Assessment of an active industrial exoskeleton to aid dynamic lifting and lowering manual handling tasks

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Abstract

The aim of this study is to evaluate the effect of an industrial exoskeleton on muscle activity, perceived physical exertion, measured and perceived contact pressure at the trunk, thighs and shoulders, and subjective usability for cyclical lifting and lowering. Twelve male participants lifted and lowered a box of 7.5kg and 15kg, respectively, from mid-shin height to waist height, five times, both with and without the exoskeleton. The device significantly reduced muscle activity of the Erector Spinae (12%-15%) and Biceps Femoris (5%). Ratings of physical exertion in the trunk region were significantly less with the device (9.5%-11.4%). The measured contact pressure was highest on the trunk (91.7kPa-93.8kPa) and least on shoulders (47.6kPa-51.7kPa), whereas pressure was perceived highest on the thighs (35-44% of Max LPP). Seven of the users rated the device usability as acceptable. The exoskeleton reduced musculoskeletal loading on the lower back and assisted with hip extensor torque during lifting and lowering. Contact pressures fell below the Pain Pressure Threshold. Perceived pressure was not exceptionally high, but sufficiently high to cause discomfort if used for long durations.

Introduction

Manual handling activities are associated with high rates of Work-Related Musculoskeletal Disorders (WMSDs) (Zurada, 2012, Collins and O'Sullivan, 2015). Despite the widespread use of robots, automation, mechanisation and work-related interventions in industry, many tasks are still performed manually by workers. In some jobs, workers are necessary to perform the work when it comes to observation and decision-making, and in other instances tasks benefit from human precision, skill and movement capabilities (Bos et al., 2004; Zurada, 2012, de Looze et al., 2015). Hence, despite increased automation, many jobs still require workers to perform manual handling tasks.

There is a growing interest in industry towards the use of wearable sensors and robotics technoloiges, including exoskeletons, to assist workers with performing manual handling activities (de Looze et al., 2015). The principle of an exoskeleton is to add mechanical power to the human body, thereby reducing the biomechanical load and reducing risk of WMSDs. Exoskeletons are typically classified as active or passive. Active systems comprise of one or more actuators to augment the human's power, whereas passive systems use material compliance to provide gravity compensation, and spring/elastic members to store and release energy during movements to assist workers to perform physical movements (de Looze et al., 2015; Matthew et al., 2015). Exoskeletons are also defined based on the fit and resemblance to the human body limbs. Anthropomorphic exoskeletons have joints with rotational axes aligned with the rotational movements of the major human joints, which is not the case with non-anthropomorphic types (de Looze et al., 2015).

Commercially available exoskeletons have been predominately developed for rehabilitation purposes, where the devices are aimed to support and assist physically weak, injured or disabled people with prescribed exercises and activities (Viteckova et al., 2013). A relatively small number of exoskeletons have been designed for military applications to enhance muscular strength and physical carrying capacity of soldiers (Anam and Al-Jumaily, 2012; Yan et al., 2015). Active industrial exoskeletons are remain mainly at research and development stage while passive exoskeletons have already entered the market. It is necessary for these technologies, particularly active exoskeletons, to demonstrate efficacy and safety in order to support their commercial opportunity and uptake in industry (de Looze et al., 2015).

Manual lifting has been well established as an occupational risk factor for back WMSDs (Zurada, 2012). While the objective of an industrial exoskeleton is to provide assistive power to the worker to reduce the risks in the work, the device must also have sufficient usability to be comfortable to use, so that workers accept and are willing to adopt the technology. Studies on exoskeleton prototypes have shown that they do not always achieve their objectives initially, by failing to meet the needs of the end users or stakeholders (Almenara et al., 2017). Nonetheless, the basic principle of providing biomechanical assistance has been proven, but sometimes with increased loading elsewhere in the body. For instance, the BNDR, HappyBack and Bendezy exoskeletons have been demonstrated to reduce erector spinae muscle activity by 21-31% but increase leg muscle activity (Barret and Fathallah, 2001).

