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Evaluation of a passive exoskeleton for static upper limb activities

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ABSTRACT

The aim of this study was to evaluate the effect of a passive upper body exoskeleton on muscle activity, perceived musculoskeletal effort, local perceived pressure and subjective usability for a static overhead task. Eight participants (4 male, 4 female) held a load (0 kg and 2 kg) three times overhead for a duration of 30 s each, both with and without the exoskeleton. Muscle activity was significantly reduced for the Biceps Brachii (49%) and Medial Deltoid (62%) by the device for the 2 kg load. Perceived effort of the arms was significantly lower with the device for the 2 kg load (41%). The device did not have a significant effect on trunk or leg muscle activity (for the 2 kg load) or perceived effort. Local perceived pressure was rated below 2 (low pressure levels) for all contact areas assessed. Half of the participants rated the device usability as acceptable. The exoskeleton reduced muscle activity and perceived effort by the arms, and had no significant negative effect on the trunk and lower body with regards to muscle activity, perceived effort and localised discomfort.

1. Introduction

Work-related Musculoskeletal Disorders (WMSDs) of the upper extremities are an important issue in the modern workplace (Shin et al., 2012). In the USA, the shoulder was involved in 13% of WMSD cases reported in 2011 (Bureau of Labor Statistics, 2012), second to the back with 42% of WMSD cases. Disorders related to the shoulder have been associated with overhead work, which is a frequent task conducted in industry (Shin et al., 2012; Phelan and O'Sullivan, 2014). A great deal of overhead tasks require workers to maintain prolonged static postures while exerting forces with the hand, which is well recognised as a risk factor for WMSDs (Rashedi et al., 2014). Overhead work is still widely conducted in industry despite the increase in automation. If a muscle has no opportunity to relax, the onset of muscular fatigue is rapid, even at low-force levels, which impairs muscle function (Ng et al., 2014). Continuous contraction of muscles can restrict blood flow, further accelerating fatigue (Ng et al., 2014). Overhead work often requires static postures when holding the weight of hand tools, while also exerting forces with the hand and supporting the deviated posture of the upper limb (Simoneau et al., 1996).

Industry 4.0 is a recent trend of automation and data exchange in manufacturing. This concept has been classified as the fourth industrial revolution, where cyber-physical systems monitor the physical processes of the factory and make decentralized decisions as a ‘smart factory’ (MacDougall, 2014). One of the philosophies of Industry 4.0 is technical assistance, whereby the system has the ability to assist humans with tasks that are difficult or unsafe (MacDougall, 2014). There are many manual handling tasks that could be automated but many others are difficult to do as they require human precision, skills, decision-making, flexibility and movement capabilities (Bos et al., 2002; Zurada, 2012; de Looze et al., 2016).

A further evolution from Industry 4.0 is Operator 4.0, which considers technology-augmented workers (Romero et al., 2016). One such enhancement could be the use of exoskeletons, which can help to reduce the trade-off between automation and manual tasks requiring human capabilities (Romero et al., 2016). An exoskeleton is a wearable technology to augment and assist human motion, thereby reducing the physical stress applied to the wearer, which, in turn should reduce the risk of developing WMSDs (de Looze et al., 2016; Romero et al., 2016). Exoskeletons can be classified as either 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/or spring/elastic members to store and release energy during movements to assist workers to perform physical movements (Matthew et al., 2015; de Looze et al., 2016).

The main application of exoskeletons to date has been for medical/

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rehabilitation purposes, where the devices are aimed at assisting and/or supporting physically weak, disabled or injured people with activities of daily living or rehabilitation exercises (Viteckova et al., 2013). A small number of exoskeletons have been designed for military applications to increase the muscular strength or carrying capability of soldiers (Anam and Al-Jumaily, 2012; Yan et al., 2015). With regards to industrial applications, the concept is fairly recent, and as such, research and development is still in its infancy with many concepts not tested beyond the laboratory (de Looze et al., 2016). Most industrial exoskeletons can be considered as either trunk exoskeletons that assist with trunk flexion/support to prevent back injuries, or upper body exoskeletons supporting the upper limbs in lifting or providing postural support (de Looze et al., 2016).

An upper body exoskeleton could be beneficial in assisting with static overhead work. In theory, a passive exoskeleton compensates for gravity, arm weight and the load being handled, thereby reducing risk of WMSDs. In a review conducted by de Looze et al. (2016), it is evident that commercially developed exoskeletons are mainly passive in nature with the focus on reducing physical load during dynamic lifting and static bending. The benefits of exoskeletons in reducing the physical load on the human have been proven in laboratory environments. Barrett and Fathallah (2001) reported that the PLAD, HappyBack and Bendezy passive trunk exoskeletons reduced Erector Spinae muscle activity levels by 21–31% for static bending while holding loads. Regarding active systems, Huysamen et al. (2018) studied the effect of an active trunk exoskeleton for dynamic lifting and reported a significant decrease in muscle activity of the Erector Spinae (from 55 to 45% MVC, a reduction of 27%) and Biceps Femoris (from 24 to 19% MVC, a reduction of 20%).

Various passive upper arm devices have been developed in the last few years including the Levitate exoskeleton. In a study conducted by Spada et al. (2017b), this exoskeleton revealed a positive effect for activities that involve a posture with raised arms, where, on average, work performance increased by 30% and fatigue was perceived to be less when wearing the exoskeleton than when not. However, little information is known on the potential benefits of these exoskeletons regarding the biomechanical strains associated with manual handling tasks. Theurel et al. (2018) assessed the physiological consequences of using a passive upper-limb exoskeleton (EXHAUSS Stronger®) during manual handling tasks and concluded that the exoskeleton effectively reduced the workload of the shoulder flexor muscles during manual lifting/lowering and stacking/unstacking tasks.

