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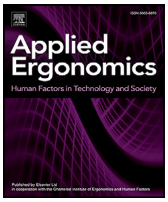

Design and evaluation of the OmniSuit: A passive occupational exoskeleton for back and shoulder support

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ABSTRACT

Many physically straining occupations involve lifting movements over the full-vertical range of motion, which over time may lead to the development of musculoskeletal injuries. To address this, occupational exoskeletons can be designed to provide meaningful support to the back and shoulders during lifting movements.

This paper introduces the main functional design features of the OmniSuit, a novel passive occupational exoskeleton. We present the technical and biomechanical considerations for the expected support level, as well as an evaluation of the physiological benefit and usability of the exoskeleton in a sample of 31 healthy volunteers performing physically demanding tasks in a laboratory setting.

The OmniSuit exoskeleton significantly reduced Deltoid, Trapezius and Erector Spinae muscle activity between 4.1%MVC and 15.7%MVC when lifting a 2.5 kg weight above shoulder level ($p < 0.001$), corresponding to a reduction of up to 49.1% compared to without exoskeleton. A position-dependent reduction of Erector Spinae muscle activity was observed ($p < 0.001$), with reductions ranging between 4.6%MVC and 14.0%MVC during leaning and squatting, corresponding to a reduction up to 41.5% compared to without exoskeleton. The measured muscular support and the predicted support torque based on the biomechanical model were found to show a similar profile for those phases of the movement which are most straining to the shoulder and back muscles. Participants reported experiencing good device usability and minimal discomfort (<1/10) in the shoulder and back during task execution with exoskeleton support.

These first results validate that the considered biomechanical model helped design an ergonomic and efficient exoskeleton, and confirm the potential of such wearable assistive devices to provide support over multiple joints during physically demanding tasks.

1. Introduction

Work-related musculoskeletal disorders (MSDs) are the leading cause of work disability, sickness, absence from work, and loss of productivity in the European Union (Bevan, 2015). MSDs are most frequently observed in the lower back and shoulder joint (Bevan, 2015). In different construction trades, lower back pain has a one-year prevalence of 51% (Umer et al., 2018) and results in a median absence from work period of 8 days (Bureau of Labor Statistics, 2023). Shoulder pain has a lower prevalence, but median absence from work is as high as 30 days per case (Bureau of Labor Statistics, 2023). According to the World Health Organization, manipulation of heavy loads, working in unfavorable body postures and repetitive movements are the main risk factors for the development of MSDs (Luttmann et al., 2003).

Occupational exoskeletons are devices designed to be worn on the body and to support workers in an occupational setting to perform physically demanding activities. Exoskeletons, used in occupational settings, may have the potential to reduce the physical effort and the burden of manual labor (Baer et al., 2021; Kermavnar et al., 2021). This may contribute to a reduction in productivity loss and reduced negative socioeconomic impact (Pesenti et al., 2021). Various exoskeletons have been proposed and evaluated over the last few years, including active as well as passive systems. Active exoskeletons add additional energy into the system by electrical motors or pneumatic actuators, whereas passive exoskeletons use the user's movement to store and release energy using gas or coil springs, flexible beams, or elastic elements (Poliero et al., 2020; Toxiri et al., 2019). However, it is important to find the right balance between the strain of a specific type of labor, the support provided by the exoskeleton, and the potential constraints wearing such a device may pose to the user.

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Fig. 1. The OmniSuit back and shoulder support exoskeleton from the front (a) and back (b).

Most exoskeleton developed to date have been designed to support a single joint or one dedicated body segment, such as the knee, back, or shoulder joint. These exoskeletons provide either static support at one joint angle or dynamic support, here defined as joint angle adaptive torque. It has been shown that single joint exoskeletons can effectively reduce muscle activity in the hip extensor, torso and shoulder flexor muscles (Baer et al., 2021; Kermavnar et al., 2021). In many occupations, lifting loads over a large vertical range (from ground to above shoulder level) is required, a movement that involves almost all body parts and joints. Therefore, the development and evaluation of occupational exoskeletons providing a dynamic support torque for both the back and shoulder is important.

To our knowledge, only three systems providing back and shoulder support over a range of hip and shoulder flexion angles were developed (a research prototype by Muramatsu et al. (2011), the MAX by SuitX, the Muscle Upper by Innophys Co., and the UPLIFT by Mawashi Science & Technology) and no rigorous scientific evaluation of their performance (in terms of usability and muscle activity reduction) has been published to date. The challenge for any multi-joint exoskeleton is the added complexity compared to single-joint exoskeletons, which quickly results in limited performance as size, weight, and usability issues increase especially in dynamic work tasks (Baldassarre et al., 2022). Additionally, anatomical compatibility or joint misalignment become more dominant when multiple joints are connected through rigid structures. These challenges can be amplified in modular systems, due to the need for mechanical interfaces between the different modules, redundancies between the modules, and the need for the modules to function independently from each other. All these aspects bear the risk that multi-joint exoskeletons offer reduced performance and, as a result, negatively affect user acceptance.

This paper introduces and experimentally evaluates the OmniSuit exoskeleton, a fully integrated multi-joint passive exoskeleton developed to provide dynamic back and shoulder support during activities that require a large vertical range of motion. The aim of the OmniSuit is to achieve high overall performance by combining a good level of support with a low profile, lightweight design, maximum freedom of movement, and good usability. Here, we first introduce the technical concept and design of the exoskeleton, including a biomechanical model of how supporting torques can be provided to the joints of interest. We then validate this concept by reporting the results of a study with 31 healthy participants using the exoskeleton to hold postures which are part of a full-range vertical lifting (incl. squatting and reaching overhead. We hypothesized that the OmniSuit would help decrease muscle activity in both back and shoulder muscles when considering different postures spread over the full vertical range of motion, while providing high usability.