A key factor affecting exoskeleton acceptance is local discomfort caused by the force applied to the body at the exoskeleton interface (contact pressure). If not carefully designed, the user may experience significant discomfort and possibly injury, which no doubt will lead lead to reluctance to use the device. There have been few studies of local discomfort and Pain Pressure Treshold (PPT) on exoskeletons.

The purpose of the current study was to perform an ergonomics assessment of an exoskeleton aimed to provide mechanical assistance to the body during lifting tasks to reduce WMSD risk of the back, while also aiming to minimise discomfort and contact pressure. The exoskeleton tested was developed as part of the EU-funded project Robomate (www.robo-mate.eu). Specifically, the objectives were to assess the effect of the exoskeleton on muscle activity, physical exertion, contact pressure, local perceived pressure and subjective usability for short duration cyclical lifting and lowering.

Method

Participants and ethics approval

Twelve healthy male participants with no prior or current injuries/musculoskeletal disorders gave written consent to participate in the study (Means & SD: Age: 27 years ± 2, Mass: 75.38kg ± 10.1, Stature: 1794mm ± 6.56). However, one of these participants was unable to complete the experiment, resulting in the exclusion of these data.

This study was performed in accordance with the Research Ethics Procedures of the Italian Institute of Technology, where the testing occurred.

Experimental design

The independent variables were LOAD (7.5kg and 15kg) and SYSTEM (with/without exoskeleton). The dependent variables were muscle activity (EMG: Rectus Abdominis, Erector Spinae at level of L3 vertebrae, Biceps Femoris) and perceived physical exertion. Additionally, contact pressure, perceived musculoskeletal pressure and usability were assessed for the ‘with exoskeleton’ conditions.

There were four treatments (LOAD X 2, SYSTEM X 2) in a full factorial design, which were performed by each participant in a randomised order (for LOAD and SYSTEM). The treatments involved lifting and lowering a box from mid-shin height to waist height five times.

Procedure

On entering the laboratory, participants were informed of the testing procedure and equipment involved. At that point anthropometric measurements were obtained followed by the preparation and attachment of the EMG electrodes on the muscles. After a detailed explanation, demonstration and setup of equipment (relative to participants’ shin and waist) by the lead investigator, participants first practiced the lifting task. Testing commenced once participants were proficient and comfortable with the testing requirements and procedure. The pressure mats were positioned at the three regions whilst the exoskeleton was being placed on the individual for the ‘with exoskeleton’ conditions.

Each participant performed cyclical lifting and lowering. When they had achieved the required proficiency level in the movements, they performed five cycles as the experimental run for each LOAD and SYSTEM treatment. Once experimentation was completed, the participants were required to perform two MVC measurements per muscle. MVC was conducted at the end to avoid fatigue prior to testing with the exoskeleton. Each muscle was maximally contracted for three seconds, with a one-minute rest period between trials. There was a break of a minimum of five minutes between treatments.

Equipment

Testing Equipment

A box (L: 43cm, W: 29cm, H: 16cm) and two loads (7.5kg and 15kg) were used. The box with handholes was positioned on an adjustable platform set to each participant's mid-shin height. The loads studied reflect a range from moderate to high in industrial tasks, whilst falling within lifting and lowering guideline weights suggested by Pheasant (2006). Similarly, the origin and destination for lift/lower were based on guidelines by Pheasant (2006) and ISO standards (ISO 14738:2008).

Exoskeleton

The exoskeleton is an active wearable type aimed to reduce back loading during lifting/lowering manual handling activities by providing assistive torque at the user's hip. The exoskeleton is attached to the trunk and the thighs and articulated to coincide with rotation about the hip region. The exoskeleton comprises three linked segments: a back unit with two leg units for both thighs (attachment via Velcro straps). The exoskeleton is worn by the user like a backpack (Figure 1). When put on, it is adjusted/aligned on the body via a number of straps on the back unit, and then the attachments at the thighs are secured. The physical assistance is adjusted in real time based on posture. No assistance is provided when the user is standing upright. Torques are gradually increased with forward inclination of the torso, so as to support it against gravity. Before testing commenced, starting at 20Nm, each participant could adjust the torque by ±5Nm. This was to assist with comfort and to enable the wearer to adjust the power as per their preference. After this adjustment, the selected torque remained constant throughout the testing duration.