Previous research and developments have proven that it is a challenge to achieve both technically feasible and user-centred design exoskeletons with good usability. 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, i.e. physical loading was not reduced or low device acceptance (Almenara et al., 2017). In other instances, the key objectives were met by reduced loading of targeted muscle groups, but elsewhere on the body had increased loading and high localised discomfort caused by the forces applied by the exoskeleton on the body (de Looze et al., 2016). For instance, the EXHAUSS Stronger® passive upper limb exoskeleton increased antagonistic upper arm muscle activity, postural strains, cardiovascular demand and even changes in upper limb kinematics were noted (Theurel et al., 2018). Moreover, the three passive trunk exoskeletons mentioned above increased muscle activity of one or more leg muscles (Barrett and Fathallah, 2001).

The purpose of the current study was to perform an ergonomic assessment of a passive arm exoskeleton aimed at providing mechanical support to the upper limbs during static overhead work to reduce the risk of WMSDs. The hypothesis tested was whether a passive exoskeleton reduces muscle activity and perceived effort for a simulated overhead task. Specifically, the objectives were to assess the effect of the device on muscle activity, physical effort, local perceived pressure and subjective usability in a static overhead task. The exoskeleton was developed as part of the EU-funded project Robomate (www.robo-mate.eu).

2. Method

2.1. Participants and ethical approval

Four male and four female participants gave written consent to participate in the study (Means & SD: Age: 38years ± 10, Mass: 72.6 kg ± 7.87, Stature: 1761 mm ± 50). No participant had prior or current musculoskeletal disorders. The experiment was approved by the Research Ethics Committee of the Canton Zurich.

2.2. Experimental design

The independent variables were LOAD (0 kg and 2 kg) and SYSTEM (With Exoskeleton: ES, WithOut Exoskeleton: W-ES). The dependent variables were muscle activity (EMG: Biceps Brachii, Medial Deltoid, Erector Spinae at level L3 and T9, Rectus Abdominis, Biceps Femoris, Rectus Femoris, Tibialis Anterior and Gastrocnemius) and perceived effort of the arms, trunk and legs. Additionally, local perceived pressure and usability were assessed for the 'with exoskeleton' conditions.

The study comprised of four conditions (LOAD ×2, SYSTEM ×2) in a full factorial design, which were performed by each participant in a randomised order (for LOAD and SYSTEM). The 2 kg cylindrical load (diameter 5 cm) was held in the hand, whereas no load was held for the 0 kg conditions. The 2 kg load was chosen as being indicative of the common weight of a powered industrial hand tool.

This was the first evaluation of this nature of the arm exoskeleton, and therefore, on safety grounds, the tasks were limited to simple short duration overhead static exertions. The participants were requested to assume a predefined overhead reaching posture with the dominant elbow and shoulder both flexed at 90°, wrist in a neutral position, and knuckles facing upwards (forearm prone).

2.3. Procedure

On entering the laboratory, participants were informed of the testing procedure and equipment involved. Anthropometric measurements (stature and mass) were obtained followed by the preparation and placement of the EMG electrodes. After a detailed explanation and demonstration by the investigators, participants were required to practice the task and demonstrate their understanding of the subjective measurements being assessed. Testing commenced once the participants were proficient and comfortable with the testing requirements.

Each participant held the load overhead at a fixed height for 30 s. This was repeated three times for each condition with a rest of at least 1 min and 5 min between trials and conditions respectively to avoid fatigue.

In order to get to the overhead reach point, each participant was required to stand upright, with shoulder and elbow flexed at 90°, wrist in a neutral position and hand closed. Finally, the distance between the ground and knuckles was measured and set as the fixed overhead height for each participant. An adjustable stand, set to each participant's fixed overhead height, was placed next to and in-line with the arm being lifted. Each participant was required to line up the top of their knuckles with the height of the stand. EMG recording commenced once the hand and arm postures were correctly positioned and steady. EMG was recorded during the 30 s of each trial.

At the end of the experiment, participants performed two 3s Maximum Voluntary Contractions (MVCs) for each of the muscles examined (as per the SENIAM protocol, Hermens et al., 2000). Thereafter, two 10s Reference Voluntary Exertion (RVE) measurements were obtained for the upper limb muscles (Mathiassen et al., 1995). The RVE measurement required the participants to be seated with both shoulders abducted to 90° and elbows extended to 180° with palms facing

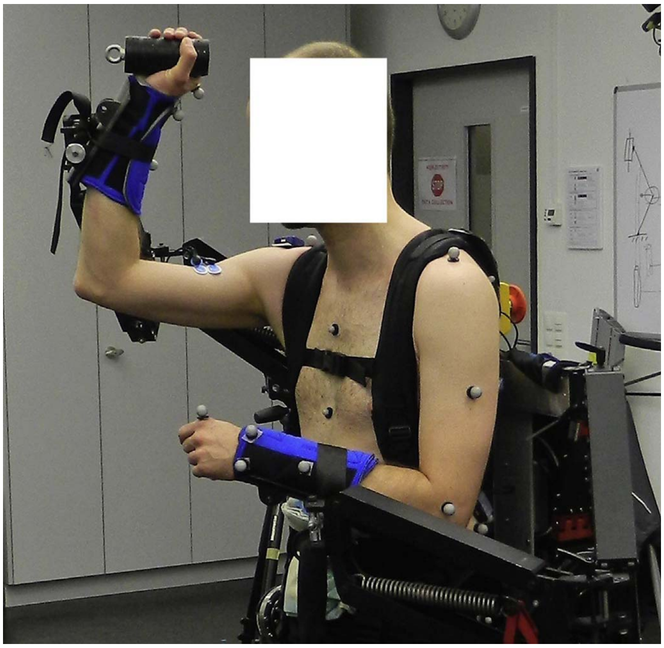

Fig. 1. Photograph of the passive arm exoskeleton during the experiment.

downwards. A 1-min rest period was given between trials. MVC and RVE measurements were conducted at the end to avoid these exertions having a fatiguing effect prior to testing with the exoskeleton.