2. Methods

2.1. The OmniSuit exoskeleton

The OmniSuit exoskeleton is a multi-joint passive exoskeleton providing dynamic back and shoulder support during overhead, lifting, and forward-leaning work (Auxivo AG, Fig. 1). It consists of a semi-rigid shoulder exoskeleton that is integrated with a soft, textile back support exosuit. The design was inspired by the previously introduced LiftSuit back support exoskeleton and the DeltaSuit shoulder support exoskeletons (both Auxivo AG, Schwerzenbach, Switzerland), with the objective of combining the benefits from each system (Brunner et al., 2023a; Van Sluijs et al., 2023b). However, for the OmniSuit design, both systems were adapted and fully integrated into one single exoskeleton. This involved redesigning parts and components to achieve the best possible multi-joint performance.

The shoulder exoskeleton on each side offers two degrees of freedom, a passive internal/external rotation, and supported shoulder flexion/extension via a custom made spring mechanism. At the level of the upper arm, the OmniSuit incorporates an auxiliary degree of freedom in the form of a telescopic mechanism in the upper arm structure to dynamically retract or extend to reduce or increase the distance between the upper arm cuff and the shoulder's rotational axes. Although the exoskeleton's shoulder joint, with its two degrees of freedom, does not exactly mimic human shoulder anatomy, it still allows for natural shoulder movements. This is because there is always a slight flexion angle present during use, which enables the shoulder to perform horizontal abduction and adduction movements. Such mechanisms have been shown to efficiently reduce movement constraints imposed by joint misalignment in exoskeletons in the upper and lower extremities (Schiele and Van Der Helm, 2006, Bartenbach, 2017). The shoulder exoskeleton section is attached through a vest to the thorax. No rigid connection exists to the hip. This design choice aims to achieve maximum freedom of movement by not restricting lower spine mobility. The back support segment avoids any rigid structure and instead relies on a textile frame and thigh cuffs to transfer the supporting force to the human body. This approach also aims to minimize size and weight and potential movement constraints. To optimize fit and comfort, the OmniSuit comes in two sizes and allows for further size adjustment by shortening and extending straps at the leg, back, chest and arm. The

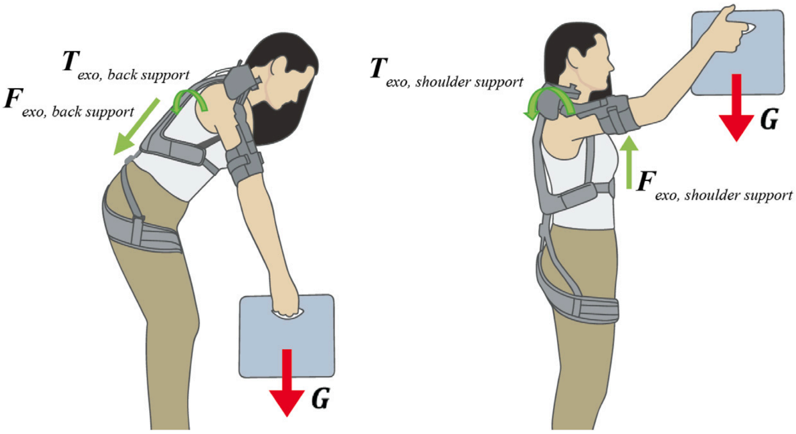


Fig. 2. Illustration of the gravity compensation for the back and shoulder provided by the OmniSuit. When leaning forward the force provided by the exoskeleton ($F_{exo,\ back\ support}$) acts in parallel to the back muscles. This force results in a torque around the hip and at each vertebra ($T_{exo,\ back\ support}$) to compensate the gravitation force (G) and resulting torques imposed by the weight of the user and an external load. When lifting the arms at or above shoulder level the OmniSuit provides an upward force ($F_{exo,\ shoulder\ support}$) at the arm cuff. This upward force results in a torque around the shoulder joint ($T_{exo,\ shoulder\ support}$) to compensate the gravitation force imposed by the user's arm and the external load.

total weight of the device is 2.7 kg for the smaller size, and 3 kg for the larger size.

Conceptually, the OmniSuit is designed to provide partial gravity compensation for the back and shoulders against the gravity-induced force imposed by handling an external load or the weight of body parts in certain postures (Fig. 2). This means neither support mechanism is designed to compensate for gravity completely but rather offsets a percentage of the gravity-induced force on the body. Partial compensation was chosen so that gravity-induced forces can be used to tension the springs, and thus, to prevent that muscle force is required to tension the springs. Both support mechanisms are designed to provide gravity compensation specifically in those body positions when gravity imposes a load on the corresponding joints.

The shoulder flexion support is achieved via a spring mechanism positioned in the shoulder joint with a mechanical switch to select from two levels of support. When lifting the arm without exoskeleton support, the $\text{Deltoid}_{\text{medial}}$ generates shoulder abduction, while the $\text{Deltoid}_{\text{anterior}}$ assists in generating horizontal adduction movements. The rotator cuff muscles stabilize the joint. The spring arrangement is engineered to provide an upward support torque similar to the Deltoid muscles (Fig. 2). To optimally compensate for gravity-induced force, almost no support is provided when the arms are hanging vertically on the side of the body and the support progressively increases to reach maximal support when the arm is in a horizontal position and is maximally "exposed" to gravity.

The OmniSuit back support is achieved via two textile springs arranged on the user's back to support the back muscles directly. The users can activate, deactivate, or adjust the support using a tensioning mechanism integrated into the front of the vest. Gravity pulls the upper body downwards during forward leaning and generates a torque around the hip and back as a lever arm appears between the gravitational force and the hip center of rotation.

Without exoskeleton support, the back and hip muscles must compensate for this gravitational pull by contracting and pulling the upper body upward. When wearing the OmniSuit, the elastic springs on the back are stretched by gravity when the upper body bends forward. When stretched, the springs create a permanent mechanical force that is arranged in parallel with the user's back muscles, allowing them to relax (Fig. 2).

By utilizing a rigid frame segment to transfer the shoulder support torque as a perpendicular force to the upper arm and transferring the assisted load around the shoulder joint through the rigid frame segment (Fig. 3), this concept aims to reduce the load on the muscles and tendons and additionally reduce the strain on the shoulder joint during overhead object handling to reduce the risk of injuries to the joint cartilage and ligaments.

