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User-Centered Back-Support Exoskeleton: Design and Prototyping

Loris Roveda[a,*], Mattia Pesenti[b], Michele Rossi[c], Mario Covarrubias Rodriguez[d], Alessandra Pedrocchi[b], Francesco Braghin[c], Marta Gandolla[c]

[a] *Istituto Dalle Molle di studi sull'Intelligenza Artificiale (IDSIA), Scuola Universitaria Professionale della Svizzera Italiana (SUPSI), Università della Svizzera Italiana (USI), 6962 Lugano-Viganello, Switzerland*

[b] *Politecnico di Milano, Department of Electronics, Information and Bioengineering, NearLab, 20133 Milan, Italy*

[c] *Politecnico di Milano, Department of Mechanical Engineering, 20156 Milano, Italy*

[d] *Politecnico di Milano, Department of Mechanical Engineering, 23900 Lecco, Italy*

* Corresponding author. Tel.: +0039-331-864-8725. *E-mail address:* loris.roveda@idsia.ch

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Abstract

Exhausting manual labor is still predominant in the industrial context. It typically consists in manipulating heavy parts or working in non-ergonomic conditions. The resulting work-related musculoskeletal disorders are a major problem to tackle. The most-affected body section is the the lumbar spine. Recently, exoskeletons have been identified as a possible non-invasive solution to reduce the impact of low-back pain. State-of-the-art prototypes have been optimized to: follow unconstrained human kinematics, (partially) relieve the load on assisted joints, and allow anthropometric adaptation. Yet, this technology still has limited adoption. Manufacturing optimization may address the following limitations: bulky/heavy resulting designs, complex assembly and maintenance, high manufacturing costs, long procedures for adaptation and wearing, and psychological effects (*e.g.*, cognitive load and usability). In this contribution, the aforementioned issues are tackled improving a previous low-back exoskeleton prototype. In particular, kinematic analysis, Finite-Element-Method, and topological optimization have been combined to obtain a lightweight prototype, testing different materials (Nylon, carbon-fiber reinforced PC/ABS, etc.). We applied both Design for Assembly and Design for Manufacturability. The resulting exoskeleton prototype is described in the paper, ready for end-user field tests.

Keywords: back-support; exoskeleton; topological optimization, mechanical design, materials selection, backbone-based kinematics, industry4.0, industry5.0.

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1. Introduction

Manual operations are still highly present in the industrial context [1], requiring human operators to execute onerous and exhausting tasks. In particular, these include repetitive heavy-load manipulation (*e.g.*, logistic sector), tasks to be executed in non-ergonomic posture (*e.g.*, automotive production line). Work-related musculoskeletal disorders are a huge issue to be addressed in the industrial context [2]. Back-pain is the most recorded work-related pathology [3], causing only in the United States costs for 100 billion $ per year [4]. Wearable robots may represent a highly-flexible solution to be exploited in industrial environments [5]. Many solutions have been developed to empower and assist the human operator (*i.e.*, to relieve them from the workload), spanning from upper limbs exoskeletons [6] to lower limbs exoskeletons [7]. Back-support exoskeletons may represent the optimal solution to correctly redistribute the spinal load, improving the ergonomics while relieving the human operator from the load.