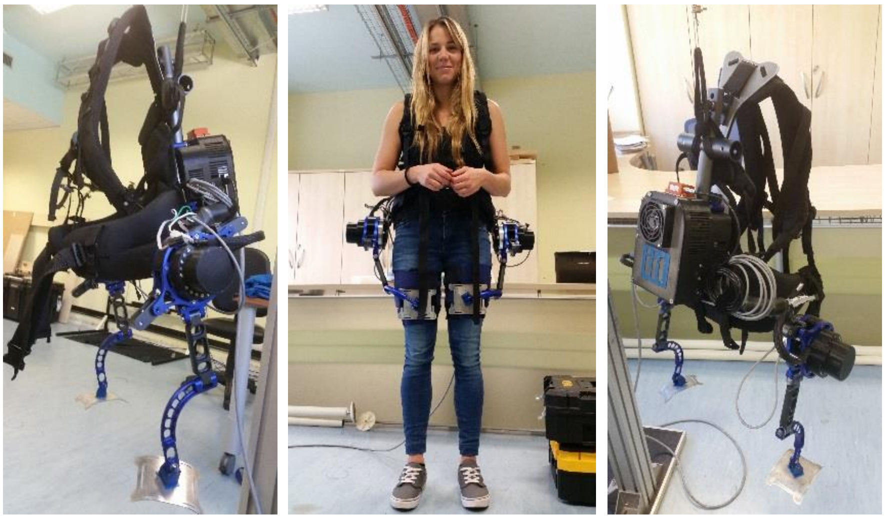

Figure 1: The active anthropomorphic exoskeleton tested

Surface electromyography

Muscle activity of three muscles on the right side of the body was studied: Rectus Abdominis, Erector Spinae at the level of L3 vertebrae and Biceps Femoris. Data were collected using a portable NeXus Mark II EMG system (Sampling rate: 2048Hz) with bipolar electrodes placed over each muscle (inter-electrode distance: 20mm) as per the guidance in the SENIAM protocol (Hermens et al., 2000). Nexus Bio Trace software was used to inspect and analyse the data. A ground electrode was placed on the C7 spinous process. Before electrodes were applied, the skin was shaved, scrubbed and cleaned with alcohol, again in accordance with the SENIAM protocol (Hermens et al., 2000). A digital filter was applied to the signals (IIR Band Pass filter Butterworth 3rd Order, 20-500Hz). The RMS of the EMG data was calculated to determine the signal amplitudes. Participants performed a maximum exertion of each muscle group at the end of the experiment. Maximum amplitude normalised to MVC was determined for the last three lifting and lowering repetitions per treatment. In the end, data from three participants had to be excluded as the data were contaminated, often because electrodes made contact with the exoskeleton during testing.

Contact pressure

Contact pressure at the interface between the participant and the exoskeleton was measured using BodiTrak pressure measurement mats, and recorded and analysed using the FSA software supplied. Three mats were inserted between the exoskeleton and the body on the left side, one proximal to the shoulder (Shoulder), one at the hip/lower back (Trunk), and one around the upper leg (Thigh). The sensing area, sensor arrangement and sensor quantity for the Trunk mat was 228mmx228mm, 16x16 array and 256 sensors, and for the Shoulder and Thigh mats were 350mmx350mm, 24x24 array and 567 sensors. Pressure was recorded throughout each treatment. Due to signal contamination, pressure data from nine participants are reported.

Subjective responses

Rating of Perceived Exertion (RPE) was rated using the Borg Category Ratio (CR-10) scale (Borg, 1982). On the left it indicated *zero* (no physical exertion) and on the right *ten* (almost maximal exertion). RPE was assessed for the back and legs separately, for each condition, with and without the exoskeleton.