2.4. Equipment

2.4.1. Exoskeleton

The passive arm exoskeleton tested is a wearable device aimed at reducing upper limb effort for static holding tasks by means of springs mounted in support arms to compensate for the load (Altenburger et al., 2016). The exoskeleton is comprised of three segments: a single back unit weighing 2.8 kg with two arm attachments weighing 4.1 kg each, totalling 11 kg of exoskeleton weight. The exoskeleton is worn by the user like a backpack (Fig. 1). When put on, it is adjusted/aligned on the body via several straps on the back unit, and then the attachments at the arms are secured. The exoskeleton support force was set to 1 kg to support the weight of the upper limb for the 0 kg load condition. The exoskeleton support force was set to 3 kg for the 2 kg LOAD condition, to support the load lifted and the weight of the upper limb.

2.4.2. Surface electromyography

Muscle activity was recorded using a MYON 320 Surface Electromyography (sEMG) System (Sampling rate: 2000Hz, Gain: 2500) with bipolar electrodes placed over each muscle at an inter-electrode distance of 20 mm, as per the guidance in the SENIAM protocol (Hermens et al., 2000). EMG signals were measured for nine muscles: biceps femoris, gastrocnemius, tibialis anterior, rectus femoris, medial deltoid, biceps brachii caput longum, erector spinae at level T9 vertebrae, erector spinae at level L3 vertebrae and rectus abdominis. 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). The two upper limb muscles were assessed as they are associated with upper arm and neck WMSDs. The trunk and leg muscles were assessed to determine the effect of the exoskeleton on trunk and lower body loading, as previous devices revealed negative effects, which in turn could lead to the development of other WMSDs.

A customised script in MATLAB (The MathWorks Inc. Natrick, MA, USA) applied a band pass filter (10-400Hz) to the data and rectified the EMG signals. The first and last second of each trial were removed from the analysis, to have a stable signal without movement artefacts. The average value for the remaining 28 s has been used for the EMG analysis. EMG activity for the leg and trunk muscles was normalised to the maximal MVC. The upper limb muscles were normalised to their RVE measurements due to a technical issue of their corresponding MVC measurements. As performed by Bosch et al. (2016), a 0.5-s moving window (100 sample overlap) was used to determine the maximum rectified and average value for each muscle across both MVCs and RVEs.

2.4.3. Subjective measures

Participants rated their perceived musculoskeletal effort for the arms, trunk and legs separately using the Borg category ratio (CR-10) for each treatment (Borg, 1982). Participants also rated Local Perceived Pressure (LPP) (Van der Grinten and Smitt, 1992) at the back/shoulders, arms, chest and belly/hips for the with exoskeleton conditions. The LPP scale ranged from zero (no pressure at all) to ten (extremely strong pressure). Usability of the exoskeleton was rated using a subjective rating scale - System Usability Scale (SUS) (Bangor et al., 2009) - consisting of ten questions rated from one (strongly disagree) to five (strongly agree). A score over 70 is deemed to indicate acceptable usability.

2.5. Data analysis

All data were analysed using SPSS Statistics Software Version 21, with significance set at $p < 0.05$. The Kolmogorov-Smirnov test static was applied to the data to assess normality. Some cases violated the assumption of normality, therefore all statistical tests performed were non-parametric. The Wilcoxon signed rank test was conducted on the mean perceived effort (CR-10) and mean %MVC/RVE data. Thus, the effect of SYSTEM (with and without exoskeleton) and the effect of LOAD (0kg/2 kg) were analysed separately for each condition, resulting in four analyses being performed per dependent variable being statically analysed (Table 1).

3. Results

3.1. Study of exoskeleton effect on body loading

3.1.1. Muscle activity

The exoskeleton resulted in significant reduction in muscle activity of the Biceps Brachii ($p = 0.036$) and Medial Deltoid ($p = 0.017$), 49% and 62% respectively, compared to without the exoskeleton for the 2 kg load (Table 2, Fig. 2). No significant effect was observed for the 0 kg load for either upper limb muscle assessed. Without the exoskeleton, muscle activity was higher for the Biceps Brachii ($p = 0.012$) and Medial Deltoid ($p = 0.017$) with the higher in load (as is to be expected). In contrast, with the exoskeleton the Medial Deltoid muscle activity decreased for the 2 kg load condition compared to the unloaded condition ($p = 0.05$).

Rectus Abdominis muscle activity was significantly lower ($p = 0.017$) with the exoskeleton compared to without for the 0 kg load, with a reduction of 13% on average (Table 3, Fig. 3). A similar but not significant tendency was noted for the 2 kg load. In contrast, the

Table 1
Wilcoxon signed rank non-parametric test conducted for each of the effects being analysed (W-ES: Without Exoskeleton, ES: With Exoskeleton).

Effect	Analysis	Variable 1		Variable 2
SYSTEM	1	W-ES_0 kg	vs.	ES_0 kg
	2	W-ES_2 kg	vs.	ES_2 kg
LOAD	3	W-ES_0 kg	vs.	W-ES_2 kg
	4	ES_0 kg	vs.	ES_2 kg

Table 2
Statistical analysis of mean percentage RVE of the upper limb muscles for the static overhead task with and without the exoskeleton for both loads (n = 8).

Effects		Conditions			
		Biceps Brachii		Medial Deltoid	
		0 kg	2 kg	0 kg	2 kg
SYSTEM	Z	−0.280	−2.100	−0.840	−2.380
	P	0.779	0.036	0.401	0.017
		Biceps Brachii		Medial Deltoid	
		W-ES	ES	W-ES	ES
LOAD	Z	−2.521	−0.980	−2.380	−1.960
	P	0.012	0.327	0.017	0.050
		Biceps Brachii		Medial Deltoid	
		0 kg	2 kg	0 kg	2 kg
MEAN (SD)	W-ES	26% (± 19)	42% (± 31)	34% (± 12)	49% (± 13)
	ES	24% (± 24)	22% (± 26)	39% (± 15)	19% (± 12)

Erector Spinae L3 muscle activity appeared to be higher for both load conditions with the exoskeleton compared to without the exoskeleton, but this was not statistically significant. This was also observed for the Erector Spinae T9 muscle for the 0 kg condition. Without the exoskeleton, muscle activity of all three trunk muscles was significantly higher for the 2 kg condition compared to the 0 kg condition (again as is to be expected). With the exoskeleton, this effect was only noted for the Erector Spinae L3 muscle activity ($p = 0.036$).