1.1. Related work

Back-support exoskeletons prototypes have been published in the scientific literature. Some of them have been optimized towards products to support and relieve the human operator from heavy loads and non-ergonomic postures in the industrial context [8]). In the literature, exoskeletons are often classified based on the implemented actuation type – passive or active devices. Passive devices include mechanisms based on (mechanically variable) elastic elements mainly aimed at counterbalancing gravity. In [9] a passive back-support exoskeleton was developed based on a mechanism composed by flexible beams parallel to the spine, allowing a large range of motion and providing assistance at the lumbo-sacral joint level. In [10] a trunk exoskeleton has been designed based on multi-body dynamic modelling. In [11], the SPEXOR passive spinal exoskeleton is described. Works investigating passive exoskeletons performance have been proposed, analyzing the achieved results in terms of user performance [12]. Many commercially-available solutions exploit a passive approach [13–20]. On the other hand, active solutions exploit the flexibility of motors to adapt the assistance. Among the prototypes proposed in the scientific literature, it is possible to highlight a low-back exoskeleton to support manual material handling in industrial contexts actuated by a rigid-transmission servo-motor [21], a waist exoskeleton implementing a wire-driven single actuator mechanism [22], and an exoskeleton to provide back-support and to reduce lumbar spine compression exploiting serial elastic actuators (SEA) [23]. In [24], a pelvis orthosis has been proposed to assist workers during lifting operations. [25] proposes a parallel-elastic actuation for a back-support exoskeleton in order to improve the performance of the device. Works investigating active exoskeletons performance have been proposed, analyzing the achieved results in terms of user performance [26]. Indeed, active solutions are available on the market as well [27–30]. Passive solutions are predominant in the industrial field, both in terms of adoption and end-user validation [31]. Active solutions generally provide higher power to the wearer, while being more expensive and complex.

In general, although obtaining satisfactory results in terms of lumbo-sacral joint assistance, state-of-the-art and commercial solutions are optimized in order to satisfy (some) of the following requirements: i) follow the natural kinematics of the unconstrained human motion (*i.e.*, trunk and hip flexion-extension), ii) (partially) relieve the load of the assisted joints (*i.e.*, impulsive compression loads on the spine), and iii) anthropometric adaptation (*i.e.*, taking into account anthropometric variability). Although positive achievements in the field, very limited adoption of such a technology has been obtained in the relevant environment. Possible reasons which can be addressed by manufacturing optimization include: i) bulky/heavy resulting designs, ii) complex assembly and maintenance of the device, iii) high manufacturing costs, iv) long procedures to adapt and don/doff the device, and v) psychological effects (*e.g.*, cognitive load and usability). The adoption rate for wearable technology – such as exoskeletons – may be limited because of poor fit/wearability. The *one-size-fits-all* approach is common for commercial products, as it is a rather effective cost-limiting strategy [32]. Psychological effects are also often neglected in the design phase of the device. The literature on exoskeletons shows research focusing on material science, control theory, mechanical design, among other relevant topics. Very few publications concerning user-centered design are found [33]. Recently, researchers and experts in the field have been acknowledging the importance of a user-centered approach in exoskeleton development. However, standardized frameworks for appropriate user-centered design and testing methods are still lacking [34]. Therefore, in the attempt to favor the adoption of back-support exoskeletons in real production environments, such issues have to be considered in the design of the device presented in this contribution.

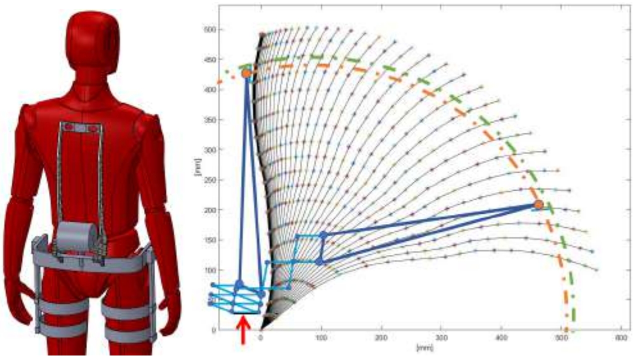

Fig. 1: Back-support exoskeleton with backbone-based kinematics: prototype design (left) and human motion tracking capabilities of the mechanism (right) [35].

1.2. *Paper contribution*

This contribution aims to incorporate the kinematic analysis reported in [35], with Finite-Element-Method (FEM) analysis, and topological optimization in the design phase of a back-support exoskeleton for industrial applications towards a manufacturing optimization process to favor technology adoption. Starting from the preliminary design in [35], such methodologies have been exploited in order to improve the resulting prototype. More in detail, different materials have been used in the digital simulation (ABS, Nylon, PAEK, PBT PPS and PC/ABS with Carbon Fiber reinforcement). In the low-cost prototype design, both approaches have been applied to improve the resulting device: i) Design for Assembly and ii) Design for Manufacturability. The starting prototype described in [35] introduced the backbone-tracking kinematics. Then, in §3, we describe the re-design process, aimed at tackling manufacturing complexity, optimization of the human-exoskeleton interface and psychological impact. Then, we face device bulkiness and manufacturing optimization in §4 and §5. Finally, in §6.2 we show the resulting prototype, highlighting its main modifications w.r.t. the starting point, and highlighting the objectives achieved by the exploitation of the proposed methodologies.

