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REVIEW

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Back-Support Exoskeletons for Occupational Use: An Overview of Technological Advances and Trends

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OCCUPATIONAL APPLICATIONS Many new occupational back-support exoskeletons have been developed in the past few years both as research prototypes and as commercial products. These devices are intended to reduce the risk of lower-back pain and injury for workers in various possible application sectors, including assembly in automotive and aerospace, logistics, construction, healthcare, and agriculture. This article describes the technologies adopted for back-support exoskeletons and discusses their advantages and drawbacks. Such an overview is intended to promote a common understanding and to encourage discussion among different stakeholders such as developers, ergonomics practitioners, customers, and workers.

TECHNICAL ABSTRACT ***Background*:** The large prevalence and risk of occupational lower-back pain and injury associated with manual material handling activities has raised interest in novel technical solutions. Wearable back-support exoskeletons promise to improve ergonomics by reducing the loading on the lumbar spine. ***Purpose*:** Since many new prototypes and products are being developed, this article presents an up-to-date overview of the different technologies. By discussing the corresponding advantages and drawbacks, the objective is to promote awareness and communication among developers, ergonomics practitioners, customers, and factory workers. ***Methods*:** The state-of-the-art is presented with a focus on three technological aspects: (i) the actuators generating assistive forces/torques, with a main distinction between passive and active devices; (ii) the structures and physical attachments that transfer those forces/torques to the user, with structures being soft, rigid, or a combination of the two; and (iii) the control strategies employed (i.e., how devices adjust assistive forces/torques to accommodate different activities and parameters). ***Discussion*:** The choice of actuation technology may determine the applicability of a device to different scenarios. Passive exoskeletons appear more suitable for tasks requiring relatively light assistance and little dynamic movements. By contrast, heavier and more dynamic tasks will justify the use of more complex active exoskeletons. While on-board battery power is increasingly present on active exoskeletons, the tradeoff between power autonomy and additional battery mass will probably depend on the specific application. Most back-support exoskeletons are implemented using rigid articulated structures, which tend to be heavy and bulky, but generate more appropriate patterns of forces. Fewer soft exoskeletons have been developed to date, although they could be integrated with or worn underneath standard working attire and offer greater user comfort. The adoption of any given device will ultimately depend on several factors, including user acceptance and the costs and benefits associated with specific applications.

KEYWORDS Exoskeletons, manual handling, personal protective equipment, back support

INTRODUCTION

Manual material handling (MMH) is a common, physically demanding activity in many occupational scenarios (e.g., automotive and aerospace manufacturing, logistics, construction, and agriculture). MMH includes tasks such as dynamic lifting and prolonged stooped postures, can generate large compressive on the lumbar spine, and is one of the main risk factors for musculoskeletal injury (EU-OSHA, 2000). Work-related injuries not only increase the costs sustained by companies, but most importantly have a severe impact on workers' quality of life (Katz, 2006). Safety and ergonomics guidelines for the workplace aim to reduce the workload on workers, often resulting in very strict limitations on MMH operations in terms of object weights and movement frequency (Garg, 1995; Konz, 1982; Waters, Putz-Anderson, Garg, & Fine, 1993). While the physical workload on workers may be reduced with devices such as external manipulators, which unload all or part of the weight to be handled, such devices can be impractical or infeasible in some circumstances.

Exoskeletons are wearable devices that generate forces/torques on one or multiple human joints to support the execution of physical activities. There are many possible applications of exoskeletons, which include physical therapy for clinical motor rehabilitation (Colombo, Joerg, Schreier, & Dietz, 2000), assistance for people with motor impairments (Ortiz, Di Natali, & Caldwell, 2018; XoSoft, 2018) or those in the military (Kazerooni et al., 2005), and even protective or enhancing gear for sports (RoamRobotics, 2018). Recently, there has been increasing interest in employing exoskeletons to reduce the physical loading on workers carrying out demanding activities in several occupational sectors, because these devices may offer an alternative to existing solutions. de Looze, Bosch, Krause, Stadler, and O'Sullivan (2016) provided a comprehensive review of scientific studies reporting the biomechanical effects of existing occupational exoskeletons. Since their review was published, the landscape of occupational exoskeletons has expanded substantially, including several new research prototypes as well as products by existing or new companies. More recently, a white paper by Sugar et al. (2018) listed the newest "lift assist wearables" and their applications, with a particular focus on devices for reducing lumbar loading. A dedicated web blog was also recently created, offering a catalog of exoskeletons including those for industrial applications (Marinov, 2018).

The objective of the current article is to provide an up-to-date overview of the most recent technological developments, focusing on exoskeletons for lumbar support. To support this objective, we aimed to establish a common understanding and foster discussion among stakeholders. These stakeholders include both managers and end users, who may benefit from learning about the working principles of available solutions, along with their pros and cons; manufacturers, who may create enhanced design decisions with a wider perspective; and researchers, who may find interesting technological challenges to address. This article does not cover the ongoing efforts toward standards, regulations, and guidelines to support the use of exoskeletons in the workplace. These aspects are covered in recent articles (Lowe, Billotte, & Peterson, 2019; Nabeshima, Ayusawa, Hochberg, & Yoshida, 2018) and may be extended in future publications.

Our article describes (Section "State of the art") and discusses (Section "Discussion") the state of the art with an emphasis on three technological aspects of exoskeleton implementation: (i) actuation, or the component of an exoskeleton that produces forces/torques; (ii) force transfer to the user, which is a function of exoskeleton structures and attachments; and (iii) control strategies, i.e., how exoskeletons can make use of sensory information to adjust the provided forces/torques during operation in order to offer the most appropriate assistance profiles.

STATE OF THE ART

Many different terms have been used to describe exoskeletons that have been designed to unload the lumbar spine, such as "back support," "lift assist," "lumbar support," "hip orthosis," "spinal exoskeleton." For the sake of simplicity, we refer to them as "back-support exoskeletons." We particularly refer to those exoskeletons that are built around the following concept: forces/torques are applied in the sagittal plane, between the user's torso and thighs, to assist with extension of the back and/or hip joints. These devices aim to assist the user by providing a portion of the torque required to achieve a physical task (e.g., lifting, or maintaining a stooped posture). In doing so, the devices are designed to reduce the activity required of the para-spinal muscles. The required torques may be estimated based on inverse dynamic models, as in the work by Koopman, Kingma, Faber, Bornmann, and van Dieën (2018).