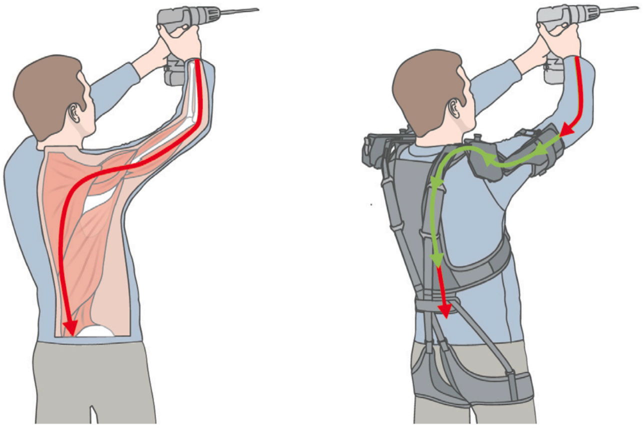
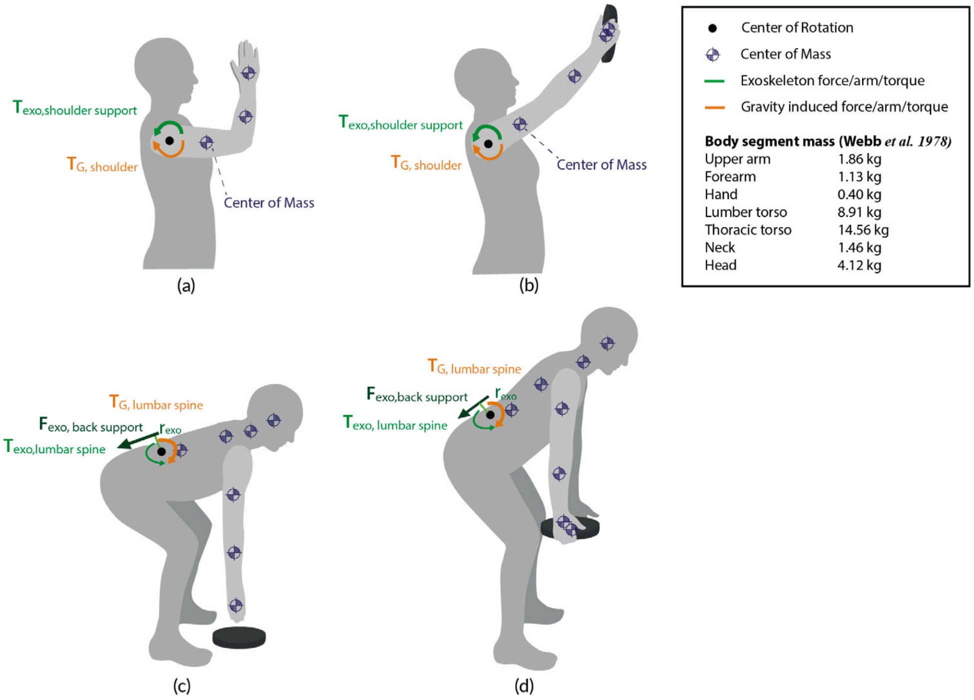


Fig. 3. Illustration of the shoulder support exoskeleton routing the load around the users' shoulder joint to reduce the strain in the joint.

2.2. Biomechanical model for support mechanism optimization

The desired support level requirement was defined to be over 15% in muscle load reduction of the shoulder and lower back muscles during phases of high physical load in each individual joint. Since springs are used, the support is variable based on the joint angle leading to spring deformation. We aimed to support the shoulder muscles over a range from 70° to 135° shoulder flexion and the lower back muscles over a range from 30° to 135° hip flexion. Previous studies with the LiftSuit and DeltaSuit exoskeletons have shown that this level of muscle support is well-perceived by users (Brunner et al., 2023a) and can lead to a significant reduction in muscle fatigue (Brunner et al., 2023b; Van Sluijs et al., 2023a) and cardiovascular load (Brunner et al., 2023c; Van Sluijs et al., 2023b). Furthermore, a field study in automotive industry reported that users of a passive shoulder support exoskeleton exclusively picked the settings with a peak support of 20 or 30% of arm weight (out of six settings with peak support ranging from 10 to 60%arm weight) for 16 different tasks (Gillette et al., 2022).

In order to meet this requirement, both the shoulder and back support modules needed to be finalized by designing appropriate spring mechanisms. This was done in two steps. In the first step, the gravity-induced loads during work activities were estimated using a biomechanical load model. In the second step, the springs were engineered to provide the desired level of support.



Body segment mass (Webb *et al. 1978)*

Upper arm	1.86 kg
Forearm	1.13 kg
Hand	0.40 kg
Lumber torso	8.91 kg
Thoracic torso	14.56 kg
Neck	1.46 kg
Head	4.12 kg

Fig. 4. Load and support model for the (a, b) Shoulder, and (c, d) Lumbar Spine. The support provided is variable based on the joint angle leading to spring deformation, in the figure the measured positions with highest and lowest support are illustrated. The shoulder exoskeleton is designed to provide the highest level of support at 90° shoulder flexion, thus the change in the torque provided by the shoulder muscles ($\Delta\ T_{\text{muscle}}$) is reduced most at 90° shoulder flexion without external load (a), whereas the change in the torque provided by the back muscles ($\Delta\ T_{\text{muscle}}$) is reduced most when reaching to pick up an external load from the ground (c). During a lift cycle with 2.5 kg external load the smallest changes are expected at 120° shoulder flexion with external load for the shoulder muscles (b) and during forward leaning with the external load for the back muscles (d).

2.2.1. Biomechanical load model definition

The model used for predicting the gravity-induced loads and the exoskeleton support is a simplified two-dimensional model in the sagittal plane (Fig. 4). Using anthropometric data from literature (Webb Associates and Yellow Springs, 1978), the human upper body was segmented into seven parts to model the average distribution of upper-body mass, including the length of the body segment as a percentage of stature, the mass of each segment, and the position of the center of mass of each body part (Fig. 4).