The exoskeleton did not have a significant effect on leg muscle activity (Table 4, Fig. 4). With the exoskeleton, load had a significant effect on activity of the Biceps Femoris ($p = 0.028$) and Gastrocnemius muscle ($p = 0.012$): the heavier load resulted in higher activity.

3.1.2. *Perceived musculoskeletal effort (Borg CR-10)*

Perceived arm effort was significantly lower for the 2 kg load condition by 41% with the exoskeleton than without ($p = 0.03$, Table 5, Fig. 5). A similar effect was indicated for the 0 kg condition; however, this was not significant. Additionally, the exoskeleton slightly increased perceived effort of the trunk and legs compared to without the exoskeleton; however, the difference was not significant.

3.2. *User assessment of exoskeleton*

3.2.1. *Local perceived pressure*

Mean ratings of perceived pressure for all body regions assessed were all less than 2, corresponding to 'very weak pressure' (Fig. 6). Perceived pressure was highest for the arms and lowest for the chest region. Pressure on the arms was rated higher for the 2 kg condition compared to the 0 kg condition.

3.2.2. *Usability*

The System Usability Scores across the eight subjects are summarised in Fig. 7. Half the participants rated the exoskeleton above the criterion for acceptable usability.

4. Discussion

The purpose of the study was to perform an ergonomic assessment of a passive arm exoskeleton aimed at providing mechanical support to the upper limbs during static overhead work.

4.1. *Study of exoskeleton effect on body loading*

The key finding is of reduced muscle activity and perceived effort of the upper limbs studied during static overhead work while wearing the passive exoskeleton. This was evident by significant reductions in perceived arm effort (41%) and muscle activity of the Biceps Brachii (49%) and Medial Deltoid (62%) muscles with the exoskeleton than without for the 2 kg load. As muscle activity and perceived effort is reduced, fatigue is also expected to decrease, thereby decreasing the possible risk of upper limb WMSD. Similar results were found with the EXHAUSS Stronger® and Levitate passive upper limb exoskeletons, where EXHAUSS Stronger® significantly reduced deltoid anterior muscle activity during manual lifting/lowering and stacking/unstacking tasks (Theurel et al., 2018), and the Levitate exoskeleton increased worker endurance time and level of precision (Spada et al., 2017a).

Both muscle activity and perceived effort data for the legs did not increase significantly for the exoskeleton conditions, which is a positive finding considering the added weight of the device on the user. Even though passive upper limb industrial exoskeletons are commercially available, there is minimal available research of their effect on lower body loading. Other devices, such as PLAD, HappyBack and Bendezy, each passive trunk exoskeletons, revealed increased muscle activity of the lower limb muscles during use (Barrett and Fathallah, 2001; Ulrey and Fathallah, 2013).

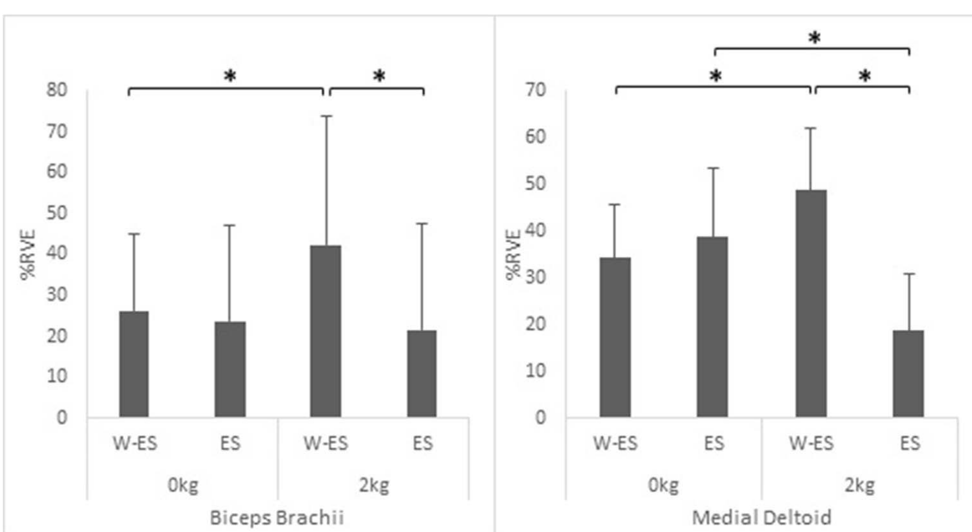

Fig. 2. Mean percentage RVE (+/- 1SD) of upper limb muscles for a static overhead task with and without exoskeleton for two loads: 0 kg and 2 kg (n = 8).

Table 3
Statistical analysis of mean percentage MVC of trunk muscles for static overhead task with and without the exoskeleton for both loads (n = 8).

Effects		Conditions					
		ES T9		ES L3		Rectus Abdominis	
		0 kg	2 kg	0 kg	2 kg	0 kg	2 kg
SYSTEM	Z	−1.680	−0.980	−1.680	−1.820	−2.380	−1.540
	P	0.093	0.327	0.093	0.069	0.017	0.123
		ES T9		ES L3		Rectus Abdominis	
		W-ES	ES	W-ES	ES	W-ES	ES
LOAD	Z	−2.521	−0.560	−2.240	−2.100	−1.960	−1.680
	P	0.012	0.575	0.025	0.036	0.05	0.093
		ES T9		ES L3		Rectus Abdominis	
		0 kg	2 kg	0 kg	2 kg	0 kg	2 kg
MEAN (SD)	W-ES	11% (± 4)	12% (± 5)	7% (± 4)	8% (± 3)	3% (± 2)	4% (± 2)
	ES	14% (± 6)	14% (± 8)	8% (± 3)	10% (± 4)	3% (± 2)	3% (± 2)

For both upper limb muscles examined, the exoskeleton did not have an effect for the 0 kg condition, but it did for the 2 kg condition. This was attributed to limited support provided for the 0 kg condition as stated above, compared to sufficient, and possibly more than anticipated, compensating support provided for the 2 kg condition. It is reasonable to suggest that the exoskeleton support level could be increased for 0 kg conditions with more pronounced effects than observed here, especially for long duration static postures. Thus, an exoskeleton supporting the weight of the arm may be beneficial for static overhead tasks, including those that do not involve hand tool use.