The information presented in this article was collected by combining the authors' personal databases with scientific papers found via a literature search using Scopus. Search terms in the latter used the names noted above as keywords (i.e., "back," "lift," "lumbar," "hip," "spinal," "assist," "support," "orthosis," "exoskeleton"). Only devices providing back support were considered. A list of the back-support exoskeletons available at the time of writing (August 2018) is provided in Table 1. The latest version of each device was considered (e.g., Atoun Model Y, but not Models A or As).

Actuation

An exoskeleton generates assistive forces/torques employing either passive components, such as springs, or powered actuators, such as electric motors. Due to the physical nature of the components used, a passive exoskeleton can store and/or dissipate energy provided by the user, while an active one has the capability to introduce additional energy from external sources (e.g., batteries) on demand.

Passive

Existing passive back-support exoskeletons employ elastic elements of different types. Coil springs are integrated on the Wearable Moment Storing Device (WMRD) (Wehner, Rempel, & Kazerooni, 2009) and on the hip actuator of the recent SPEXOR device (Figure 1) (Näf, Koopman et al., 2018), while the bending non demand return (BNDR) (Ulrey & Fathallah, 2013) employs compact rotational springs. Similar use of integrated gas springs is found on the Laevo (Laevo, 2017) and BackX (SuitX, 2017). Elastic bands are used on a number of devices, including the Personal Lift Augmentation Device (PLAD) (Abdoli-E, Agnew, & Stevenson, 2006), Smart Suit Lite (SSL) (Imamura, Tanaka, Suzuki, Takizawa, & Yamanaka, 2011), Wearable Assistive Device (WAD) (Heydari, Hoviattalab, Azghani, Ramezanzadehkoldeh, & Parnianpour, 2013), and biomechanically assistive (B.A.) garment (Lamers, Yang, & Zelik, 2017). On the other hand, the SPEXOR device (Näf, Koopman et al., 2018) employs flexible beams to transfer the assistive torque between the pelvis and the torso. Flexible carbon fiber beams are also found on the VT/Lowe's exoskeleton to generate torques both between the pelvis and the torso and between the torso and the hip (Alemi, Geissinger, Simon, Chang, & Asbeck, 2019; Manna & Asbeck, 2017). Assistance levels and profiles for these exoskeletons are decided at the design stage, and cannot typically be adjusted during use, with the exception of set screws (e.g., variable pretension on the springs) and mechanical on/off switches capable of disengaging the elastic elements.

Active

Active exoskeletons employ actuators whose action is controlled during operation by a computer program based on sensor information. For this reason, they are considered to be potentially more versatile (relying on underlying control strategies, as expanded in Section "Control Strategies"). Most active exoskeletons use electric motors, but examples of pneumatic actuation exist (e.g., Muscle Suit (Aida, Nozaki, & Kobayashi, 2009), AB-Wear (Inose et al., 2017)). Electric motors are used in combination with reduction gears to achieve the necessary forces/torques. Harmonic Drive (Harmonic Drive AG, Germany) reduction gears enable very compact designs and are therefore used commonly despite

TABLE 1 List of existing back-support exoskeletons, corresponding references, and their classification with respect to the three technological aspects described in this paper.

Actuation class	Actuation technology	Structure	Mass (kg)	Control strategy	Device name	Reference
Passive	Elastic bands	Soft	n/a	–	PLAD	(Abdoli-E et al., 2006)
	Elastic bands	Soft	n/a	–	SSL	(Imamura et al., 2011)
	Elastic bands	Soft	1.5	–	WAD	(Heydari et al., 2013)
	Elastic bands	Soft	2.0	–	B.A. Garment	(Lamers et al., 2017)
	Carbon fiber beams	Soft/Rigid	n/a	–	VT/Lowe's	(Alemi et al., 2019; Manna & Asbeck, 2017)
	Coil springs + flexible beams	Soft/Rigid	6.6	–	SPEXOR	(Näf, Koopman et al., 2018b)
	Coil springs	Rigid	n/a	–	WMRD	(Wehner et al., 2009)
	Torsion springs	Rigid	n/a	–	BNDR	(Ulrey & Fathallah, 2013)
	Gas springs	Rigid	2.3	–	Laevo[a]	(Laevo, 2017)
	Gas springs	Rigid	3.3–4.5	–	BackX[a]	(SuitX, 2017)
Active	Electric	Soft	n/a	Motion	WSAD	(Luo & Yu, 2013)
	Pneumatic	Rigid	2.9[b]	External operator	AB-Wear	(Inose et al., 2017)
	Pneumatic	Rigid	9.2[b]	Mouthpiece, chin pad	Muscle Suit	(Aida et al., 2009)
	Electric	Rigid	n/a	Motion + EMG (spinal muscles)	HAL Lumbar Support[a]	(Hara & Sankai, 2010; 2012)
	Electric	Rigid	8.0	Motion	Waist Power Assist	(Yu et al., 2015)
	Electric	Rigid	11.0[b]	Motion + EMG (forearm)	Robo-Mate EU active trunk	(Toxiri, Calanca et al., 2018; Toxiri, Koopman et al., 2018)
	Electric	Rigid	n/a	Motion	German Bionic CRAY X[a]	(German Bionic, 2018)
	Electric	Rigid	4.5	Motion (3 modes)	Atoun Model Y[a]	(ATOUN, 2018)
	Electric	Rigid	6.5	Motion (states)	APO (HuMan EU)	(Chen et al., 2018)
	Electric	Rigid	11.2[b]	Motion	Lower-Back Exoskeleton	(Zhang & Huang, 2018)
	Electric	Rigid	4.5	Motion	Hyundai H-WEX	(Ko et al., 2018)

The table lists 10 passive and 11 active exoskeletons. Only eight in this list are soft or have soft elements. Among the active devices, only two employ direct control strategies (via EMG).

[a]Commercially available.

[b]Not including battery or other power supply.

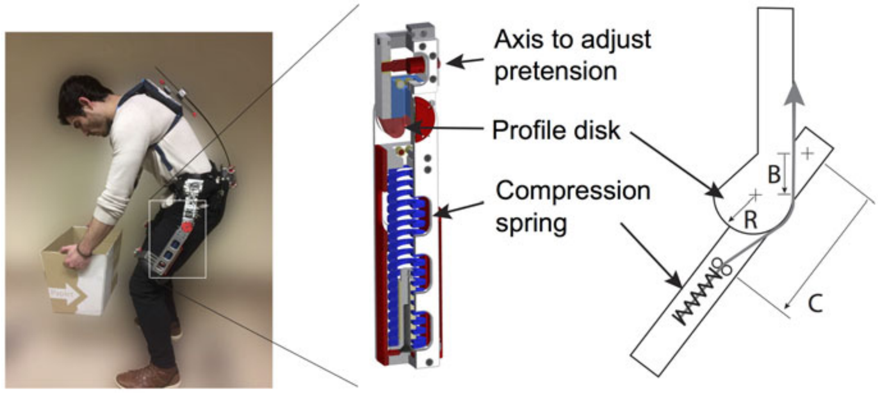

FIGURE 1 Picture and illustration of the spring-based, passive actuator on the SPEXOR prototype described by Näf, Koopman et al. (2018). The coil spring is compressed during hip flexion.