The gravity-induced torque (T_G) around each human joint induced by gravity is the sum of the torques induced by each body segment i above the respective joint. This, in turn, is the gravitational force on each segment (G_i) multiplied by the horizontal lever arm (perpendicular to the direction of gravity) of the body segment around the analyzed joint (r_{Gi}).

$$T_{\mathrm{G}} = \sum_{i=1}^{N} r_{\mathrm{Gi}} \cdot G_{\mathrm{i}}$$

The lever arm of each center of mass around the analyzed joint (r_G) is calculated based on the average stature (h) as reported by Webb Associates and Yellow Springs (1978), the position of the center of mass of the body segment (p_h) and the angle of the relevant joints and body segments (α) in the analyzed body posture. For example, when a person holds a weight in front of them with 90° shoulder flexion and 90° elbow flexion (Fig. 4a), $r_{G,\text{upper arm}}$ equals the distance between the shoulder center of rotation and the position of the center of mass of the upper arm (Webb Associates and Yellow Springs, 1978) and $r_{G,\text{forearm}}$ / $r_{G,\text{hand}}$ / $r_{G,\text{external weight}}$ all equal the length of the upper arm (Webb Associates and Yellow Springs, 1978).

To estimate the shoulder load during overhead work, we calculate the torque around the shoulder joint generated by gravity acting on the human arm (Fig. 4a) and on the combined weight of the human arm and a 2.5 kg external weight (Fig. 4b). For the upper back, the gravity-induced torques of the head and neck segments are added, and finally, for the lower back, the indicated torques of the thoracic torso and lumbar torso are added, considering the respective horizontal lever arms off all body segments.

Using this model, the total gravity-induced torque around the shoulder and the lumbar spine can be estimated for the body positions assumed during full-range lifting. To create equilibrium, the gravity-induced torque needs to be counteracted by the sum of the exoskeleton support force and the user's muscle activity. Thus, the expected change in the torque provided by the muscles ($\Delta\ T_{\text{muscle}}$) when wearing the exoskeleton is estimated as the torque generated by the exoskeleton split by the gravity-induced torque times 100%.

$$\Delta T_{\text{muscle}} = \frac{T_{\text{exo}}}{T_{\text{G}}} \cdot 100$$

The physiological data collection performed during the evaluation of the exoskeleton (see Section 2.3) aims to confirm these estimations. The reduction in torque the muscles need to provide during a supported movement is expressed in percentage of the torque needed to generate an unsupported movement. This torque reduction is expected to lead to a reduction in muscle activity in all muscles contributing to this movement, according to their contribution in the unsupported movement. For example, we hypothesize that a reduction of 20% shoulder flexion torque is expected to influence both Deltoid$_{\text{anterior}}$ and Deltoid$_{\text{medial}}$ and reduce muscle activity in these muscles by 20% of their activity during the unsupported movement. While torques and muscle activity cannot be directly compared, a similarity in support patterns and muscle activity decrease expressed in % of the unsupported condition was expected.

2.2.2. Shoulder support specification

Using the biomechanical model, the shoulder torque generated by the weight of the human arm and an external load was estimated to range between 7.6 Nm with shoulders and elbow flexed 90°, and 19.8 Nm with 45° shoulder flexion, stretched elbows, while holding a 2.5 kg weight. Across an array of modeled shoulder positions, the

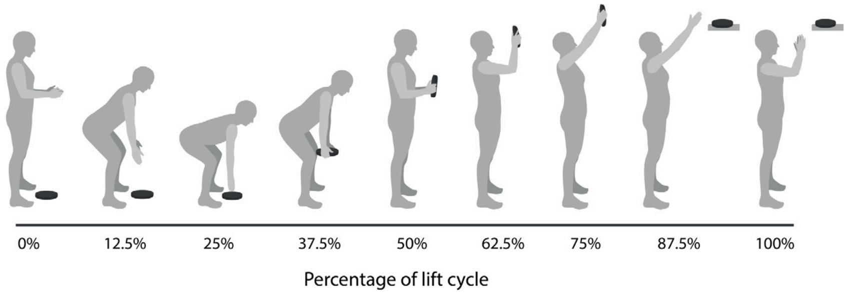


Fig. 5. A full range vertical lift cycle consisting of nine postures was used to evaluate the effect of the exoskeleton. The movement starts in upright stand with hands on hip height (0%), followed by forward leaning with hands on knee height (12.5%) and forward leaning in squat stand (25%). After picking up an external load follows loaded forward leaning with hands on knee height (37.5%), loaded upright stand with hands on hip height (50%), loaded upright stand with 90° shoulder and elbow flexion (62.5%), and loaded upright stand with 120° shoulder flexion (75%). After depositing the load on a shelve follows unloaded upright stand with 120° shoulder flexion (87.5%) and unloaded upright stand with 90° shoulder and elbow flexion (100%).

shoulder spring arrangement was finalized to provide a shoulder flexion angle dependent support profile with a peak supportive torque generated at 90° of around 7.2 Nm.

2.2.3. Back support specification

Using the biomechanical model, we estimated the gravity-induced torque in the lumbar spine during the lowering phase of the lifting movement. The torque generated in the lumbar spine was estimated to range between 68.7 Nm when leaning forward 45°, and 88.0 Nm in squat stand. To meet the requirements, the counter torque provided by the exoskeleton needed to be between 11.6 and 28.5 Nm. The back support is provided as a support force that indirectly generates a torque around the respective part of the spine through a lever arm between the force vector and the center of rotation in the spine, which was estimated to be 0.06 m in the lumbar spine. We assumed that the spring force is similar along the spine, neglecting any potential losses due to friction between the springs and the vest. Considering spring strain across multiple positions, we calculated that the desired assistance would be achieved if the device delivered was 240 N per spring in the squat stand position to meet the requirements for lumbar spine support.

The spring development involved several iterations of springs with different stiffnesses, which were tested in a series of pilot tests with the aim to achieve the defined support force. This experimental approach was necessary because we observed that with increased stiffness, the stretch during lifting was typically reduced. As a result, increasing stiffness did not guarantee a linear increase in support torque, and a lower stiffness did not necessarily result in a lower support torque. This is a result of compliance in the exosuit, slipping of the interfaces relative to the human skin/clothes, and especially compliance of the human soft tissue. The higher the supporting spring force gets, the more all these additional soft elements deform, which limits the exoskeleton support.