With regards to the trunk, the exoskeleton significantly affected Rectus Abdominis muscle activity for the 0 kg condition, but not for the other muscles. The device had a positive effect with reduced muscle activity of 13% for the 0 kg condition and 11% for the 2 kg condition; however, the 2 kg was not significantly different. This, in conjunction with the non-significant effect for the back muscles and perceived trunk effort, could indicate the device had little additional loading on the trunk which is an important finding.

4.2. User assessment of the exoskeleton

The ratings of localised perceived pressure indicated the device applied low levels of pressure to the user. This is a positive result, as the issue of local discomfort is one of the main factors affecting acceptance of exoskeletons (de Looze et al., 2016). Pressure was perceived highest on the arms, which is expected due to the arm straps needing to be tight to reduce slippage and movement, and also due to the transfer of force from the arms to the device. The slightly higher perceived pressure scores for the heavier load are also likely to be expected.

Half of the participants rated the exoskeleton as having acceptable usability. The users who rated the device below the required criterion found it to be somewhat cumbersome. The current design, because it is non-anthropomorphic, has a wide footprint during some movements. Our experience is that this type of design has a preferable range of movement over alternative anthropomorphic designs, but that the trade-off is a bulkier device with a larger footprint during use. A challenge in the design of non-anthropomorphic exoskeletons is the issue of device footprint, and this should be considered in future designs, along with the challenges of light weight.

4.3. Limitations

The current assessment was of relatively short duration and for a simple static task. This needs to be expanded to longer duration use and for more realistic industrial tasks for the results to provide further insight in this respect. A larger sample size, including experienced manual handling workers, is necessary to ascertain the usability of the device for the working population. The task in this study was conducted for just 3 repetitions of 30s durations due to safety precautions. This is not a true reflection of how exoskeletons are envisaged to be used in

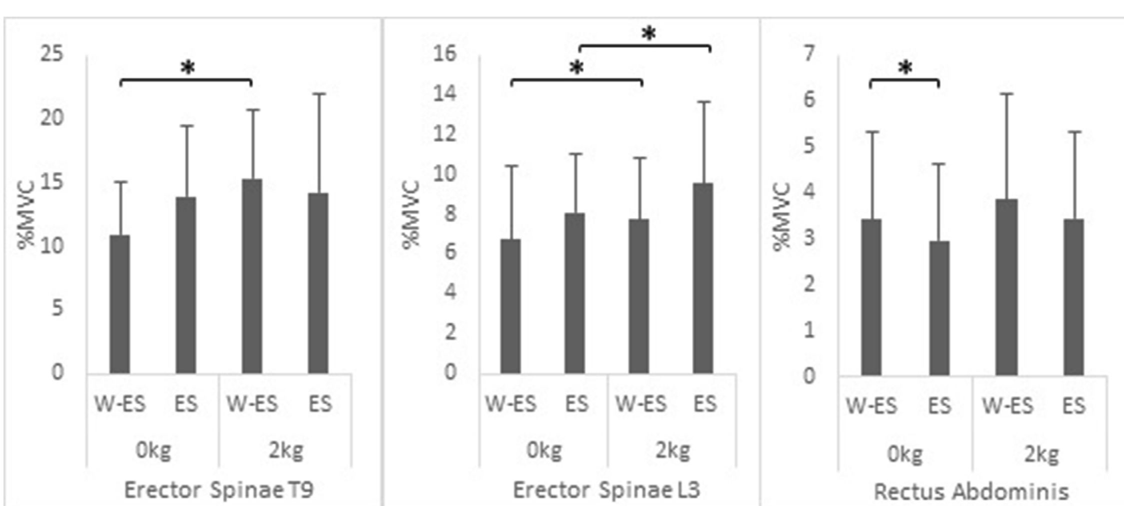

Fig. 3. Mean percentage MVC (+/- 1SD) of trunk muscles for static overhead task with and without the exoskeleton for two loads: 0 kg and 2 kg (n = 8).

Table 4
Statistical analysis of mean percentage MVC of leg muscles for static overhead task with and without the exoskeleton for both loads (n = 8).

Effects		Conditions							
		Biceps Femoris		Tibialis Anterior		Gastrocnemius		Rectus Femoris	
		0 kg	2 kg	0 kg	2 kg	0 kg	2 kg	0 kg	2 kg
SYSTEM	Z	−1.014	0	−0.560	−1.120	−0.280	−0.560	−0.700	−0.280
	P	0.310	1	0.575	0.263	0.779	0.575	0.484	0.779
		Biceps Femoris		Tibialis Anterior		Gastrocnemius		Rectus Femoris	
		W-ES	ES	W-ES	ES	W-ES	ES	W-ES	ES
LOAD	Z	−1.521	−2.197	−0.560	−0.140	−1.680	−2.521	−0.700	−1.540
	P	0.128	0.028	0.575	0.889	0.093	0.012	0.484	0.123
		Biceps Femoris		Tibialis Anterior		Gastrocnemius		Rectus Femoris	
		0 kg	2 kg	0 kg	2 kg	0 kg	2 kg	0 kg	2 kg
MEAN (SD)	W-ES	2.7% (± 2)	3.4% (± 2)	1.7% (± 1)	1.6% (± 1)	6% (± 3)	8% (± 6)	2.4% (± 2)	2.7% (± 3)
	ES	2.3% (± 2)	3.2% (± 2)	1.9% (± 1)	1.8% (± 1)	6% (± 2)	8% (± 3)	2.6% (± 2)	2.1% (± 2)