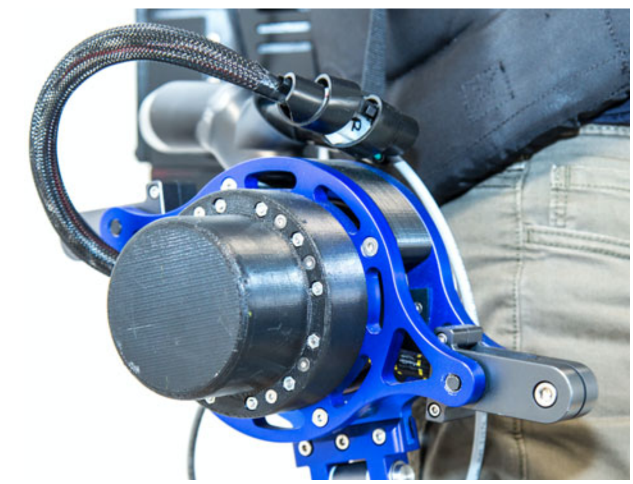

FIGURE 2 Picture of the parallel-elastic actuator on the Robo-Mate active trunk, described by Toxiri, Calanca et al., (2018). The spring is implemented with a bungee cord and acts in parallel to a gear motor, hidden by the black cover in this picture.

their relatively high costs. Geared motors, however, introduce undesirable dynamics on the user due to added friction and large resulting inertia. To enable the use of less powerful geared motors, and thus mitigate their drawbacks, mechanical arrangements of elastic components with electric motors have been proposed (Hara & Sankai, 2012; Toxiri, Calanca, Ortiz, Fiorini, & Caldwell, 2018). One example of a parallel arrangement from Toxiri, Calanca et al. (2018) is shown in Figure 2. More comprehensive references on the use of the parallel spring-motor arrangement on exoskeletons may be found in Wang, Van Dijk, and Van Der Kooij (2011) and Beckerle et al. (2017).

An additional approach employs electromagnetic clutches capable of decoupling the actuator from the exoskeleton when no assistance is necessary (Zhang & Huang, 2018). Advantages of this approach may include reduced energy consumption and reduced undesirable actuator dynamics, although both would depend on an appropriate strategy to determine when to engage and disengage the clutch. This approach can be extended to the concept of *quasi-passive* or *semi-active* devices, in which the coupling/decoupling or the mechanical properties of passive elements (e.g., spring or dampers) could be modulated automatically during operation. No *quasi-passive* back-support exoskeleton was found at the time of writing.

Among active exoskeletons, some are powered by onboard batteries and are therefore more mobile compared to tethered ones. However, batteries also contribute to the total mass of a device. Power autonomy, although difficult to predict accurately, has been claimed to be 3 h for the Hybrid Assistive Limb (HAL) (Hara & Sankai, 2010), 4 h for the Atoun Model Y (ATOUN, 2018), and up to 8 h for the Cray X (German Bionic, 2018).

Structures and Attachments

Forces/torques on a back-support exoskeleton aim to contribute to back extension (and, in some cases, hip extension). These forces/torques may be applied on the user in different ways. One major distinction between existing devices is the direction of the assistive forces, which are either parallel or perpendicular to the body segments (Figure 3). In addition to assisting with low-back extension, a force parallel to the spine also contributes to internal spine loading (i.e., undesirable compression on the intervertebral discs), whereas a perpendicular force does not have this drawback (Abdoli-E, Stevenson, Reid, & Bryant, 2007; Toxiri et al., 2015). Soft exoskeletons, as described below, do not have rigid structures and contribute to compression forces on the lower back, similar to the effects of paraspinal muscle contractions. On the other hand, rigid exoskeletons are built with rigid frames that transmit forces perpendicular to the limbs.

Soft (exosuits)

Soft exoskeletons (also known as *exosuits*) are devices consisting of garments worn on body segments adjacent to the joint that is assisted, for example the thigh and shank for a knee exosuit. Assistance is generated by using the garments to pull two body segments together, typically via a cable or strap (see Figure 3a). Joint flexion and extension must be achieved separately, each by a dedicated cable or strap. Examples of back-support exosuits are the PLAD (Abdoli-E et al., 2006), SSL (Imamura et al., 2011), and the biomechanically assistive garment detailed in the work by Lamers et al. (2017). All three devices apply forces on the upper body using dedicated shoulder straps. On the lower body, the PLAD pulls on the shank just under the knee joint, whereas the other two devices apply those forces on the thighs. All three devices generate forces via elastic bands that are situated rather close to the user's body, thus potentially making it possible to wear the exoskeleton underneath clothes.

Rigid

Rigid exoskeletons are built with hard articulated structures that connect actuators to garments worn by the user. These articulated rigid structures run in parallel with body segments and apply forces perpendicular to them (see Figure 3b). These types of exoskeletons also tend to use space lateral to the user's body, increasing the lateral footprint in some scenarios. A back-extension moment is generated from pressure exerted posteriorly, on the chest, via a rigid pad with the BNDR (Ulrey & Fathallah, 2013), Laevo (Laevo, 2017), and BackX (SuitX, 2017). In contrast, the vast majority of rigid exoskeletons support back extension by pulling the upper torso backwards via backpack-like shoulder straps. Some examples of this latter solution are the Muscle Suit (Aida et al., 2009), Atoun Model Y (ATOUN, 2018), and Hyundai H-WEX (Ko, Lee, Koo, Lee, & Hyun, 2018). Hip-extension is supported by forces on the thighs, which are applied either by pushing the front of the thigh (BNDR (Ulrey & Fathallah, 2013), Laevo (Laevo, 2017), Hyundai H-WEX (Ko et al., 2018)), or by pulling from the back of the leg (Atoun Model Y (ATOUN, 2018)). When pushing the front of the thigh, the attachment may rest on the limb without the need to be secured onto the limb with tight straps (e.g., Laevo (Laevo, 2017), Hyundai H-WEX (Ko et al., 2018)). This possibility depends on whether additional joints for alignment are present (see below for additional discussion).