2. Back-support exoskeleton: preliminary design

The device in [35] proposes a backbone-based kinematics to adapt its motion based on the user's motion. As shown in Figure 1, the kinematic structure is designed in order to follow the motion of the human spine. This mechanism has been obtained as an optimized, subject-specific design, tracking the motion of the second thoracic vertebra (T2). In the previous work, the kinematic structure of the exoskeleton was designed and validated. Yet, the exoskeleton did not feature any actuation system, as it was intended as a proof of concept to evaluate the backbone-tracking kinematics. Such a design has been considered as a starting point to re-design a passive, lightweight, and easily-maintainable exoskeleton, exploiting kinematic analysis, Finite-Element-Method (FEM) analysis, and topological optimization.

Table 1: Passive compensation springs. l_0: initial length; K: spring constant; Δl_{max}: maximum elongation; F_{max}: maximum load.

l_0 [mm]	K [N/mm]	Δl_{max} [mm]	F_{max} [N]
157	1.10	182	304.0
183	1.42	216	375.8

3. Exoskeleton re-design

3.1. Wearable suit

The re-design of the device has been performed on the basis of the anthropometric tables in [36], considering data related to the 75th percentile for male subjects. The preliminary design in [35] has been revised in order to introduce three main improvements w.r.t. the wearability of the device: (i) introducing adaptable interfaces to improve the fit of the device for the specific user, (ii) adding degrees of freedom (DoF) to enhance the device motion capabilities and the usability of the device, and (iii) improving the user-exoskeleton interfaces. In the following, these re-design steps are analyzed in order to described the implemented methodology and resulting modifications.

The re-design step (i) consists in the development of wearable-suit interfaces that can be adapted to various sizes. This is intended to assure adaptability to different anthropometries. The upper connection (*i.e.*, to the reference vertebra) has been re-designed in order to be adjusted to the wearer, improving wearability. Link dimensions have been set starting from anthropometric tables in [36]. In particular, a single-waist-size have been defined, while four different sizes have been identified to improve the hip-to-shoulder wearability, adapting the device to the different subject's height. The described modifications are highlighted in §6.

The re-design step (ii) consists in the improvement of the non-actuated DoFs, to improve the comfort of the device, and not to hinder the wearer in walking, sitting, and other daily-life activities. The connection between the waist and the legs was improved w.r.t. the preliminary design. Initially, rigid connections were adopted, being characterized by a 3-DoF joint between the legs and the hips, guarantying hip internal–external rotation, flexion–extension, and abduction–adduction. These rigid connections have been replaced with compliant connections. A rigid belt has been proposed in order to increase the motion capabilities of the device. An additional DoF (*i.e.*, the axial rotation of the spine) has been included in the re-designed device to improve user comfort. A circular guide has been designed in order to allow free motion along the torsional DoF. Such a guide has been designed on the basis of the human back motion to maximize the comfort of the device. The described modifications are highlighted in §6.

The re-design step (iii) consists in the improvement of the human-exoskeleton interfaces. Three main improvements have been implemented: (a) at the level of the shoulders; (b) at the level of the lumbar region; (c) on the legs. Interface (a) has been implemented as backpack-like straps, easily wearable and adjustable. Interface (b) has been made by means of an ergonomic belt. Finally, interface (c) has been implemented by means of elastic bands integrated at the end of the leg bars, allowing to have a soft interface at the level of the legs. The described modifications are highlighted in §6.