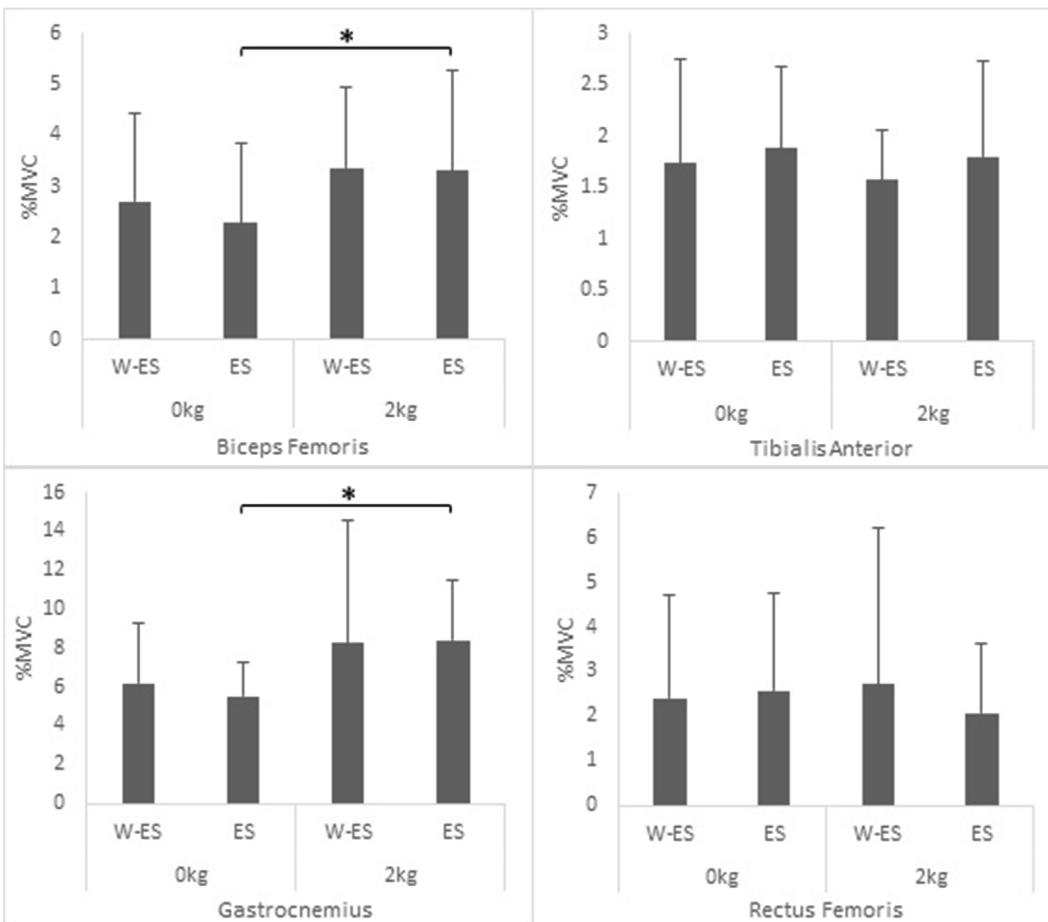

Fig. 4. Mean percentage MVC (+/- 1SD) of leg muscles for a static overhead task with and without the exoskeleton for two loads: 0 kg and 2 kg (n = 8).

industrial tasks, where they may eventually be worn for several hours at a time. This will affect the muscle loading with time, the perceived pressure and usability. A longer training phase could be implemented before the use of the device so that users are more familiar and comfortable with the exoskeleton. This may alter the perception and hence usability of the device during use, especially as minimal negative measured parameters were observed. We assessed only a 2 kg load whereas many power tools are a lot heavier than this, especially in construction work. The current results indicate a need for future testing relating to the duration of conditions and varying loads. The study did not investigate antagonistic muscle activity of the upper arms. It should be noted that a decrease in muscle activity may be attributed to altered muscle recruitment patterns. It is advisable that future studies assess this effect. A downside of passive systems is that they generally do not have dynamic variation in power assistance, as is the case with active exoskeletons. Methods to dynamically vary power assistance with passive systems would greatly improve their suitability, efficacy and usability across tasks.

Table 5
Mean perceived effort of the arms, trunk and legs for a static overhead task with and without the exoskeleton for both loads (n = 8).

Effects		Conditions					
		Arms		Trunk		Legs	
		0 kg	2 kg	0 kg	2 kg	0 kg	2 kg
SYSTEM	Z	−0.857	−2.136	−1.633	−0.378	−1.414	−1.604
	P	0.391	0.033	0.102	0.705	0.157	0.109
		Arms		Trunk		Legs	
		W-ES	ES	W-ES	ES	W-ES	ES
LOAD	Z	−2.136	−1.166	−1.857	−0.447	0	−1.414
	P	0.16	0.244	0.063	0.655	1	0.157
		Arms		Trunk		Legs	
		0 kg	2 kg	0 kg	2 kg	0 kg	2 kg
MEAN (SD)	W-ES	1.5% (± 0.6)	2.7% (± 0.7)	0.4% (± 0.7)	0.8% (± 1)	0.3% (± 0.4)	0.3% (± 0.4)
	ES	1.1% (± 1)	1.6% (± 1)	0.9% (± 1.3)	0.9% (± 1.1)	0.5% (± 0.8)	0.6% (± 0.9)