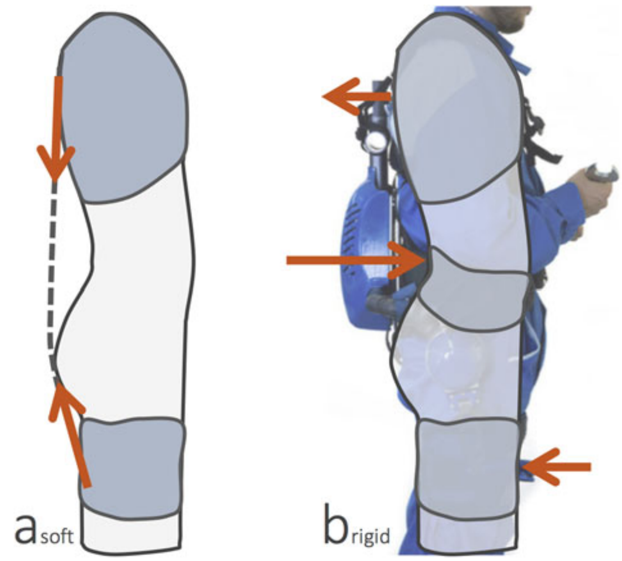

FIGURE 3 **(a) An illustration of the principle of a soft exoskeleton (or exosuit, such as Lamers et al., 2017). Red arrows indicate the forces applied on the user, parallel to the trunk and thighs. (b) An example of rigid exoskeleton: Robo-Mate active trunk (Toxiri, Koopman et al., 2018). Red arrows indicate forces applied on the user, perpendicular to trunk and thighs.**

Combinations of Soft and Rigid Components

Exoskeletons that combine soft and rigid components aim to exploit the best of these two types. In the device by Lowe's and Virginia Tech (Alemi et al., 2019; Manna & Asbeck, 2017), and the back support in the recent prototype by the SPEXOR EU consortium (Näf, Koopman et al., 2018) shown in Figure 1 on the left, carbon fiber rods act both as force generators as well as structures to transfer forces between the user's pelvis and torso. The Lowe's/Virginia Tech device also uses carbon fiber beams to transfer forces from the pelvis to the thighs, while the SPEXOR prototype uses a more traditional rigid chain actuated by a coil spring. In these combined approaches, despite the absence of a completely rigid structure, the contribution to intervertebral compression forces is reduced as compared to soft exoskeletons. Another example of a combined device is the AB-Wear (Inose et al., 2017), which is a soft device augmented with a "compressive force reduction mechanism," The latter consists of a flat spring and "McKibben-type" artificial pneumatic muscles in parallel. In contrast to the use of carbon fiber rods in the Lowe's/Virginia Tech exoskeleton and SPEXOR, a torque is generated in the AB-Wear by artificial pneumatic muscles.

Joint Alignment

Coupling articulated rigid exoskeletons with complex human joints introduces challenges associated with their kinematic compatibility. Misalignment between the human joints and the artificial joints gives rise to undesirable "parasitic" forces that may substantially compromise user comfort. Appropriate articulated structures capable of minimizing these adverse effects, while still transferring assistive forces, are therefore desirable. Two main approaches have been proposed to this end (Näf, Junius et al., 2018). The first approach aims to align the joints of the exoskeleton with the corresponding anatomical joints. This alignment can be done either manually (Hara & Sankai, 2010; SuitX, 2017; Ulrey & Fathallah, 2013) or by the use of sophisticated mechanisms (e.g., four-bar linkages in the work by Tucker, Moser, Lambercy, Sulzer, and Gassert (2013)). However, a challenge with this approach is that, although initially aligned, migration of the exoskeleton over time can lead to undesired interaction forces. Despite this shortcoming, commercial devices mostly adopt manual adjustments (Hara & Sankai, 2010; Laevo, 2017; SuitX, 2017).

A second approach has been explored in some shoulder and lower-back exoskeletons – especially due to the complexity of the kinematics of the corresponding joints (e.g., Näf, Koopman et al., 2018; Schiele & Van Der Helm, 2006; Toxiri, Koopman et al., 2018). In this approach, the goal is to minimize relative movement between the exoskeleton interface and the user. In this case, a certain amount of misalignment between the exoskeleton and user joints is accepted. However, in order to mitigate unwanted forces resulting from this misalignment, additional kinematic structures (joints, sliders, and elastic elements) are added to these devices, such that only very small or no relative movement occurs at those places where the exoskeleton interacts with the user. These misalignment compensation mechanisms can be used for various joints. Of particular importance for back-support exoskeletons are the hips and lower-back, because the aim of the exoskeleton is to reduce loading at these joints. The Robo-Mate prototype is an example where misalignment compensation is adopted for the hip joint. In this prototype, the structures include sets of pin and spherical joints that allow unhindered translations and rotations, dissipating parasitic forces outside the sagittal plane in which assistance is provided. The SPEXOR prototype is an example where this approach additionally makes use of sliders to cope with the elongation of the spine during lumbar flexion (Näf, Koopman et al., 2018).

As a consequence of the assistive forces exerted on the torso and legs, a reaction force is typically generated on the user at the pelvis, lower-back, and/or abdomen (depending on the specific implementation), and many exoskeletons anchor via straps that support the mass of the device (see Figure 3b). Some of the reviewed exoskeletons (i.e., Laevo (Laevo, 2017), Lowe's/Virginia Tech (Alemi et al., 2019; Manna & Asbeck, 2017), B.E. Garment (Lamers et al., 2017), Atoun Model Y (ATOUN, 2018)) adopt an additional strap that wraps around the buttocks, absorbing a portion of the above-mentioned reaction force.

Control Strategies

Control strategies modulate the assistive action provided by an active exoskeleton. This is achieved by mapping user intent (as measured by physical sensors) into desired patterns of assistance. In other words, the problem addressed by a control strategy is to generate appropriate reference signals to control the speed, torque, or impedance of the actuated joints over time (Tucker et al., 2015). By contrast, fully passive exoskeletons have no means of autonomously adapting to user intent during operation, although some of them are endowed with manual switches or regulators to mechanically adjust their characteristics. *Semi-active* (clutched or adjustable passive) devices would, in principle, be able to adapt to different activities, but no example of a back-support exoskeleton using this approach was found. The ability to implement more meaningful patterns of assistance compared to passive and semi-active devices, along with the possibility to offer multiple assistive strategies in one device, is what makes active exoskeletons particularly versatile and potentially more effective.