The iterative design approach led to a spring design with a stiffness of each spring of around 5.5 N/mm. In a 45° forward-leaning posture, an average stretch of 17.5 mm was observed during pilot testing ($n = 6$), which resulted in an average support force of 96 N per spring. During squat stand, an average stretch of 43.2 mm was observed, which resulted in an average support force of 238 N per spring.

2.3. Study protocol

The measurements took place at the Rehabilitation Engineering Laboratory of ETH Zurich. The study protocol was approved by the ethics committee of ETH Zurich (EK 2023-N-180). After signing the informed consent, anthropometric measures were taken from the participant. Next, the experimenter fitted the participant into the OmniSuit exoskeleton, and a 10-minute training on exoskeleton use was given for familiarization purpose. After sensor placement, normalization values for muscle activity (maximal voluntary contraction) were obtained. The 2 h experiment started with an isometric task, followed by three 3 min dynamic tasks simulating overhead manufacturing, as well as squat and full-range lifting. The isometric task reported in this paper consisted of a series of statically help postures representative of the different phases of a full-range lifting motion, as seen in logistics work, where a 2.5 kg load is picked up from the ground and placed overhead (Fig. 5). Each of the nine postures was held for 10 s, with the aim of identifying how the exoskeleton supports the user during specific, functionally relevant, positions. Participants were shown a series of images of a person holding the different positions, corresponding to the lift cycle visible in Fig. 5, as part of the explanation of the task. To measure the effect of the exoskeleton, the task was carried out in two conditions, without the exoskeleton (OFF) and with the exoskeleton (EXO) with maximal support. To avoid biases and strengthen the internal validity, the conditions were done in randomized order.

2.4. Data collection and processing

Muscle activity of the shoulder, neck, back, hip, and abdomen was recorded on the participant's dominant hand side. The following six muscles/muscle groups were measured using surface electromyography sensors (Trigno Avanti sensors, Delsys Inc, USA): Deltoid$_{\text{medial}}$, Deltoid$_{\text{anterior}}$, Trapezius Descendens, Erector Spinae$_{\text{thoracic}}$, Iliocostalis, Erector Spinae$_{\text{lumbar}}$, Rectus Abdominis and Gluteus Maximus. The Erector Spinae$_{\text{thoracic}}$ sensor was placed according to McGill (1991), the other sensors were placed according to SENIAM guidelines (Stegeman and Hermens, 2007). Next, maximal voluntary contraction (MVC) exercises were performed, with the targeted muscle(s) indicated in brackets: 90° shoulder flexion for the Deltoid$_{\text{anterior}}$ (Kim et al., 2018), 90° shoulder abduction for the Deltoid$_{\text{medial}}$ (Boettcher et al., 2008), scapular elevation in sitting posture for the Trapezius Descendens (Boettcher et al., 2008), prone spinal extension for all back muscles (Al-Qaisi et al., 2021), upward push in prone position with 90° flexion in the knee for the Gluteus Maximus (Worrell et al., 2001) and isometric curl-up for the Rectus Abdominis (Lehman and McGill, 2001). During the MVC exercises, the experimenter applied resisting force, except during the MVC for the Erector Spinae, where gravity and prone posture restricted the range of motion and resistance to the movement. Two rounds of MVC measurements were done, with each exercise lasting 10 s. Data analysis, visualization and statistical testing were performed using Matlab 2022b (MathWorks, USA). The EMG signals were filtered according to SENIAM guidelines with a 4th-order Butterworth bandpass filter with cut-off frequencies of 10 and 500 Hz (Stegeman and Hermens, 2007). The signal amplitude normalized to maximal voluntary contraction is reported. As outcome measure, the root mean square (RMS) muscle activity during the 10 s duration of each posture is reported.

After completion of the entire protocol, including static and dynamic tasks, participants rated device discomfort on a 10-point Likert

Table 1

Measured change in mean RMS muscle activity over all participants expressed in %MVC calculated as (M_{OFF} - M_{EXO}),the p-values of the two-way ANOVA factors exoskeleton condition (Exo), lift cycle bodyposition (Pos) and the interaction between Exo and Pos, as well as the measured change in muscle activity in %OFF calculated as (M_{OFF} - M_{EXO})/M_{OFF} *100 are reported. P-values < 0.00625 (Bonferroni correction for muscles) are in bold font.

	Lift cycle									RM-ANOVA		
%MVC	0%	12.5%	25%	37.5%	50%	62.5%	75%	87.5%	100%	Pos	Exo	Int
Deltoid$_{\text{medial}}$	0.2	0.8	1.4	0.7	0.9	10.1	7.0	7.6	9.7	**<0.001**	**<0.001**	**<0.001**
Deltoid$_{\text{anterior}}$	0.7	1.7	3.8	0.6	2.9	15.7	4.1	8.9	15.7	**<0.001**	**<0.001**	**<0.001**
Trapezius Descendens	0.9	0.6	0.8	−0.1	1.1	5.1	5.7	6.0	5.8	**<0.001**	**<0.001**	**<0.001**
Erector Spinae$_{\text{thoracic}}$	−0.2	5.6	6.8	5.1	3.3	5.2	6.2	4.7	5.4	**<0.001**	**<0.001**	**<0.001**
Erector Spinae$_{\text{lumbar}}$	0.2	4.6	14.0	7.4	0.8	1.6	1.2	2.2	1.9	**<0.001**	0.021	**<0.001**
Iliocostalis	0	2.7	10.4	5.1	−0.1	1.2	1.4	1.1	0.5	**<0.001**	0.009	**<0.001**
Rectus abdominis	1.9	1.5	0.5	1.1	1.3	1.2	−1.1	0.6	2.0	**<0.001**	0.565	0.227
Gluteus maximus	−0.4	−0.1	1.9	0.6	0.3	0.6	−0.3	−0.3	−0.7	**<0.001**	0.937	0.059

