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An integrated survey-simulation approach for exoskeleton performance estimation

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Abstract

The paper presents a hybrid user-centred/simulation approach to populate the design specification. It presents an application in the field of exoskeleton design, with the final goal to support workers to carry out their professional tasks. More than 100 professionals (mostly health workers) participated in the survey. The qualitative requirements were extracted are then tested in simulation environments. The approach proved to generate meaningful results for product concept generation. Beyond the expectations, the simulation also showed more adequate product architectures.

Keywords: product planning, requirements management, product design, exoskeletons, user-centred design

1. Introduction

1.1. Motivation of the study

Historically, a large part of human inventions was designed to reduce fatigue, while increasing productivity and assuring safety at the same time. Indeed, physical fatigue, caused by exertion and manifesting as a reduced strength and capacity, has been already demonstrated to be a precursor of several short-term and long-term adverse health outcomes. Work-related Musculoskeletal Disorders (WMSD) are one of the main causes of lost or restricted work and account for one-third of all worker injury and illness cases. In Europe, WMSD constitutes around 38% of all lost or restricted work. According to the literature, the most relevant WMSD are low back and shoulder disorders (Bernard et al, 1997). The economic burden of low back pain alone varies between 0.1- 2% of the gross domestic product, due to lost worker productivity and direct healthcare expenses. Within the industry 5.0 paradigm, humans and machines share the same working environment, working side-by-side toward the objective of industrial production. In this context, body-worn assisting devices are enabling the user to benefit from additional support, retaining the flexibility of humans (Saldivar et al, 2015).

1.2. Related studies

Technology advancements have led to the development of primarily two types of industrial exoskeletons: i) lower back exoskeletons (e.g., LAEVO (Bosch et al, 2016), SPEXOR (Naf et al, 2018), BackX (SuitX, 2016), and ii) Upper body exoskeletons (e.g., EksoVest (EksoBionics, 2016), ShoulderX (Van Engelhoven et al, 2018)). Despite the high interest in exoskeletons with an industrial application purpose, their large-scale implementation in the industry has still a long way to go. Indeed, although they can reduce demands on specific body parts, they may also have unintended consequences, such as increasing loading and/or discomfort on "other" regions of the wearer's body (Looze et al, 2016). Detecting such consequences is considered critical, as they can hinder acceptance and relevance in the workplace. To analyse these side effects, the scientific community has opted for subjective metrics, including Borg Scale (Borg, 1982), and usability metrics questionnaires (Bangor et al, 2009). In addition, objective metrics have been proposed, including analysis of muscular activity (Bosch et al, 2016), measurement of contact pressure at the interface between the participant and the exoskeleton (Huysamen et al, 2018), and measurement of oxygen consumption. To gather these data and extract relevant information to steer the design process of exoskeletons, both subjective and objective metrics have to be implemented in a laboratory environment. Moreover, all these analyses have to be conducted in a real scenario, which also requires the wearable device to be at least physically prototyped. Additional possible limitations lay in the difficulty of analysing the biomechanical load at several joints during the execution of the tasks. Moreover, experimental campaigns need to face logistic difficulties, such as the recruitment of a consistent number of participants, ethical concerns, the cost of the experimental set-up, as well as the limited available space. To mimic what happens in the real working scenario, different subjects need to adopt different postures (that might be unhealthy), and carry out different activities without and with the exoskeleton(s), which are all factors that complicate the implementation of the experiment. However, the essential role of field tests is to provide first-hand data on functionality and usability in real(-like) work scenarios. Now, this can be complemented with simulations in virtual environments, which can help reduce some of the abovementioned limits of experimental tests. Previous studies have been performed in a simulation environment to assess loads on the human back with different computational models (e.g., Arjmand et al., 2012). OpenSim and AnyBody allow the estimation of spine loads and the integration of external objects such as exoskeletons (Bruno et al., 2015; M. Damsgaart et al., 2006). All these environments are enhancing a better understanding of the human back/spine biomechanics.