The general goal of active back-support exoskeletons is to allow the user to be free to move as intended while experiencing substantial assistive forces with appropriate timing and extent. This concept has been referred to as *following user intent*, and it remains an open challenge due to the difficulty in acquiring meaningful information on user intent (Ansari, Atkeson, Choset, & Travers, 2015; Lobo-Prat et al., 2014; Toxiri et al., 2016). Inferring user intent requires some type of sensor information. It should be noted that the need for physical sensors may pose practical limitations to occupational use in terms of physical hindrance. It is helpful at this point to distinguish two common control approaches. *Indirect* control relies on measurements from the device or the environment (e.g., joints motion or interaction forces), whereas in *direct* control volitional information is captured from the user (e.g., biosignals, such as electromyography) (Tucker et al., 2015).

Indirect Control

Motions of relevant body segments can be measured via IMUs (Inertial Measurements Units, capable of measuring, among other quantities, the inclination of a body segment with respect to gravity) or encoders (joints angle) integrated into the exoskeleton. Motion information can be used in a variety of ways. For example, the WSAD detects when the user holds a static posture and activates correspondingly to provide assistance (Luo & Yu, 2013). Another use is to compensate for gravitational forces acting on body segments by measuring the inclination of those segments, such as is done in the HAL (Hara & Sankai, 2010), Robo-Mate EU trunk (Toxiri, Koopman et al., 2018), CRAY X (German Bionic, 2018), and H-WEX (Ko et al., 2018). It should be noted that none of the above approaches can distinguish whether or not the user is holding an external object. The approach described by Zhang and Huang (2018) addresses this shortcoming by equipping the user with custom gloves that sense the mechanical pressure between the fingertips and an external object. This information is then used to command the engagement of electromagnetic clutches in the actuators.

Direct Control

Volitional information in *direct* control can be acquired using surface electromyography (EMG). This technique requires the use of electrodes in direct contact with the skin surface at a location corresponding to the target muscle(s). Such direct contact may not be practical in combination with the numerous straps needed on an exoskeleton, particularly in areas such as the lower back. The EMG signal carries information on the level of muscle activation, but it typically needs relatively heavy filtering and can suffer from several artifacts. EMG has been used in the HAL (Hara & Sankai, 2010), which measures the activity of lower-back muscles and proportionally determines the assistive torque to be provided. Robo-Mate EU trunk (Toxiri, Koopman et al., 2018) adopts a different approach. Instead of placing surface EMG electrodes on the muscles at the lower back, the activity of the forearm muscles is detected and sent to the main computer via a wireless and unobtrusive armband. The signal is assumed to contain information on the presence and mass of an external object being handled, and is therefore used to command for correspondingly increasing assistive torque. Combinations of direct and indirect control are in principle possible and should attempt to exploit the advantages of each approach (see, Hara & Sankai, 2010; Toxiri, Koopman et al., 2018). Another option is to make the control interface require user input more explicitly (e.g., by means of buttons as in (Aida et al., 2009; Lamers et al., 2017)), but this requires active participation from the user, possibly distracting from their activity.

Activity Recognition

Sensor information may also be used to distinguish among different activities and to adopt different strategies accordingly. For example, the APO (Chen, Grazi, Lanotte, Vitiello, & Crea, 2018) can identify when the user is walking (and not interfere with it) and provide different torque profiles corresponding to lifting or lowering when handling objects. Similarly, the Atoun Model Y is described as implementing different strategies, such as "assist," "walk," and "brake" (ATOUN, 2018).

DISCUSSION

While many different implementation details of an exoskeleton determine, to a large extent, the effectiveness and comfort of the device, its total mass surely plays a dominant role in overall acceptance. In fact, a heavy exoskeleton would not only generate substantial pressure on the attachments, but would also make movements more cumbersome due to need to move the added mass. However, the mass of an exoskeleton should not be considered separately, but rather together with a measure of the assistance it provides. In other words, a heavier exoskeleton will not be well accepted if the mechanical assistance it provides is not correspondingly large. The mass distribution of a device will also likely impact user comfort. In this respect, distributing the exoskeleton mass closer to the user's own center of mass may feel more natural and comfortable.

The assistance provided by an exoskeleton should be such that it contributes to desired movements without slowing them down, which could negatively impact the productivity of individual workers or entire production lines, compromising adoption. In this respect, it is also worth noting that an exoskeleton designed to assist during lifting may hinder different activities, such as walking, making it more challenging or demanding. These outcomes depend on the specific design choices, expanded in the following sections.

Another aspect that is strongly affected by the different design tradeoffs is cost-effectiveness. Cost-effectiveness, in turn, impacts adoption, by influencing the decisions of those responsible for a cost–benefit analysis of each potential application. These considerations, very specific to each application, are outside of the scope of the present paper and are therefore not further discussed.

Actuation

Compared to passive devices, active exoskeletons are considered to have potential for even greater effectiveness in physical activities (de Looze et al., 2016). This is mainly associated with the versatility offered by their corresponding assistive strategies (see Sections "Passive" and "Control Strategies"). The potential of purely passive exoskeletons is limited by the fact that increasing their mechanical strength (and thus their physical contribution) would quickly lead to the impossibility of the user moving (e.g., against very stiff springs). To partly mitigate this drawback, *semi-active* or clutched passive devices may be able to automatically detect when to engage or disengage albeit at the expense of increased complexity. Considering this, we propose that passive exoskeletons may be more appropriate for use in tasks requiring light to moderate assistance, such as holding stooped postures or handling light loads. In contrast, active exoskeletons offer greater versatility and are potentially suited to provide stronger assistance. Active devices may therefore be more appropriate for demanding and dynamic tasks, such as handling heavier loads. The adoption of active exoskeletons, still very limited compared to passive ones, will be promoted by advances in the corresponding technologies. Among these, several advanced actuators are being developed, with torque density and form factor among the key features of interest to keep mass and footprint low. Increasing actuator power, though, generally makes their control more challenging, and perhaps compromising user experience and energy efficiency. More powerful actuators also tend to be heavier, compromising the effectiveness and overall comfort of the device. Additionally, user safety may become a concern with increasing actuator power. Although outside the scope of this article, it is worthwhile mentioning the ongoing efforts toward standards and regulations to support the use of exoskeletons in the workplace (Lowe et al., 2019; Nabeshima et al., 2018).

Another clear trend associated with actuators is the power supply, which most often is provided by on-board batteries. While mobility is certainly a beneficial feature associated with the use of on-board batteries, it is unclear to what extent power autonomy is required. Depending on the scenario, it may be more appropriate to swap and recharge light-weight batteries every few hours compared to using heavier, longer-lasting batteries.