3.2. Passive device re-design

While the preliminary design in [35] was intended to provide active assistance to the user, the re-designed device here discussed considers a passive support mechanism in order to assist the subject in the execution of target activities (*e.g.*, objects lifting and manipulation). Such a passive support mechanism has been obtained introducing a set of traction springs. If combined with different stiffness values, these can allow to modulate the provided assistance. The springs are connected to the hip support of the device, and engaged to a bar on the moving mechanism of the exoskeleton. In this way, they elongate while banding, storing energy that is then released during trunk extension. The upper engaging bar is positioned in order to achieve a zero deformation of the springs at the closure positioning of the mechanism in Figure 1, so that no force is applied by the springs to the wearer in such a configuration. The parameters of the selected springs are reported in Table 1. Such a choice is crucial (both in terms of stiffness and size). In fact, it is important to provide to the user the proper assistance, while implementing a lightweight and compact support mechanism (*i.e.*, avoiding to put the springs in contact with the human body). The implemented passive support mechanism is highlighted in §6.

4. Design for Assembly and Design for Manufacture

The components for the new concept of the back exoskeleton have been designed with several manufacture and assembly constraints. Design for assembly (DFA) and Design for manufacture (DFM) have been considered at all stages of the design process of the new concept of the back-support exoskeleton, specially in the early stage. Different concepts and alternative solutions have been proposed in order to analyse the ease of assembly of the product or sub-assembly as suggested by [37]. Some of the most important constrains are the following: use modular design; make parts easy to manipulate; make connections unique; use the same parts throughout the design and product family; design for real-world tolerances.

5. Prototype design optimization and analysis

This section describes the structural topology optimization subjected to static load with multiple boundary conditions. It was necessary to study the optimal distribution of material in the design domain to minimize structural compliance (i.e. maximum stiffness). Figure 2-a shows the isometric view of the first concept of the back-support exoskeleton while Figure 2-b shows the frontal view. In this paper, the topological optimization and the FEM analysis have been applied to the components 4 and 15 as can be seen from Figures 2-c and 2-d.

It has been decided to reduce the weight in these components without affecting the structural resistance of the final prototype.

5.1. First concept FEM analysis

A finite element model of the sub-assembly of the Back-Support Exoskeleton is defined with an appropriate theoretical model. Then, optimized and non-optimized areas are proposed according to the device kinematics. Finally, the weight ratios for optimization objectives are calculated according to the boundary conditions. Boundary conditions (displacement and loads) have been applied trying to reproduce the flexion movement of the user as can be appreciated from this video [38].

Based on the geometry shape of the different components, the finite element model of the back-support exoskeleton is shown in Figure 3. In order to ensure the accuracy of the optimization results and consider the efficiency of the optimization iteration, the assembly components were discretized into 39585 tetrahedral elements and 65253 nodes with an average element size of 0.03 (as a fraction of a bounding box element) and a minimum element size of 0.2 (as a fraction of average size) with a grading factor of 1.5 and 60 degrees as a maximum turn angle. The used material of the components is ABS.

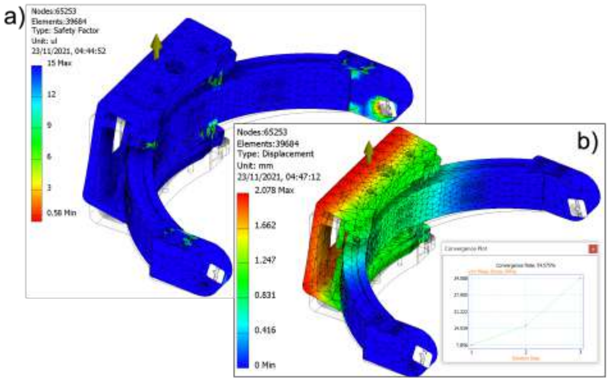

Fig. 3: FEM First Concept.