1.3. Objectives of the study

This contribution aims at showing how an original approach that combines qualitative and quantitative data acquisition and processing enables the identification and characterization of requirements during the early stages of the exoskeleton design process. It is expected that the approach provides additional insights to designers with a smaller investment of resources and with sufficient precision, i.e., comparable to what field tests can provide. We present a user-centred design approach to the technologies, where we want to focus on implementing features that are specifically designed to optimise the experience to the user's preferences. This is in contrast with what is usually presented in the literature, where we see technology-centred design, where the user adaptation or his/her response or actions to be able to use the product are reported. To do so, we collected postural problems in working environments by means of a tailored survey to identify target assistive needs to be turned into design requirements. Survey information was used in a simulation-based approach to make it possible to anticipate the target (range of) design values, as well as preferred and more useful exoskeleton architectures (e.g., upper/lower body) depending on the task.

1.4. Structure of the contribution

The next section presents the rationale of our approach within the context of a systematic technology development process. The rest of the contribution includes the survey with its outcomes; the simulation carried out in a virtual environment to set target values for design requirements; and a summary of the strengths and weaknesses of our approach, its limitations and future opportunities.

2. User-centred design requirements identification

To provide the exoskeleton design process with adequate information to support designers and their decision-making in the following phases, it is critical to spot the most essential requirements for the product. In this work, we describe our adopted approach based on user-centred design, with reference to the systematic approach proposed by Pahl and Beitz (2007), addressing the generation of the

required outputs for the Product Planning (task clarification) phase, namely elements for the design specification.
In assistive technologies design, we need clear and quantitative requirements, but the target users' input is indeed intrinsically qualitative. We hypothesized that potential users might be involved less invasively than with existing product-/prototypes-based experiments. Our approach is based on a two-phase user-centred requirements definition. Within Phase 1, remotely administered surveys, mostly based on qualitative data collection about working routines, aim at spotting recurring postural problems as well as anatomic districts that potentially showed the prodromes of WMSD from a large target population (as opposed to target interviews for example). This collection of problems, situations and opinions is at the core of the requirements definition and cannot be described with a complete information set that also includes reference values to achieve with this methodology. On the other hand, the design of an exoskeleton cannot proceed without clear references about working conditions to be translated into mechanical properties to satisfy. To overcome this barrier, in Phase 2 we propose to exploit the survey results as input to a simulation environment in order to test postures and working conditions with and without the support of exoskeletons, directly derived from the population needs. The simulations return values of mechanical stress at body joints when assisting different districts. The simulations run with no exoskeleton worn highlight and quantify the need for support from a generic user (described via a manikin). The ones with existing exoskeleton models worn by the manikin, in turn, shed light on their performance, benchmarking some of their characteristics, such as comfort, architecture/layout, etc. with reference to uncomfortable situations previously identified.

3. Phase 1: survey on demanding tasks during a workday

The questionnaire consists of 2 open questions (#1 and #4) and 3 multiple-choice questions (#2, #3 and #5) related to the topic of the study. #1) What is your job? #2) Determine the occurrence during a workday of a given sub-set of actions, i.e., 1) handle weights at ground level; 2) handle weights at table level; 3) handle weights overhead; 4) handle weights with trunk torsion; 5) handle weights when walking; 6) overhead tasks; 7) standing; 8) staying in an uncomfortable position; 9) sitting. #3) Determine the impact of fatigue/pain during a workday due to the sub-set of actions on different joints (i.e., shoulders, back, knees, ankles, hands, neck). #4) Indicate the most exhausting activity in your workday. #5) For each of the indicated joints, select the degree of fatigue at the end of your workday.
At the end of the survey, some additional questions were also proposed, with the aim of gathering some personal information (e.g., age, sex, weight, etc.). Before the administration of the questionnaire to participants, we run a preliminary round of validation of the same by means of the involvement of a tenth of respondents, which confirmed the clarity and the appropriateness of the questions to address the research objectives. It was developed according to the UE law 2016/679 and its administration approved by the Ethical Committee of Author's institution (approval n. 17/2021 - 14/06/2021).