Structures and Attachments

Considering that the main function of exoskeletons is to transfer significant assistive forces while minimizing unnecessary constraints or user discomfort, the central importance of structures for the success of exoskeletons is immediately clear. Allowing natural movements will be particularly important for workers. As one example, while existing devices mainly assist lifting tasks in the sagittal plane (back and hip extension), wearable devices should not hinder movements in different planes, and more generally designers should ensure that the user does not feel restricted.

User comfort is another area that deserves attention. The braces or attachments, which physically connect the exoskeleton structures to the corresponding human limbs, should be designed so as to promote favorable distribution of the forces into pressures, and to apply pressure at locations that minimize discomfort. For example, sustained pressure on the chest or thighs may be perceived negatively. The material used to construct an exoskeleton can also impact comfort, and ensure appropriate breathability to avoid excessive heat and sweating during extended use.

The integration or compatibility of exoskeleton attachments with standard work attire, as well as how easy it is for the user to autonomously put on and take off the exoskeleton, may also play major roles in their success in field applications. Comfort and usability during extended use will be affected by numerous factors, likely beyond the simplified laboratory scenarios in which the devices are often evaluated for biomechanical effectiveness. It is therefore important to note that an increasing number of exoskeletons are being tested in the field by companies and their workers. In fact, wearing a device for consecutive working hours may highlight (dis)comfort issues that are not observed during short laboratory experiments.

Sizing and adjustability of a device to a large population of users should be considered, due to the potential effects of fit on adoption and usability. To accommodate a variety of workers, exoskeletons must be able to adapt to different body geometries and dimensions. To this end, some existing exoskeletons are made in different sizes and/or allow the manual adjustment of some physical dimensions.

Furthermore, the shape and footprint of an exoskeleton may affect its usability in a given environment or station. Among the many components of an exoskeleton, actuators (passive or active) tend to be relatively big, which gives particular importance to their placement on the device as well as to the transmission mechanisms. Indeed, springs or motors located on the sides next to the corresponding assisted joints increase the lateral footprint of a device, possibly preventing its user from accessing tight spaces.

From an application viewpoint, the possibility for workers to autonomously and quickly put on, use, and take off a device may significantly impact the adoption or rejection of a given solution. Indeed, lengthy procedures and the need to be helped by another person to use a device may easily discourage workers. The same lengthy procedures may also negatively affect productivity, compromising the adoption of exoskeletons. Soft back-support exoskeletons are comparatively fewer than rigid ones at this point, but their practical advantage of potentially being worn underneath working clothes should not be overlooked, and might have a role in future developments.

Control Strategies

The versatility offered by active exoskeletons is one of the central points worth discussing. The ability of a device to adjust the assistance it provides during operation relies on its control strategy, which should make use of available sensor information on relevant task parameters. During lifting tasks, for example, postures, movements, and external loads are relevant factors, and it is therefore important for strategies to account for such factors. In other words, it would be desirable for an exoskeleton to offer greater assistance corresponding to more inconvenient postures and heavier loads. Not adjusting the assistance appropriately may substantially limit the effectiveness of a device as well as its potential impact in an occupational application. Control strategies can also have an impact at a different level. As described in Section "Control Strategies," it may be possible to use sensor readings to distinguish among different activities and correspondingly enable an appropriate strategy. In a factory scenario, for example, this could allow the worker to wear a device without interruptions, walking unhindered between working stations and manually or automatically switching the assistance on when necessary rather than taking it off and putting it back on.

Whatever the level and function of a control strategy, it will be important for the user to perceive the overall behavior of a device as smooth, responsive, and intuitive. As such, designers should be cautious of delays caused by signal processing and the risk of cognitive overload from any complicated strategies. All these issues may compromise user acceptance and thus the potential for adoption.

Regarding the availability of the necessary information, the obtrusiveness of any sensors is certainly an aspect to consider. The more integrated sensors are into the exoskeleton, as opposed to requiring additional sensor equipment, the better it will be in an application scenario. This is often the case with strategies based on posture and movements, which can be measured by sensors that are traditionally integrated on exoskeletons. It is, however, a different case if measures of interaction forces (gloves (Zhang & Huang, 2018) and foot insoles) or muscle activity (Hara & Sankai, 2010; Toxiri, Koopman et al., 2018)) require the use of additional devices that may be obtrusive for the worker.

Another aspect of importance in application scenarios is the ability to adjust device parameters to different users (e.g., the amount of maximal assistance provided with a given strategy, or its responsiveness to movements). This importance may be connected to both the great variability in people's body sizes as well as subjective user preferences. Adjustments of parameters does not need to be automatic, and might be offered via ad-hoc interfaces (e.g., in the form of a set of buttons or smartphone app).

CONCLUSIONS

Many new back-support exoskeletons are being designed as research prototypes or as commercial products. This paper has presented an up-to-date overview of existing back-support exoskeletons covering three important technological aspects: (i) actuation, (ii) structures and attachments, and (iii) control strategies. Design choices for each of these aspects determine the biomechanical effectiveness, user comfort, complexity, and cost-effectiveness of the resulting devices.

Concerning actuation, we have suggested that the implementation of passive exoskeletons is generally less complex, costly, and heavy compared to active ones. Active devices, in contrast, are potentially more versatile and thus have a wider range of applications. In terms of structures, soft exoskeletons tend to be more lightweight and minimize hindrances to movements compared to rigid structures, though offer lesser reductions of biomechanical joint loading. Control strategies are a key component to exploit the potential of active exoskeletons, but should not rely on excessively powerful actuators, obtrusive sensors, or distracting user interfaces.

Ultimately, the adoption of exoskeletons will also depend on user acceptance. This will be determined by whether workers feel hindered during the execution of routine physical activities while wearing an exoskeleton. The effectiveness of using an exoskeleton may vary substantially across people, depending on the device itself as well as how it is subjectively perceived by users. On the other hand, a decision-maker (or person responsible for workplace ergonomics) would need to consider whether the expense for the technology and its integration is justified by the benefits it offers (e.g., reduction in cost associated with occupational injuries, reduction in time to complete certain tasks, facilitation of task completion by a wider variety of workers). In this respect, it is reasonable to expect an increasingly important role of insurance companies, compensation, and healthcare bodies in exploring and promoting the adoption of exoskeletons as occupational equipment.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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REFERENCES

Abdoli-E, M., Agnew, M. J., & Stevenson, J. M. (2006). An on-body personal lift augmentation device (PLAD) reduces EMG amplitude of erector spinae during lifting tasks. *Clinical Biomechanics*, *21*(5), 456–465. doi:10.1016/j.clinbiomech.2005.12.021

Abdoli-E, M., Stevenson, J. M., Reid, S. A., & Bryant, T. J. (2007). Mathematical and empirical proof of principle for an on-body personal lift augmentation device (PLAD). *Journal of Biomechanics*, *40*(8), 1694–1700. doi:10.1016/j.jbiomech.2006.09.006

Aida, T., Nozaki, H., & Kobayashi, H. (2009). *Development of muscle suit and application to factory laborers*. Proceedings of the 2009 IEEE International Conference on Mechatronics and Automation August 9–12, Changchun, China.