%OFF	**0%**	**12.5%**	**25%**	**37.5%**	**50%**	**62.5%**	**75%**	**87.5%**	**100%**
Deltoid$_{\text{medial}}$	11.8	31.3	43.2	24.0	28.4	49.1	19.1	28.2	75.4
Deltoid$_{\text{anterior}}$	47.1	55.9	64.6	12.2	45.2	39.9	9.8	29.5	63.3
Trapezius Descendens	30.8	27.5	36.9	−3.3	29.5	46.8	23.1	35.7	62.1
Erector Spinae$_{\text{thoracic}}$	−3.4	38.7	41.5	30.9	25.9	37.3	30.0	36.6	43.0
Erector Spinae$_{\text{lumbar}}$	2.1	11.7	31.2	15.5	5.0	7.3	3.9	12.2	12.6
Iliocostalis	−0.2	14.3	43.3	20.5	−1.2	9.8	8.4	11.5	5.9
Rectus abdominis	32.0	20.8	7.0	15.8	21.0	19.3	−18.4	12.0	32.1
Gluteus maximus	−4.9	−0.8	17.3	4.6	2.9	4.8	−2.5	−3.6	−7.8

scale and rated system usability using two validated questionnaires: the System Usability Scale (Bangor et al., 2008) and the device sub-scale of the Quebec User Evaluation of Satisfaction with Assistive Technology (QUEST) (Demers et al., 2000).

2.5. Statistics

Percent change with respect to the OFF condition were calculated to illustrate the effect of the exoskeleton, as well as % change with respect to the MVC, to account for the magnitude of these changes with respect to the involvement of the muscle in the tested tasks. The effect of the body position (Pos), the exoskeleton (Exo) and the interaction between position and exoskeleton (Int) on muscle activity levels were assessed using two-way repeated measures ANOVAs for each muscle. Effects were considered significant if $p < 0.00625$ (Bonferroni correction for eight muscles). Post-hoc test of the seven body positions that were modeled (Deltoid$_{\text{medial}}$ lift cycle 62.5%–87.5% and Erector Spineae$_{\text{lumbar}}$ lift cycle 12.5%–37.5%) was performed using paired t-tests. Effects were considered significant if $p < 0.007$ (Bonferroni correction for seven post-hoc tests). Normality of the data was confirmed using histogram plots. The modeled reduction in torque the muscles need to provide during a supported movement was visually compared to the change in muscle activity between supported and unsupported conditions.

3. Results

3.1. Participants

Thirty-one healthy participants (15 female) of working age (22 to 64 years, Mean: 28.0 y, SD: 10.2 y) were included, without a history of upper-limb or back musculoskeletal disorders. Participant height ranged from 158 cm to 193 cm (Mean: 176.3 cm, SD: 9.6 cm) and weight ranged between 53.2 kg and 101.0 kg (Mean: 76.4 kg, SD: 12.1 kg).

3.2. Changes in muscle activity

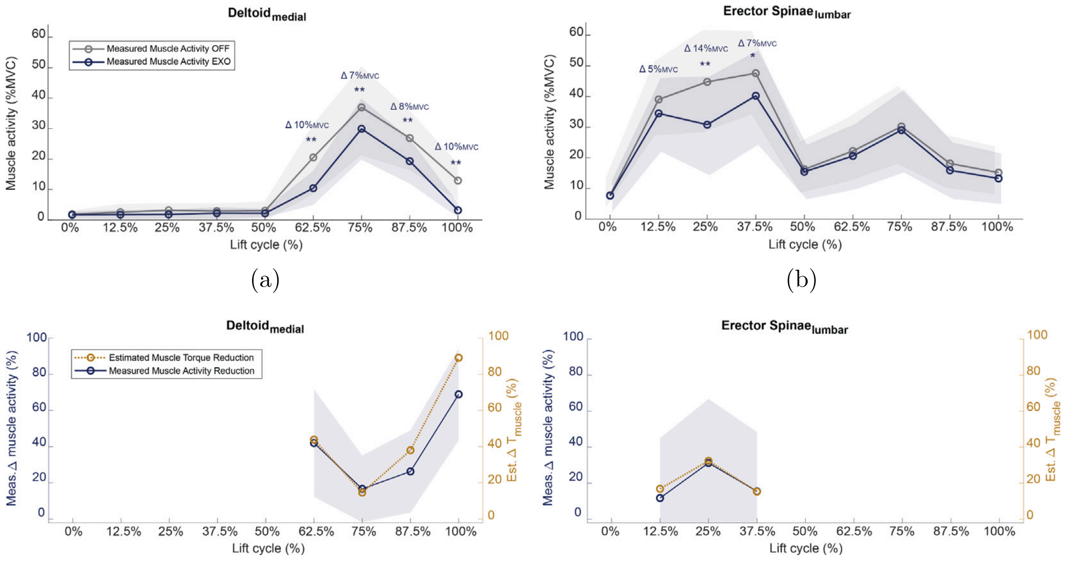
Changes in muscle activity between the no exoskeleton (OFF) and exoskeleton (EXO) conditions during the nine isometric body position are shown in Fig. 6(a) for Deltoid$_{\text{medial}}$, and in Fig. 6(b) for Erector Spinae$_{\text{lumbar}}$. The measured change in mean muscle activity during the entire lift cycle are reported both in %MVC and in % change compared to OFF condition in Table 1.