5.2. Topological Optimization

Figure 4-a shows the preserved regions applied in the topological optimization analysis. It is necessary to preserve the material in the extremities because there are two functional holes which are used to assembly other important components. Figure 4-b shows the topological optimization results considering 18% mass reduction. Figure 4-b shows the topological optimization results considering 16 % of mass reduction, passing from 2.03 kg to 1.71 kg. Figure 4-c shows the topological optimization results considering 26 % of mass reduction, passing from 2.03 kg to 1.5 kg and finally Figure 4-d shows the topological optimization results considering 39 % of mass reduction, passing from 2.03 kg to 1.05 kg. From the optimization results, it could be seen that the two components can be improved, in fact its possible to reduce some dimensions without affecting the structural properties of this sub-assembly. Figure 5 shows the difference between the first and the new concept. Figure 5-a represent the isometric view of the first concept highlighting the 2.03 kg of the sub-assembly which have been analysed. Wen can see the new concept of the sub-assembly in Figure 5-b.

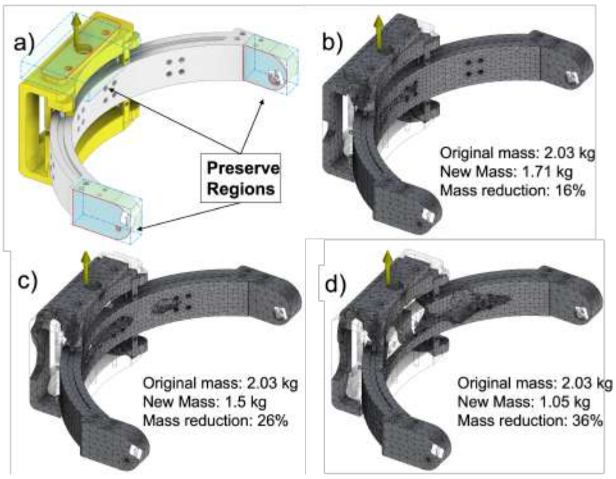

Fig. 4: Preserve Regions First Concept.

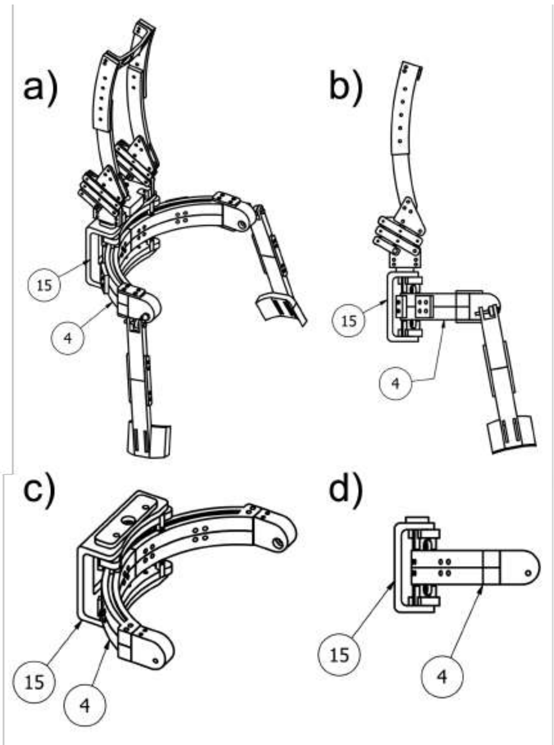

Fig. 2: First concept components to include in the Topological Optimization approach **4** and **15**.

The sub-assembly considered in the topological optimization is lighter and robust enough according with the design and manufacturing constraints.

5.3. New concept FEM analysis

As described in §5.1 and based on the new geometry model of the back-support exoskeleton's sub-assembly a FEM analysis have been performed, as shown in Figure 6.

Also in this case, in order to reach convergence, to ensure the accuracy of the optimization results and considering the efficiency of the optimization iteration, the assembly components were discretized into 83920 tetrahedral elements and 134864