Alemi, M. M., Geissinger, J., Simon, A. A., Chang, S. E., & Asbeck, A. T. (2019). A passive exoskeleton reduces peak and mean EMG during symmetric and asymmetric lifting. *Journal of Electromyography and Kinesiology*, *47*, 25–34.

Ansari, A., Atkeson, C. G., Choset, H., & Travers, M. (2015). *Estimating Operator Intent (Draft 4.0)*. Technical report. Pittsburgh, PA.

ATOUN. (2018). *Atoun Model Y*. Retrieved from http://atoun.co.jp/products/atoun-model-y

Beckerle, P., Verstraten, T., Mathijssen, G., Furnemont, R., Vanderborght, B., & Lefeber, D. (2017). Series and parallel elastic actuation: Influence of operating positions on design and control. *IEEE/ASME Transactions on Mechatronics*, *22*(1), 521–529. doi:10.1109/TMECH.2016.2621062

Chen, B., Grazi, L., Lanotte, F., Vitiello, N., & Crea, S. (2018). A real-time lift detection strategy for a hip exoskeleton. *Frontiers in Neurorobotics*, *12*, 1–11.

Colombo, G., Joerg, M., Schreier, R., & Dietz, V. (2000). Treadmill training of paraplegic patients using a robotic orthosis. *Journal of Rehabilitation Research and Development*, *37*(6), 693–700.

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. doi:10.1080/00140139.2015.1081988

EU-OSHA (European Agency for Safety and Health at Work). (2000). *OSH in Figures: Work-Related Musculoskeletal Disorders in the EU—Facts and Figures*. Bilbao, Spain: Publications Office of the European Union.

Garg, A. (1995). Revised NIOSH equation for manual lifting: A method for job evaluation. *American Association of Occupational Health Nurses Journal*, *43*(4), 211–216. doi:10.1177/216507999504300408

German Bionic. (2018). *German Bionic CRAY X*. Retrieved from https://www.germanbionic.com/

Hara, H., & Sankai, Y. (2010). *Development of HAL for lumbar support*. Paper presented at SCIS and ISIS 2010—Joint 5th International Conference on Soft Computing and Intelligent Systems and 11th International Symposium on Advanced Intelligent Systems (pp. 416–421). SCIS & ISIS 2010, Dec. 8–12, 2010, Okayama Convention Center, Okayama, Japan Development.

Hara, H., & Sankai, Y. (2012). *HAL equipped with passive mechanism*. Paper presented at 2012 IEEE/SICE International Symposium on System Integration, SII 2012, Kyushu University, Fukuoka, Japan December 16–18, 2012 (pp. 1–6).

Heydari, H., Hoviattalab, M., Azghani, M. R., Ramezanzadehkoldeh, M., & Parnianpour, M. (2013). Investigation on a developed wearable assistive device (WAD) in reduction lumbar muscles activity. *Biomedical Engineering: Applications, Basis and Communications*, *25*(03), 1350035. doi:10.4015/S101623721350035X

Imamura, Y., Tanaka, T., Suzuki, Y., Takizawa, K., & Yamanaka, M. (2011). *Motion-based design of elastic belts for passive assistive device using musculoskeletal model*. Proceedings of the 2011 IEEE International Conference on Robotics and Biomimetics December 7–11, 2011, Phuket, Thailand (pp. 1343–1348).

Inose, H., Mohri, S., Arakawa, H., Okui, M., Koide, K., Yamada, Y., … Nakamura, T. (2017). *Semi-endoskeleton-type waist assist AB-wear suit equipped with compressive force reduction mechanism*. Paper presented at Proceedings—2017 IEEE International Conference on Robotics and Automation (ICRA) Singapore, May 29–June 3, 2017 (pp. 6014–6019).

Katz, J. N. (2006). Lumbar disc disorders and low-back pain: Socioeconomic factors and consequences. *JBJS*, *88*, 21–24. doi:10.2106/00004623-200604002-00005

Kazerooni, H., Racine, J. L., Huang, L., & Steger, R. (2005, April). On the control of the berkeley lower extremity exoskeleton (BLEEX). In *Proceedings of the 2005 IEEE international conference on robotics and automation* (pp. 4353–4360). IEEE.

Ko, H. K., Lee, S. W., Koo, D. H., Lee, I., & Hyun, D. J. (2018). Waist-assistive exoskeleton powered by a singular actuation mechanism for prevention of back-injury. *Robotics and Autonomous Systems*, *107*, 1–9.

Konz, S. (1982). NIOSH lifting guidelines. *American Industrial Hygiene Association Journal*, *43*(12), 931–933. doi:10.1080/15298668291410846

Koopman, A. S., Kingma, I., Faber, G. S., Bornmann, J., & van Dieën, J. H. (2018). Estimating the L5S1 flexion/extension moment in symmetrical lifting using a simplified ambulatory measurement system. *Journal of Biomechanics*, *70*, 242–248. doi:10.1016/j.jbiomech.2017.10.001

Laevo. (2017). *Laevo*. Retrieved from http://en.laevo.nl/

Lamers, E. P., Yang, A. J., & Zelik, K. E. (2017). Feasibility of a biomechanically-assistive garment to reduce low back loading during leaning and lifting. *IEEE Transactions on Biomedical Engineering*, *9294*(c), 1–8.

Lobo-Prat, J., Kooren, P. N., Stienen, A. H., Herder, J. L., Koopman, B. F., & Veltink, P. H. (2014). Non-invasive control interfaces for intention detection in active movement-assistive devices. *Journal of NeuroEngineering and Rehabilitation*, *11*(1), 168. doi:10.1186/1743-0003-11-168

Lowe, B. D., Billotte, W. G., & Peterson, D. R. (2019). ASTM F48 Formation and Standards for Industrial Exoskeletons and Exosuits. *IISE Transactions on Occupational Ergonomics and Human Factors*, (just-accepted), 1–8.