Significant effects of body position (Pos), exoskeleton (Exo) and an interaction between these factors on measured change in %MVC were observed for the Deltoid$_{\text{medial}}$, the Deltoid$_{\text{anterior}}$, and the Trapezius Descendens ($p < 0.001$). These muscles are supported by the shoulder module of the OmniSuit during positions with arms at or above shoulder level. Post-hoc analysis of the Deltoid$_{\text{medial}}$ activity during the second half of the lifting cycle (62.5%–100%), showed significant reductions in all four body positions ($p < 0.007$). The highest change in Deltoid$_{\text{medial}}$ activity was 10.1%MVC, observed at 62.5% of the lift cycle with 90° shoulder and elbow flexion with 2.5 kg external load ($p < 0.001$). While, the highest percent reduction in Deltoid$_{\text{medial}}$ activity was 75.4% of baseline condition, and was observed at 90° shoulder and elbow flexion without external load ($p < 0.001$). When raising the arms above 90° shoulder flexion the change in Deltoid$_{\text{medial}}$ activity ranged between 7.0%MVC to 7.6%MVC, corresponding to 19.1% to 28.2% of the baseline condition. Significant effects of position, exoskeleton and interaction were observed for the Erector Spinae$_{\text{thoracic}}$ ($p < 0.001$), while a significant effect of position and an interaction between position and exoskeleton was observed for the Erector Spinae$_{\text{lumbar}}$ and Iliocostalis muscle activity was significantly ($p < 0.001$). These three back muscles are supported by the back support module of the OmniSuit during the forward leaning part of the movement (12.5% to 37.5% of the lift cycle). Post-hoc analysis of the Erector Spinae$_{\text{lumbar}}$ showed that muscle activity was significantly reduced in the squat position and forward leaning with 2.5 kg load ($p < 0.007$), and a trend towards a significant change was observed in the forward leaning without external load position ($p = 0.031$). The mean reduction in Erector Spinae$_{\text{lumbar}}$ ranged between 4.6%MVC to 14.0%MVC, corresponding a reduction of 11.7 to 31.2% from baseline.

No significant effect of exoskeleton or interaction effect on abdominal or gluteus muscle activity was observed.

3.3. Predicted exoskeleton support

Based on the biomechanical model, the estimated reduction in shoulder muscle torque ranged from 15% to 45% in arm positions with high gravity-induced strain and with a 2.5 kg external weight. The estimated reduction in muscle torque at the level of the lumbar spine was 16.8%, 32.4% and 15.3% when leaning forward with hands at knee height, squat stand and leaning forward while holding a 2.5 kg external weight respectively. There was little deviation between predicted and mean measured shoulder support (Fig. 6(c)), with mean measured support being higher than predicted with load (4% resp. 5% deviation)



(a) (b)

(c) (d)

Fig. 6. a/b. Change in muscle activity RMS amplitude as a percent of maximal voluntary contraction (%MVC) between the no exoskeleton (OFF) in gray and exoskeleton (EXO) condition in blue during the nine isometric body position for the Deltoid$_{medial}$ (a) and Erector Spinae$_{lumbar}$ (b). The line displays the sample mean and the shaded area is the standard deviation. Post-hoc tests in the form of paired t-test were performed for the seven modeled body positions, *: $p < 0.007$, **: $p < 0.001$. c/d. Comparison of change in torque provided by the shoulder flexion muscles according to the biomedical model (Est. Δ T_{muscle} in %; yellow dashed line) and measured change in muscle activity in % of the OFF condition (Δ muscle activity) for the Deltoid$_{medial}$ (c) and Erector Spinae$_{lumbar}$ (d).

and mean measured support being lower than predicted for positions without external load (−10% and −14%).

During the first half of the lift cycle, the participants lean forward and pick up a weight from the ground. Predicted exoskeleton support of the Erector Spinae was predicted to be up to 37% for the Erector Spinae$_{lumbar}$. Deviation between predicted and mean measured support was minimal for the Erector Spinae$_{lumbar}$ (<5%; Fig. 6(d)).

3.4. Usability and device comfort

The usability of the device was rated 4.2/5 on the QUEST device sub-scale score (SD: 0.4/5) and 79.6/100 on the System Usability Scale (SD: 9.2/100), indicating good usability. Ratings of the eight usability dimensions of the QUEST (Fig. 7) indicate that users are somewhat satisfied to very satisfied with the device dimensions, weight, level of adjustability and ease of use. Seven of 31 users were not very satisfied with the comfort of the device. More specifically, participants reported minimal device related discomfort at the shoulders (Mean: 0.8/10, SD: 1.5/10), back (Mean: 0.1/10, SD: 0.8/10) and arms (Mean: 0.9/10, SD: 1.5/10), and minor discomfort at the legs (Mean: 2.0/10, SD: 2.3/10). None of the participants reported device-related discomfort in the neck, chest or buttocks.

4. Discussion

The objective of this paper was to present the design of the OmniSuit, a multi-joint passive exoskeleton for combined back and shoulder assistance. Exoskeleton performance was evaluated in a study with 31 participants, in which the effect on shoulder and back muscle activity during different postures spread over the full vertical range of motion was measured and compared to a biomechanical model. We hypothesized that using the exoskeleton relieved the shoulder muscles during work above shoulder level and the back muscles during squat lifting and forward-leaning. Measurements of muscle activity, in our gender-balanced sample of individuals with a range of body shapes, confirmed that the exoskeleton relieves the lower back muscles by up to 31% when leaning forward and the shoulder muscles by up to 75% when reaching overhead.

We could not compare the support provided by the OmniSuit to the support provided by other multi-joint research or commercial exoskeletons like the SuitX MAX, Shiva, UPLIFT, and Muscle Upper, as to our knowledge, no scientific literature or systematic performance benchmarking of these exoskeletons has been published. However, the OmniSuit shoulder support and back support can be separately compared to the literature on exoskeletons providing either back or shoulder support. The back support module of the OmniSuit can be compared to back support exoskeletons such as the LiftSuit (Auxivo AG, Switzerland), HAPO (ErgonSanté SA, France), Laevo (Laevo B.V., Netherlands) and BackX (now Ottobock SE & Co. KGaA). In a forward-leaning isometric position, the back muscle activity of the Erector Spinae$_{lumbar}$ was reduced by 31% in the OmniSuit, while other exoskeletons supporting the back were shown to relieve the lower back muscle from 11% to 57%, suggesting a similar support range as in the multi-joint exoskeleton (Van Sluijs et al., 2023b; Bosch et al., 2016; Koopman et al., 2019; Jelti et al., 2021). The shoulder support module of the OmniSuit can be compared to shoulder support exoskeletons such as the DeltaSuit (Auxivo AG, Switzerland), Skelex 360 (Skelex B.V., Netherlands), and Exhauss Stronger (Exhauss SA, France). In an isometric position with a 90° flexion in the elbow and shoulder, the reduction in the Deltoid$_{anterior}$ was around 63%, which is in a similar range to the performance of the other shoulder exoskeletons (45% to 67%) (Brunner et al., 2023c; Desbrosses et al., 2021).