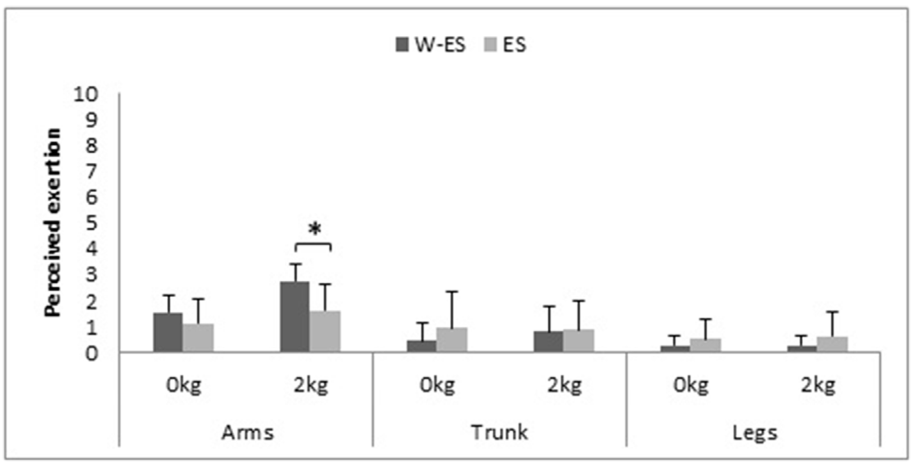

Fig. 5. Mean perceived arm, trunk and leg effort (+/- 1SD) using the Borg CR 10 scale, for a static overhead task with and without the exoskeleton for two loads: 0 kg and 2 kg (n = 8).

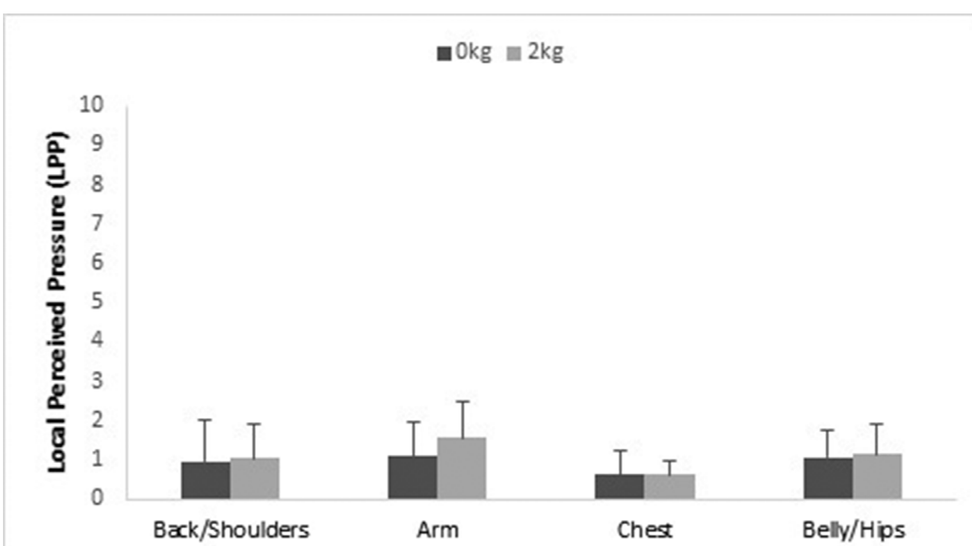

Fig. 6. Mean local perceived pressure (+/- 1SD) for a static overhead task with the exoskeleton for two loads: 0 kg and 2 kg (n = 8).

6. Conclusions

The passive arm exoskeleton significantly reduced muscle activity (for the 2 kg load) and perceived effort of the arms and had no significant negative effects on the lower body. Medial Deltoid and Biceps Brachii muscle activity reduced by 62% and 49% respectively, and perceived arm effort by 41%, with the use of the exoskeleton than without, for the 2 kg overhead task. There was no evidence of new risk

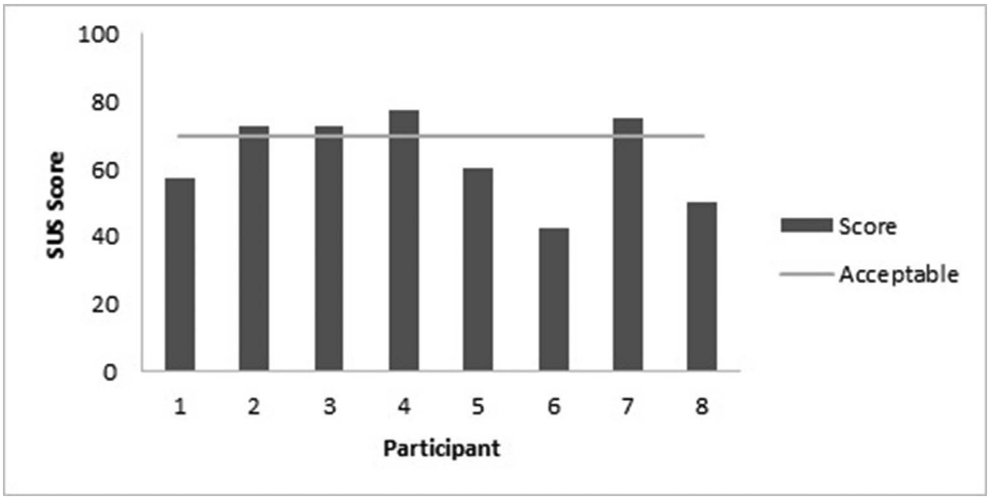

Fig. 7. Participant SUS ratings of the exoskeleton (n = 8)].

factors from its use by way of significantly increased muscle activity and perceived trunk and leg effort. The exoskeleton did not affect muscle activity or perceived effort of the arms for the 0 kg load, but an increase in the level of support by the exoskeleton would be expected to address this for long duration overhead static postures. This, and similar industrial exoskeletons in development, will continue to benefit from further design research to improve usability, especially with regards to comfort and freedom of movement during use, which can be achieved by lowering the exoskeleton mass, addressing weight distribution and streamlining the device footprint.

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References

Almenara, M., Cempini, M., Gómez, C., Cortese, M., Martín, C., Medina, J., Vitiello, N., Opisso, E., 2017. Usability test of a hand exoskeleton for activities of daily living: an example of user-centered design. Disabil. Rehabil. Assist. Technol. 12 (1), 84–96.

Altenburger, R., Scherly, D., Stadler, K.S., 2016. Design of a passive, iso-elastic upper limb exoskeleton for gravity compensation. Robomech J. 3 (1), 12.