Perceived musculoskeletal pressure was rated using the Local Perceived Pressure (LPP) method (adapted from van der Grinten and Smitt, 1992). LPP was rated on a scale from *zero* (no pressure at all) to *ten* (extremely strong pressure). It was rated for three areas of the body: Back/Shoulders, Upper Legs and Belly/Hips after each of the two conditions with the exoskeleton.

Usability of the exoskeleton was rated using the System Usability Scale (SUS) (Bangor et al., 2009). This subjective rating scale consists of ten questions rated from *one* (strongly disagree) to *five* (strongly agree). A score over 70 is deemed acceptable. One participant misinterpreted the questions due to the language barrier, thus scores of ten participants were reported.

Data Analysis

All data were analysed using SPSS Statistics Software Version 21, with significance set at $p<0.05$. Normality of the data was assessed using the Kolmogorov-Smirnov test. Some data violated the assumption of normality, thus, the non-parametric Wilcoxin signed rank test was used to analyze the data. As multiple factorial analysis is not possible with this test, the analysis required multiple separate analyses.

Study of exoskeleton effect on body loading

Maximum %MVC (Rectus Abdominis, Erector Spinae L3, Biceps Femoris) and mean RPE (Legs and Trunk) were assessed for both SYSTEM and LOAD.

User assessment of the exoskeleton

Maximum contact pressure (Trunk, Shoulder, Thigh), mean LPP and SUS scores were assessed. Statistical analysis was only performed on contact pressure data where LOAD was one factor and AREA the second.

Results

Study of exoskeleton effect on body loading

Muscle activity

Erector Spinae and Biceps Femoris muscle activity was significantly lower ($p<0.01$) with the exoskeleton, but not for the Rectus Abdominis (Table I, Figure 2). Erector Spinae activity was reduced by 12% for the 7.5kg load and by 15% for the 15kg load, whereas Biceps Femoris activity was reduced by 5% for both loads. Erector Spinae and Bicep Femoris muscle activity was significantly higher for the heavier load compared to the 7.5kg load (Table I, Figure 2). This was also noted for the 'without exoskeleton' condition for the Rectus Abdominis.

Table I: Statistical analysis of maximum %MVC EMG activity for lifting and lowering with and without the exoskeleton for both loads (n=10).

Effects		Conditions					
		Rectus Abdominis		ES L3		Biceps Femoris	
		7.5kg	15kg	7.5kg	15kg	7.5kg	15kg
SYSTEM	Z	-0.866	-0.255	-2.701	-2.803	-2.701	-2.803
	P	0.386	0.799	**0.007**	**0.005**	**0.007**	**0.005**
		Rectus Abdominis		ES L3		Biceps Femoris	
		W-ES	ES	W-ES	ES	W-ES	ES
LOAD	Z	-2.701	-1.784	-2.803	-2.803	-2.395	-2.701
	P	**0.007**	0.074	**0.005**	**0.005**	**0.017**	**0.007**