3.1. Participants

Among the 102 people who completed the questionnaire, 30 are nurses, 7 medical doctors, 9 physiotherapists/osteopaths, 27 office workers, 19 labourers, and 10 retiree/frail persons. It has to be noted that we grouped together, on purpose, workers with different task characteristics to investigate whether it is possible to derive a set of primitive actions that determine joints fatigue that can be addressed both in terms of prevention and rehabilitation, whatever the specific work task.

3.2. Results of the survey

3.2.1. Frequency of actions during the workday (Q2)

We proposed 9 main actions due to the recorded frequency in previous on-field observations (Fig.1), indicated in titles of Fig.1. Some of them are more frequent, namely postural/static positions as 50% claim standing or sitting for a long period of time.

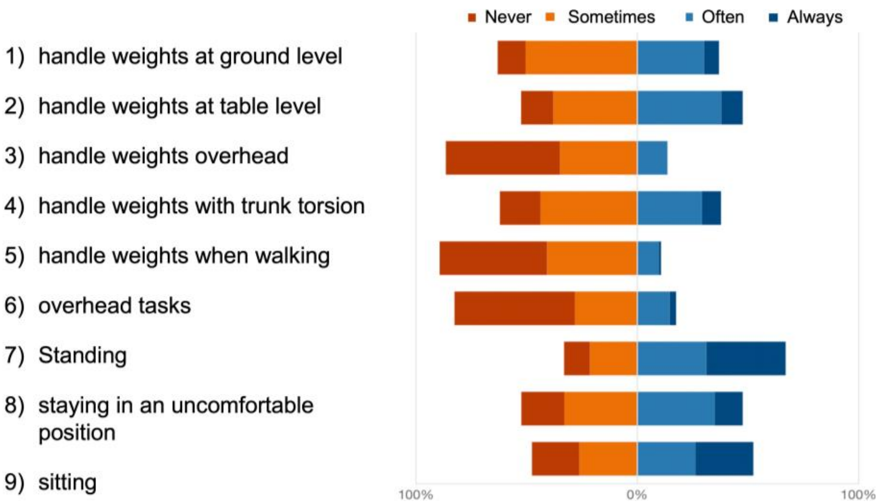

Figure 1. Frequency of actions during the work day

3.2.2. Impact of fatigue/pain on joints (Q3)

For the most fatigued joints, we only focused on subjects who answered "often" or "always" to the frequency of occurrence of the action. The results are reported in Fig.2 and show that the most affected joints are by far shoulders (54 instances) and back (150).