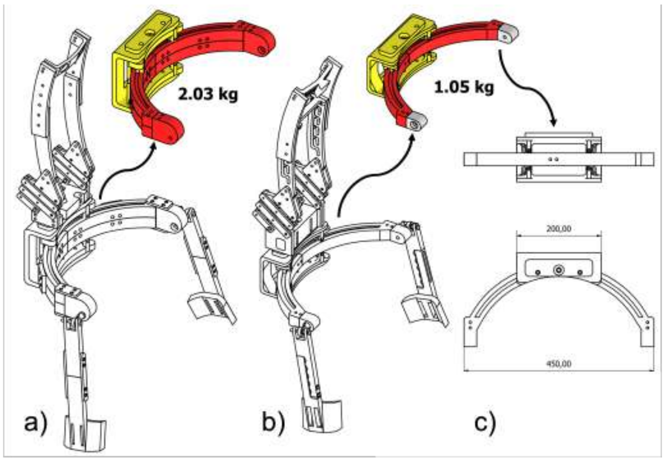

Fig. 5: New Concept after Topological Optimization.

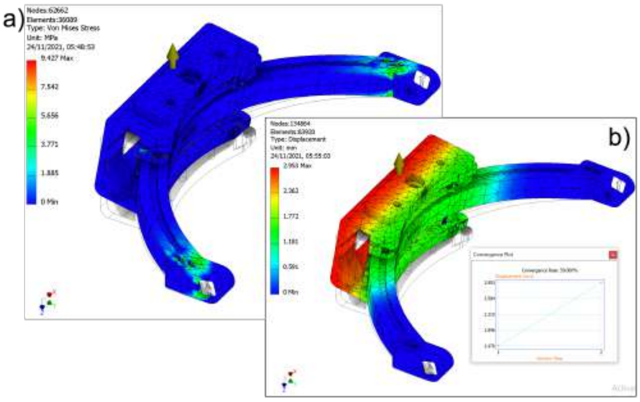

Fig. 6: FEM New Concept.

Table 2: 3D printing material analysis

	Material	Von Mises MPa	Displacement mm	S.F.
1	ABS	9.427	2.953	2.12
2	Nylon	9.403	2.248	8.8
3	PAEK Plastic	9.25	6.04	10.8
4	PBT Plastic	9.205	0.7393	5.99
5	PC/ABS/CF	9.297	2.385	5.85
6	PPS Plastic	9.298	2.456	7.41
7	PLA	9.87	3.46	3.65

nodes. The used material of the components is ABS. Some movements of the new concept are shown in this video [39].
The results of the FEM analysis for different 3D printed materials are shown in Table 2. The components of the back-support exoskeleton have been printed with two devices: The Sharebot One and The Sharebot Next Generation 3D printers.
The bill of material of the back support exoskeleton is composed of 22 different parts without considering bearings and bolted connection systems.

6. Discussion

6.1. Re-designed Prototype

The prototype has been re-designed and assembled as discussed in §3-5. The final result is shown in Figure 7, where the introduced modifications to improve the wearability and to reduce the production costs of the device are highlighted. The prototype is now ready for field-tests.

6.2. Conclusions

This paper proposes the re-design of a low-back support exoskeleton taking into consideration the following manufacturing optimization targets: i) lightweight and compact design, ii) simplified assembly and maintenance procedure for the device development, and iii) low-cost prototype. The aforementioned issues are tackled by combining kinematic analysis, Finite-Element-Method (FEM), topological optimization, and fabrication materials selection. Both Design for Assembly and Design for Manufacturability approaches have been applied to the re-design of the exoskeleton. As a result, the manufactured prototype satisfies the stated goals. The prototype is now ready for field tests with end-user.
Future work will be devoted to further improve the design of the device. On the one hand, we are going improve the passive compensation mechanism to optimize it in terms of both size/weight and assistance to the user. On the other hand, we are designing an actuated version, featuring advanced human-robot interaction controllers. Preliminary feedback of users are going to be exploited to improve wearability and psychological effects. This includes also improving the height-/size-adaptation system. Specifically, we plan to design several subject-specific mechanisms using the original data-driven optimization algorithm presented in [35]. This is going to be done both with male

Fig. 7: Side and front view of re-designed prototype, highlighting the new elements for improved wearability.

and female users with different height and weight. Then, these models could be *interpolated* in order to improve the fit and the regulation system for the wearer, independently of their height, weight or sex. Usability comments form users during preliminary tests will be collected, and transformed into additional requirements.

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