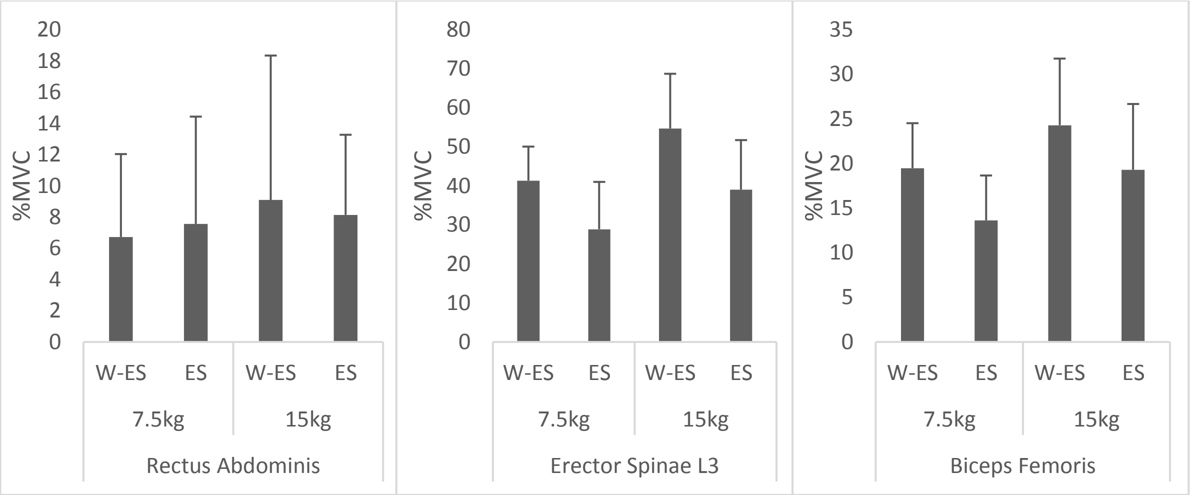

Figure 2: Maximum percentage MVC for the Rectus Abdominis (left), Erector Spinae (Middle) and Biceps Femoris (right) for lifting and lowering with (ES) and without (W-ES) the exoskeleton for both loads (n=10).

Rating of Perceived Exertion

The exoskeleton reduced the RPE scores of the trunk by 9.5%/11.4%, and of the legs by 4.5%/8.1% for the 7.5kg/15kg load respectively (Table II, Figure 3). This effect was only significant for the trunk RPE scores (p<0.01, Table II). Perceived exertion was significantly higher (p<0.01) for both body regions for the heavier load (Table II).

Table II: Statistical analysis of perceived physical exertion for lifting and lowering with and without the exoskeleton for both loads (n=10).

Effects		**Body region**			
		Trunk		Legs	
		7.5kg	15kg	7.5kg	15kg
SYSTEM	Z	-2.154	-2.232	-0.997	-1.309
	P	**0.031**	**0.026**	0.319	0.191
		Trunk		Legs	
		W-ES	ES	W-ES	ES
LOAD	Z	-2.714	-2.699	-2.555	-2.308
	P	**0.007**	**0.007**	**0.011**	**0.021**

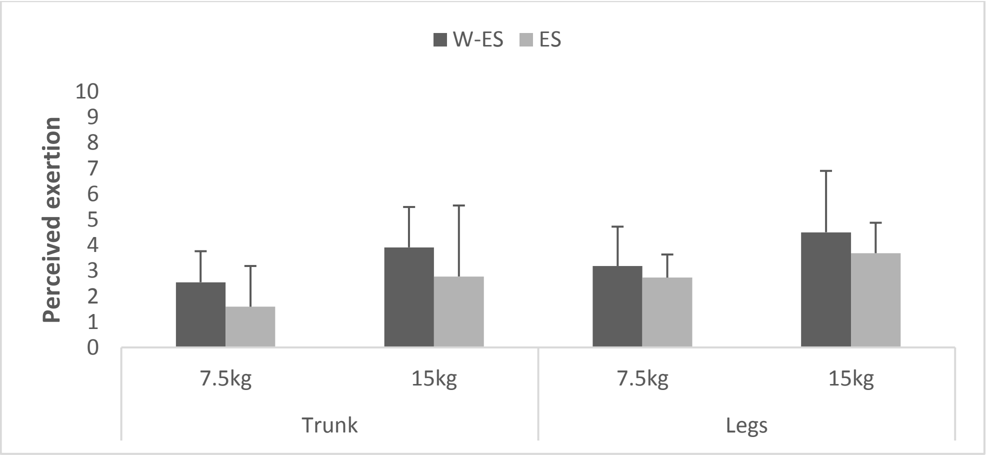

Figure 3: Mean perceived physical exertion for lifting and lowering with (ES) and without (W-ES) the exoskeleton for both loads (n=11).

User assessment of the exoskeleton

Contact pressure

The exoskeleton applied highest pressure to the Trunk region and least on the Shoulder (Figure 4). Pressure was significantly higher for the thighs and trunk compared to the shoulders (Table III, Figure 4). Additionally, Shoulder and Thigh pressure was significantly higher for the heavier load (Table III, Figure 4). The pressure applied to the trunk and thighs was on average 91.6kPa /93.6kPa and 69.1kPa/81.2kPa for the 7.5kg/15kg loads respectively. Contact pressure on the shoulder was approximately 47%/44% and 30%/36% less than the trunk and thigh pressure for the 7.5kg/15kg loads respectively, where pressure was on average 48kPa/51.9kPa.