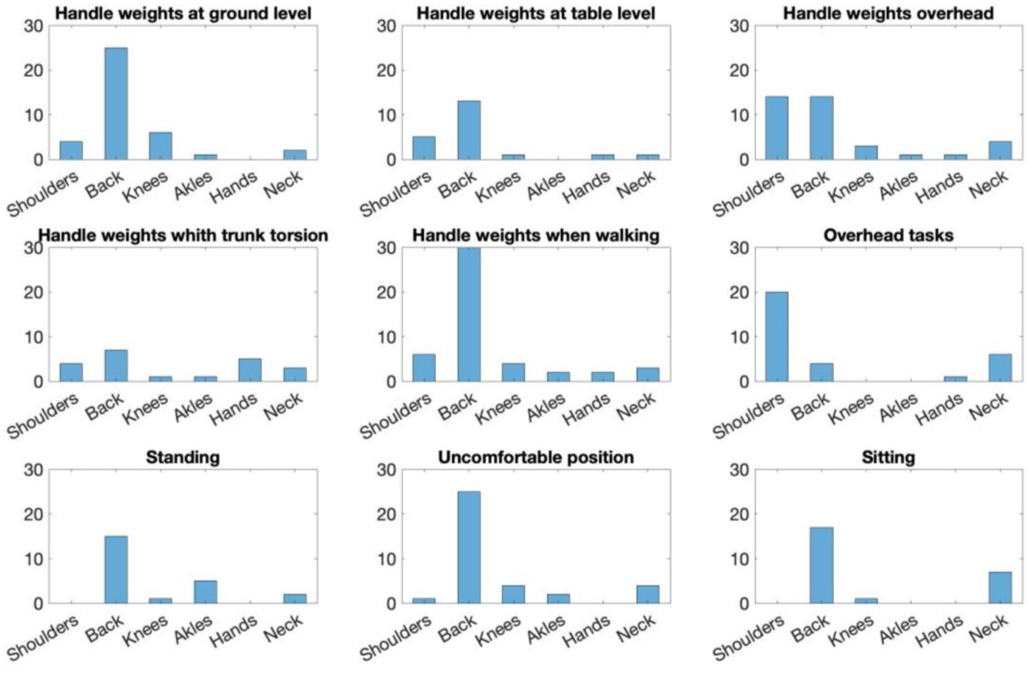

Figure 2. Joints where fatigue is mostly suffered, by task

3.2.3. Most exhausting activity in the workday (Q4-5)

The most exhausting activity reported by the subject can be grouped into five categories, and in particular: handling weights (46pp), sitting (25pp), staying in uncomfortable positions (11pp), walking for long distances (7pp), standing for long time (10 pp). The subjects were then asked to rate the pain/fatigue at different joints at the end of the workday, independently from the performed action, and the results are reported in Fig. 3. Again, the most affected joints were shoulders and back.

