectively. This might be interesting form a practical and performance perspective, as workers may continue to work for longer periods of time without feelings of discomfort, that are unpleasant, may distract them and are risky in the end.

4.3. Final considerations

The observed reductions of muscle activity in the low back region illustrate the good potential of the passive exoskeleton to reduce the internal muscle forces and (reactive) spinal forces in the lumbar region. From these, we can conclude that the passive exoskeleton might form an effective strategy to reduce the risks of developing work-related low back pain in forward bent work. However, there also some concerns.

In our experiment we observed that subject had their knees in an over-extended position when using the exoskeleton. If this knee position would be adopted for longer periods, this may shift a health risk from the back to the knees. It should be studied whether this phenomenon had to do with our static task and specific work station set-up and whether this would also happen in other, more dynamic circumstances (where people would be less constrained to their position).

Another issue concerns the potential weakening of back muscles. In a study by Eisinger et al. (1996) on lumbar orthotics, it was concluded that prolonged use of these orthotics might result in weakening of the trunk musculature. Therefore they recommended either to limit the duration of the use or to combine the use with strengthening exercises. For the exoskeletons, it should be noted that reductions in muscle activity were significant but only partial. So muscles remain active, but to a lesser degree. Nonetheless, we would favour the recommendation to limit the use of exoskeletons to specific tasks and periods of time.

Passive exoskeleton systems have an absolute contribution and are independent of external forces such as a load that is lifted. As a result the exoskeleton can only compensate for the trunk moment from gravity. Effects of external forces were not taken into consideration in this study but might reduce the relative contribution of a passive exoskeleton. Moreover, lifting technique could affect the effectiveness of a passive exoskeleton considerably (Ulrey and Fathallah, 2013b).

Limitation of discomfort is a challenge in the design of exoskeletons, and might be a big issue standing in the way of wide application in the industrial field. Even a minimal level of discomfort might hinder user's acceptance. The latter might be different from the non-industrial exoskeletons aimed at supporting disabled people, where the exoskeleton could make the difference being able to walk or grasp or not.

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