Table III: Statistical analysis of maximum pressure applied to the human body by the exoskeleton during lifting and lowering for both loads (n=9).

Effects		Conditions					
		Trunk		Shoulder		Thigh	
LOAD	Z	-0.59		-1.960		-2.197	
	P	0.953		**0.05**		**0.028**	
		Trunk vs. Shoulder		Trunk vs. Thigh		Shoulder vs. Thigh	
		7.5kg	15kg	7.5kg	15kg	7.5kg	15kg
AREA	Z	-2.380	-2.100	-1.352	-0.507	-2.201	-2.201
	P	**0.017**	**0.036**	0.176	0.612	**0.028**	**0.028**

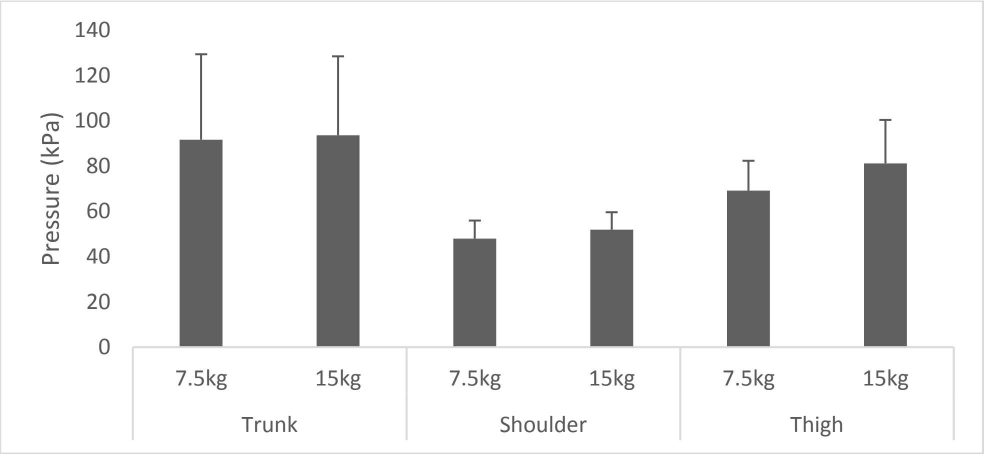

Figure 4: Maximum pressure (+/-1sd) exerted on the trunk, shoulder and thigh by the exoskeleton during lifting and lowering, for two loads (n=9).

Local Perceived Pressure

Perceived pressure was higher for the 15kg load than 7.5kg on average across all body regions (Figure 5). The Upper Legs were rated the highest, with average ratings 'Somewhat Strong' (35%/44% of Max LPP for 7.5kg/15kg). The Back/Shoulder and Belly/Hips were rated as 'Light' pressure (Figure 5): 25%/28% and 24%/27% of maximum LPP for 7.5kg/15kg respectively.

Figure 5: Mean local perceived pressure (+/- 1SD) for lifting and lowering with the exoskeleton for two loads (n=11).

Usability

The System Usability Scores are detailed in Figure 6. Six of the ten participants rated SUS scores above the criterion for acceptable usability.