Anam, K., Al-Jumaily, A.A., 2012. Active exoskeleton control systems: state of the art. Procedia Eng. 41, 988–994.

Bangor, A., Kortum, P., Miller, J., 2009. Determining what individual SUS scores mean: adding an adjective rating scale. J. Usability Stud. 4 (3), 114–123.

Barrett, A.L., Fathallah, F.A., 2001. Evaluation of four weight transfer devices for reducing loads on the lower back during agricultural stoop labor. In: ASAE meeting, Sacramento, USA.

Borg, G.A., 1982. Psychophysical bases of perceived exertion. Med. Sci. Sport .Exerc. 14 (5), 377–381.

Bos, J., Kuijer, P., Frings-Dresen, M., 2002. Definition and assessment of specific occupational demands concerning lifting, pushing, and pulling based on a systematic literature search. Occup. Environ. Med. 59 (12), 800–806.

Bosch, T., van Eck, J., Knitel, K., de Looze, M., 2016. The effects of a passive exoskeleton on muscle activity, discomfort and endurance time in forward bending work. Appl. Ergon. 54, 212–217.

Bureau of Labor Statistics, 2012. Nonfatal Occupational Injuries and Illnesses Requiring Days Away from Work, 2011. Bureau of Labor Statistics, US Department of Labor, Washington, DC.

de Looze, M.P., Bosch, T., Krause, F., Stadler, K.S., O'Sullivan, L.W., 2016. Exoskeletons for industrial application and their potential effects on physical work load. Ergonomics 59 (5), 671–681.

Hermens, H.J., Freriks, B., Disselhorst-Klug, C., Rau, G., 2000. Development of recommendations for SEMG sensors and sensor placement procedures. J. Electromyogr. Kinesiol. 10 (5), 361–374.

Huysamen, K., de Looze, M., Bosch, T., Ortiz, J., O'Sullivan, L.W., 2018. Assessment of an industrial exoskeleton to aid dynamic lifting and lowering manual handling tasks. Appl. Ergon. 68, 125–131.

MacDougall, W., 2014. Industrie 4.0: Smart Manufacturing for the Future. Germany Trade & Invest, Berlin.

Mathiassen, S., Winkel, J., Hägg, G., 1995. Normalization of surface EMG amplitude from the upper trapezius muscle in ergonomic studies—a review. J. Electromyogr. Kinesiol. 5 (4), 197–226.

Matthew, R.P., Mica, E.J., Meinhold, W., Loeza, J.A., Tomizuka, M., Bajcsy, R., 2015. Introduction and initial exploration of an active/passive exoskeleton framework for portable assistance. In: International Conference on Intelligent Robots and Systems (IROS). IEEE, Hamburg, Germany, pp. 5351–5356.

Ng, D., McNee, C., Kieser, J., Farella, M., 2014. Neck and shoulder muscle activity during standardized work-related postural tasks. Appl. Ergon. 45 (3), 556–563.

Phelan, D., O'Sullivan, L., 2014. Shoulder muscle loading and task performance at head level on ladder versus mobile elevated work platforms. Appl. Ergon. 15 (6), 1384–1391.

Rashedi, E., Kim, S., Nussbaum, M.A., Agnew, M.J., 2014. Ergonomic evaluation of a wearable assistive device for overhead work. Ergonomics 57 (12), 1864–1874.

Romero, D., Stahre, J., Wuest, T., Noran, O., Bernus, P., Fast-Berglund, Å., Gorecky, D., 2016. Towards an operator 4.0 typology: a human-centric perspective on the fourth industrial revolution technologies. In: International Conference on Computers and Industrial Engineering (CIE46) Proceedings, Tianjin, China.

Shin, S.-J., Yoo, W.-G., Kim, T.Y., 2012. Effects of different overhead work conditions on the neck and shoulder muscles. J. Phys. Ther. Sci. 24 (2), 197–199.

Simoneau, S., St-Vincent, M., Chicoine, D., 1996. Work-related Musculoskeletal Disorders (WMSDs)–a Better Understanding for More Effective Prevention. IRSST and A.S.P Mètal- Électrique, Québec.

Spada, S., Ghibaudo, L., Gilotta, S., Gastaldi, L., Cavatorta, M.P., 2017a. Analysis of exoskeleton introduction in industrial reality: main issues and EAWS risk assessment. In: Goonetilleke, R., Karwowski, W. (Eds.), Advances in Physical Ergonomics and Human Factors. AHFE 2017. Advances in Intelligent Systems and Computing. Springer, Cham, Switzerland, pp. 236–244.

Spada, S., Ghibaudo, L., Gilotta, S., Gastaldi, L., Cavatorta, M.P., 2017b. Investigation into the applicability of a passive upper-limb exoskeleton in automotive industry. Procedia Manuf. 11, 1255–1262.

Theurel, J., Desbrosses, K., Roux, T., Savescu, A., 2018. Physiological consequences of using an upper limb exoskeleton during manual handling tasks. Appl. Ergon. 67, 211–217.

Ulrey, B.L., Fathallah, F.A., 2013. Effect of a personal weight transfer device on muscle activities and joint flexions in the stooped posture. J. Electromyogr. Kinesiol. 23 (1), 195–205.

Van der Grinten, M.P., Smitt, P., 1992. Development of a practical method for measuring body part discomfort. Adv. Ind. Ergon. Saf. 4, 311–318.

Viteckova, S., Kutilek, P., Jirina, M., 2013. Wearable lower limb robotics: a review. Biocybern. Biomed. Eng. 33 (2), 96–105.

Yan, T., Cempini, M., Oddo, C.M., Vitiello, N., 2015. Review of assistive strategies in powered lower-limb orthoses and exoskeletons. Robot. Autonom. Syst. 64, 120–136.

Zurada, J., 2012. Classifying the risk of work related low back disorders due to manual material handling tasks. Expert Syst. Appl. 39 (12), 11125–11134.