Luo, Z., & Yu, Y. (2013). *Wearable stooping-assist device in reducing risk of low back disorders during stooped work*. Paper presented at 2013 IEEE International Conference on Mechatronics and Automation, IEEE ICMA, Takamatsu, Kagawa, Japan from August 4 to August 7, 2013 (pp. 230–236).

Manna, A., & Asbeck, A. (2017). *Development of an Exosuit to support the back during lifting*. *Presentation at: U.S. Department of Energy Technical Interchange Meeting on Industrial Exoskeletons*. Washington DC, June 28, 2017. Retrieved from https://www.nist.gov/sites/default/files/documents/2017/09/21/alan_asbeck_exoconference_june17-3.pdf

Marinov, B. (2018). *Exoskeleton Report Catalog*. Retrieved from https://exoskeletonreport.com/product-category/exoskeleton-catalog/

Nabeshima, C., Ayusawa, K., Hochberg, C., & Yoshida, E. (2018). Standard performance test of wearable robots for lumbar support. *IEEE Robotics and Automation Letters*, *3*(3), 2182–2189. doi:10.1109/LRA.2018.2810860

Näf, M. B., Junius, K., Rossini, M., Rodriguez-Guerrero, C., Vanderborght, B., & Lefeber, D. (2018). Misalignment compensation for full human-exoskeleton kinematic compatibility: state of the art and evaluation. *Applied Mechanics Reviews*, *70*(5), 050802. doi:10.1115/1.4042523

Näf, M. B., Koopman, A. S., Baltrusch, S., Rodriguez-Guerrero, C., Vanderborght, B., & Lefeber, D. (2018). Passive back support exoskeleton improves range of motion using flexible beams. *Frontiers in Robotics and AI*, *5*(72). https://doi.org/10.3389/frobt.2018.00072

Ortiz, J., Di Natali, C., & Caldwell, D. G. (2018, October). *XoSoft-iterative design of a modular soft lower limb exoskeleton*. Paper presented at International Symposium on Wearable Robotics, Pisa, Italy (pp. 351–355). Cham: Springer.

RoamRobotics. (2018). *Roam Robotics.* Retrieved from http://www.roamrobotics.com

Schiele, A., & Van Der Helm, F. C. T. (2006). Kinematic design to improve ergonomics in human machine interaction. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, *14*(4), 456–469. doi:10.1109/TNSRE.2006.881565

Sugar, T., Veneman, J., Hochberg, C., Shourijeh, M. S., Acosta, A., Vazquez-Torres, R., … Nabeshima, C. (2018). *Hip exoskeleton market—Review of lift assist wearables*. Wearable Robotics Association. Retrieved from http://www.wearablerobotics.com/wp-content/uploads/2018/05/J12434-Hip-Exoskelton-Report-FINAL4.pdf.

SuitX. (2017). *SuitX BackX*. Retrieved from http://www.suitx.com/backx

Toxiri, S., Ortiz, J., Masood, J., Fernández, J., Mateos, L. A., & Caldwell, D. G. (2015, December). *A wearable device for reducing spinal loads during lifting tasks: Biomechanics and design concepts*. Paper presented at 2015 IEEE International Conference on Robotics and Biomimetics (ROBIO), Zhuhai, China (pp. 2295–2300). IEEE.

Toxiri, S., Calanca, A., Ortiz, J., Fiorini, P., & Caldwell, D. G. (2018). A parallel-elastic actuator for a torque-controlled back-support exoskeleton. *IEEE Robotics and Automation Letters*, *3*(1), 492–499. doi:10.1109/LRA.2017.2768120

Toxiri, S., Koopman, A. S., Lazzaroni, M., Ortiz, J., Power, V., de Looze, M. P., … Caldwell, D. G. (2018). Rationale, implementation and evaluation of assistive strategies for an active back-support exoskeleton. *Frontiers in Robotics and AI*, *5*(53).

Toxiri, S., Ortiz, J., Masood, J., Fernandez, J., Mateos, L. A., & Caldwell, D. G. (2016). *A powered low-back exoskeleton for industrial handling: considerations on controls*. Paper presented at International Symposium on Wearable Robotics, Segovia, Spain.

Tucker, M. R., Moser, A., Lambercy, O., Sulzer, J., & Gassert, R. (2013). *Design of a wearable perturbator for human knee impedance estimation during gait*. Paper presented at 2013 IEEE International Conference on Rehabilitation Robotics (ICORR) June 24–26, 2013 Seattle, Washington USA (pp. 1–6). IEEE.

Tucker, M. R., Olivier, J., Pagel, A., Bleuler, H., Bouri, M., Lambercy, O., … Gassert, R. (2015). Control strategies for active lower extremity prosthetics and orthotics: A review. *Journal of NeuroEngineering and Rehabilitation*, *12*(1), 1. doi:10.1186/1743-0003-12-1

Ulrey, B. L., & Fathallah, F. A. (2013). Subject-specific, whole-body models of the stooped posture with a personal weight transfer device. *Journal of Electromyography and Kinesiology*, *23*(1), 206–215. doi:10.1016/j.jelekin.2012.08.016

Wang, S., Van Dijk, W., & Van Der Kooij, H. (2011). *Spring uses in exoskeleton actuation design*. Paper presented at 2011 IEEE International Conference on Rehabilitation RoboticsRehab Week Zurich, ETH Zurich Science City, Switzerland, June 29–July 1, 2011 (pp. 1–6).

Waters, T. R., Putz-Anderson, V., Garg, A., & Fine, L. J. (1993). Revised NIOSH equation for the design and evaluation of manual lifting tasks. *Ergonomics*, *36*(7), 749–776. doi:10.1080/00140139308967940

Wehner, M., Rempel, D., & Kazerooni, H. (2009). *Lower extremity exoskeleton reduces back forces in lifting*. Paper presented at ASME 2009 Dynamic Systems and Control Conference October 12–14, 2009, Hollywood, California, USA (pp. 49–56).

XoSoft. (2018). XoSoft. Retrieved from http://www.xosoft.eu

Yu, H., Choi, I. S., Han, K. L., Choi, J. Y., Chung, G., & Suh, J. (2015). Development of a stand-alone powered exoskeleton robot suit in steel manufacturing. *ISIJ International*, *55*(12), 2609–2617.

Zhang, T., & Huang, H. H. (2018). A lower-back robotic exoskeleton: Industrial handling augmentation used to provide spinal support. *IEEE Robotics & Automation Magazine*, *25*(2), 95–106. doi:10.1109/MRA.2018.2815083