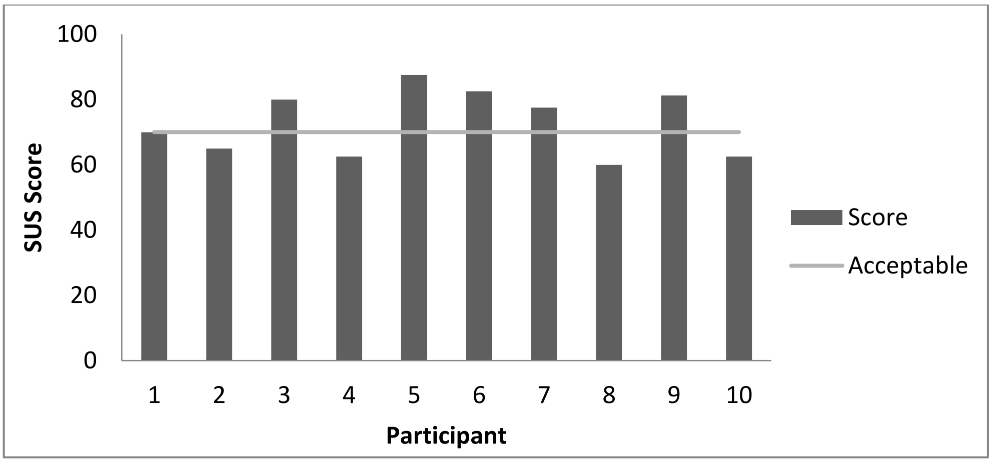

Figure 6: Participant SUS ratings of the exoskeleton (n=10).

Discussion

Study of exoskeleton effect on body loading

The key finding of this study was the reduction in muscle activity of the main trunk extending muscle group in the lower back region, which was in line with the other finding of reduced perceived trunk exertion. Thus, the exoskeleton reduced musculoskeletal loading on the lower back during the simulated industrial lifting task. Erector Spinae peak muscle activity at the lumbar level was reduced by 12-15%, with a greater reduction in activity for the higher load lifted. As peak muscle activity and trunk RPE is reduced, the worker’s endurance increases and muscle fatigue decreases, reducing the risk of developing LBD. Granata et al. (2004) suggests that lower back injuries occur when spinal loads exceed injury tolerance. In this case the load has been reduced, thereby indicating an improvement in the user’s injury tolerance, which should in turn help protect spinal structures and stability.

The results demonstrated that the exoskeleton significantly reduced muscle activity of the Bicep Femoris by 5%. Thus, the exoskeleton had a large effect on back muscle activity and a marginal effect on hip extensor activity. Similar findings were previously noted for two passive exoskeletons: PLAD and Laevo (Bosch et al., 2016).

It was unclear at the outset what the overall net effect on the body would be, especially for the legs/thighs considering the mass of the exoskeleton and the torque applied at those points. The results indicated the exoskeleton did not have an effect on perceived leg exertion for either load. Thus, participants rated the effort of the legs to be similar with and without the exoskeleton, which is interesting considering the added weight on the user. Furthermore, while RPE was not significant for the lower limbs for both loads, perceived exertion of the legs was on average less wearing the exoskeleton than without. This, in conjunction with the reduced Bicep Femoris muscle activity, indicates the exoskeleton has preferable lower body loading than other exoskeletons, such as BNDR, HappyBack and Bendezy, which have indications of high lower body loading during use (Barrett and Fathallah, 2001; Ulrey and Fathallah, 2013).

User assessment of the exoskeleton

The exoskeleton applied highest pressure to the trunk, followed by the thighs, and the least on the shoulders. Additionally, pressure on the thighs and shoulders increased for the heavier load. This trend was also observed in the LLP scores for all three body areas. This result was likely due to the increased moment and muscle circumference generated by the user to lift the heavier load.

Pain is a warning sign of damage caused by excessive contact pressure, and likewise a good indicator of potential cell damage and death (Fransson-Hall and Kilbom, 1993). The point at which a user begins to feel pain and develops lesions is often referred to as the Pain Pressure Threshold (PPT), which has been measured as occurring at around 280kPa - 480kPa (Pons, 2008; Tamez-Duque et al., 2015). The maximum pressure observed in this study was 93.6kPa, which falls below the PPT levels, suggesting the device does not pose a problem to workers with regards to pain sensation and tissue damage, at least in the short-term (Tamez-Duque et al., 2015). This was also supported in the LPP scores where the highest pressure was rated as *Somewhat Strong* (44% of maximum) for the Upper Legs and *Light* for the Back/Shoulders and Belly/Hips. However, it should be noted that LLP was only measured over five lifting cycles. Unlike contact pressure, we would expect LPP to increase with longer duration use as would be the case in industry.