That the multi-joint support provided by the OmniSuit performs similarly to passive exoskeletons providing single joint support is a positive result. When integrating both back and shoulder support components into a single system, there is a possibility that they negatively influence one another. Specifically for the OmniSuit, the weight of the shoulder support structures pushes the upper body downwards when leaning forward. This additional load needs to be counteracted by the back support and could potentially have reduced and limited the back support. However, such a potential adverse effect was not observed in this study. Furthermore, no significant changes in abdominal muscle activity were observed, suggesting no abnormal movement compensation. These findings underline that the proposed adaptation made to the back and shoulder units allowed to take best advantage of both support structures, while remaining lightweight and comfortable.

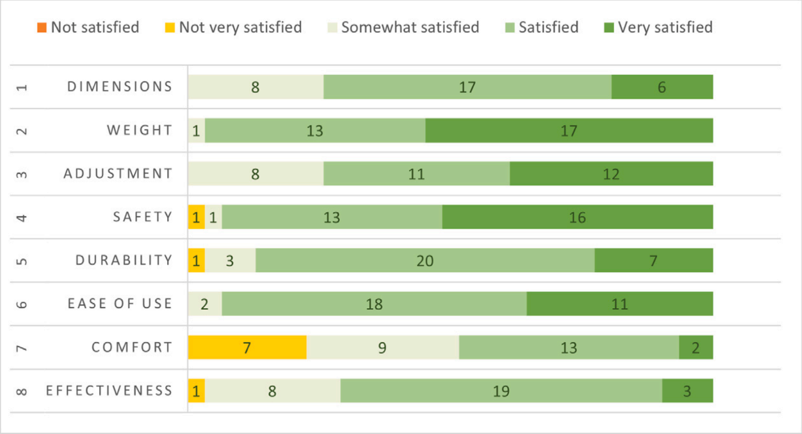


Fig. 7. Responses to the device sub-scale of the Quebec User Evaluation of Satisfaction with Assistive Technology (QUEST). Number of participants choosing a certain level of satisfaction for each dimension is reported.

Moreover, after completing the 2 h study protocol participants reported only minimal to minor levels of device-related discomfort, and rated the system usability of the device as good.

The experimentally quantified muscular support was well aligned with the support torque predicted by the biomechanical model, for those parts of the movement with high gravitational forces. The shoulder support was highest in the second half of the full-range lifting movement, where the arms and external load are lifted against gravity. While we expected the back support to be highest in the first half of the lifting movement, where the upper body is bent forward. The observed levels of reduction in %MVC suggest the exoskeleton provides a relevant level of support for full-range lifting movements, as observed in logistics work. Further, the measured level of support validates the chosen design approaches for both the rigid exoskeleton module for the shoulder support as well as the soft exosuit module for the back support. While a simple model-based method was sufficient to optimize the design of the shoulder support mechanism, an iterative method combining model and experiment-based approach was necessary to design the soft exosuit back support to account for hard-to-model dependencies between spring stiffness and resulting support.

It is important to acknowledge certain limitations of the study design. The use of a set of isometric positions to represent a dynamic movement allows to model and analyze these postures. However, in real life lifting occurs in a dynamic work environment, and spring-based exoskeleton support allows for energy retention which cannot be modeled in isometric tasks. It has been reported in the literature that passive exoskeletons may perform better (achieve larger EMG reductions) in isometric tasks than dynamic tasks (Kermavnar et al., 2021; Brunner et al., 2023a). Combining this with the knowledge that exoskeletons are generally less effective and more uncomfortable in the field (Moeller et al., 2022; Baldassarre et al., 2022; Kermavnar et al., 2021) it will be important to confirm the results of this work by performing dynamic and long-term measurements in the field. To determine whether the level of support provided is suitable for lifting tasks such future studies should also report antagonist muscle activity, such as the Latissimus Dorsi. In addition, occupational tasks involve a wide variety of lifting movements and strategies, including movements outside of the sagittal plane. It is of interest to include such movement variety in measurement protocols. Further, exoskeleton performance likely depends on a combination of factors, including the user's physique, the type of clothing, openness to novel technologies, and level of training. The participants were novel to the tasks and exoskeleton and were only given a 10–15 min training on the exoskeleton use. Movement is completed more efficiently when done in a repetitive and trained manner, this could be interrupted by exoskeleton usage and improved when a longer adaption phase is included (Moeller et al., 2022). While initial device comfort and usability were rated as good during this 2-hour lab experiment, both aspects should be evaluated during full-day use by target users in a range of work settings.

In the next steps, exoskeleton support during dynamic tasks should be quantified. It would further be of interest to evaluate multi-joint support exoskeletons in an occupational setting with target end-users. Further, the importance of potential learning effects on exoskeleton use should be investigated.

5. Conclusion

This study presents the design and first results of the effect of a novel multi-joint exoskeleton, confirming the feasibility of this wearable assistive device for occupational use. In our sample, the OmniSuit significantly reduced shoulder, neck, and back muscle activity during a full-range vertical lifting movement, including forward leaning and overhead reaching postures. Participants reported good device usability and only minor discomfort, suggesting the focus on compliance, lightweight, and unconstrained movements in the design resulted in a promising tool to relieve workers in occupations that involve lifting over a large range of vertical motion.

CRediT authorship contribution statement

Rachel van Sluijs: Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Formal analysis, Conceptualization. **Tamina Scholtysik:** Writing – original draft, Visualization, Investigation, Formal analysis. **Annina Brunner:** Writing – original draft, Investigation, Formal analysis. **Laura Kuoni:** Visualization, Investigation. **Dario Bee:** Resources. **Melanie Kos:** Resources. **Volker Bartenbach:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **Olivier Lambercy:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization.

Declaration of competing interest

Olivier Lambercy is an academic advisor to Auxivo AG. Rachel van Sluijs, Annina Brunner, Melanie Kos, Dario Bee, and Volker Bartenbach are employed by Auxivo AG.

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Ethical standards

The study protocol was approved by the university ethics committee of ETH Zurich (EK 2023-N-180).

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.apergo.2024.104332.

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