In contrast to contact pressure, LLP scores were highest for the upper legs (*Somewhat Strong*). This was also observed for the Hybrid Assistive Limb exoskeleton (Nilsson et al., 2014). For both of these devices, some participants pointed out that the connection cuffs at the thighs were too tight during use. The circumference of the thigh expands during muscle contraction. This could explain the increased LPP scores for the thighs. One might expect that we could simply loosen the cuffs. However, this is not currently feasible with this anthropomorphic exoskeleton as the circumference of the thigh will continually change during movement and it needs to be securely attached to the thighs. Thus, at certain stages during the activity the cuffs could be too slack allowing them to alter their position on the thighs. If this occurs, the force applied to the leg would produce an instability, thereby resulting in decreased assistance and potential risk of injury. Alternative materials and attachment solutions should be explored to consider this design challenge.

Even though the LPP scores were not considered excessive, over a longer duration of use they are expected to increase. Dispersing pressure over a larger area is a common approach to reducing discomfort in exoskeleton design (Pons, 2008) but this does not entirely resolve the compression issue and design solutions should again explore ways to also address this challenge. For instance, the current attachment cuffs comprise single elastic Velcro straps positioned in the middle of the thigh. Proximal and distal ends of muscles do not expand nearly as much as the central belly. An alternative could be to have two separate smaller cuffs at either end of a larger cuff with greater flexibility in the mid-section. It should be noted that the skin on the upper inner thigh is highly sensitive, thus this design may cause discomfort if the skin is pinched. Alternatively, the cuffs could comprise of soft pads. This was implemented on the DGO exoskeleton to prevent pressure sores (Colombo et al., 2000). Soft pads will, in theory, accommodate muscle size fluctuations during movement.

Backpacks are a common accessory used by individuals daily. This could explain the conflicting results between contact pressure and LPP scores, as users are familiar with the pressure being exerted on the back compared to pressure being applied around the thighs. Additionally, the straps of the back unit comprised soft pads to minimize discomfort. As detailed above, the skin on the inside and upper thighs is more sensitive than the skin on the trunk, thus pain or discomfort would be perceived higher (Pons, 2008).

A majority of the participants rated the exoskeleton as having acceptable usability. The users, which rated the device below the required criterion, found it to be either complex to use, or that at times the movements were not always completely consistent with their natural movements. From a design perspective, these factors need to be addressed both through the mechanical and sensor design, and also in the system software controls, which control the fluidity of the movements.

Limitations:

Due to safety precautions, only five lifting cycles were recorded as the main treatments. This is not a true reflection of an industrial working day. Now that we know the exposures with the current design, future testing can include longer duration testing. This will allow for a more accurate assessment of the interaction between user and device, especifically LPP scores. A larger sample size including experienced manual handling workers is necessary to ascertain the usability of the device for the working population. Furthermore, females should be assessed, as their body sizes and capabilities differ to those of males. The assessment of additional muscles, particularly of the lower limb, should be considered to inform a more complete understanding of the risks. The task performed was conducted in the sagittal plane. However, in industry, the task may include asymmetric twisting and walking.

Conclusions

The exoskeleton significantly reduced back muscle activity (12%-15%) and perceived trunk exertion (9.5%-11.4%), implying reduced lower back loading. Additionally, the exoskeleton assisted with hip extensor torque as evidence of the significantly decreased Biceps Femoris muscle activity (5%). To our knowledge, this exoskeleton is possibly the first active exoskeleton indicating a statistically significant reduction in Erector Spinae muscle activity in addition to hip extensor assistance for dynamic lifting and lowering tasks. There was no evidence of increased body loading, in fact the exoskeleton appears to have preferable lower body loading. Contact pressure values fell below the PPT, where both discomfort and usability are approaching acceptable levels. In the near future, wearable sensor and robotics devices, such as this and next generation exoskeletons, have the potential to be useful tools to assist workers with industrial lifting tasks, especially if assistive torque is further increased. This study demonstrates the need for strong emphasis on design ergonomics to ensure such technologies are comfortable and have high usability through their design, in order to ensure they are suitable and desirable for workers to use.

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