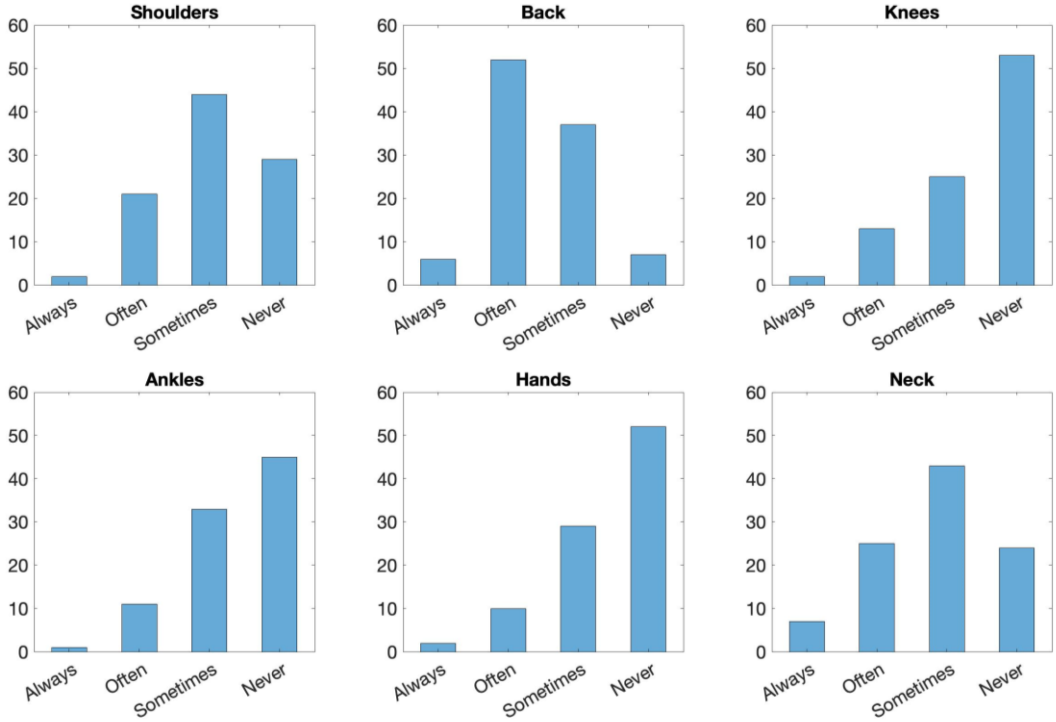

Figure 3. Frequency, by day, of the most exhausting activity

4. Phase 2: simulation

4.1. Virtual manikin

The manikin is a digital human characterized by a complete musculoskeletal model with 140 DOFs. Avatar's body, link lengths and body segment geometries are based on Standard ISO 3411 and GEBOD (Generator of Body Data) respectively [www.santoshumaninc.com]. This simulation environment has been selected since Santos predictive human models are the only optimization-based and physics-based human models capable of predicting human performance without pre-recorded data.

4.2. Postures

The postures to be analyzed were identified from the most fatiguing and performed actions, as derived from the survey. Postures analysis has been restricted to the sagittal plane since it is the most relevant action plane for all identified actions. A sitting position has been discarded since it is well-tackled by ergonomic chairs, and it probably does not benefit from the use of wearable devices. Not surprisingly, the identified postures are considered at risk of developing WMSD of the back and shoulder (Bernard, 1997). Four static postures have been defined in the virtual environment, assumed by 50 percentile manikin for the static analysis: 1) Neutral posture which accounts for standing action; 2) 90° shoulder posture, 3) Squat posture, 4) Stoop posture. For each posture, the manikin is involved in holding different loads. In static analysis seven loads are considered (0 kg, 3 kg, 5 kg, 9 kg, 13 kg, 17 kg, and 23 kg). 23 kg is the maximum weight that the worker can safety handle, following the international technical standards UNI ISO 11228.

4.3. Exoskeletons and simulation environment

Two exoskeletons derived from the literature i.e., ShoulderX and BackX have been included in the analysis, modelled and simulated in Santos Human: i) upper body exoskeleton, and ii) low back support exoskeleton. They have been modelled in Santos Human through Point Loads. The Point Loads function is used to simulate the weight of the item the avatar is manipulating (e.g., lifting, carrying, etc.), and the assisting and reaction forces acting on the avatar by means of the two configurations of exoskeleton. The distribution and the points of application of assisting and reaction forces provided by the two

exoskeletons have been modelled according to literature (Toxiri et al, 2019). The upper body exoskeleton analyzed is the ShoulderX (Figure 4). It is a rigid exoskeleton, characterized by attachment points placed onto upper arms, shoulders and hips with an assisting torque for the shoulder joint when performing the flexion/extension in the sagittal plane. In Santos, the assisting forces or anti-gravity forces (F_{ag}) are applied perpendicular to the upper arms of the avatar. We have supposed to be at 17 cm from the glenohumeral joint, and restricted on the sagittal plane. The applied F_{ag} is calculated to compensate for the shoulder flexion torque. It is designed to provide a peak value at 90° of shoulder flexion and automatically reduce support as the arm is lowered. This means that F_{ag} is simulated to be as optimal in any shoulder elevation plane. The upper body exoskeleton has been assumed to have a weight (W_{exo}) of 4 kg. The reaction forces (F_r) are concentrated at the attachment points of the ShoulderX. Fig. 4A illustrates the anti-gravity forces (in blue), and the reaction forces (in green) applied at three points on each side of the body region around the hips and on the neck-shoulder complex.
The lower back exoskeleton taken as an example is the BackX, to reduce the net joint torque on the low back, in particular at the lumbar-sacral region. According to the configuration of the BackX, its Santos model includes two F_{ag} applied at the upper torso in a perpendicular way. These forces operate in the sagittal plane to compensate for the extension torque associated with the lumbar-sacral (L5/S1) intervertebral disc. F_{ag} assumes the peak value when the back is at the maximum of its flexion, at 90° flexion and automatically reduces support as the flexion angle is reduced. Fig. 4B illustrates the anti-gravity forces (in blue), and the reaction forces (in green). The reaction forces (F_r) are applied at three points on each side of the body region around the hips (F_{rh}), and at mid-height of each upper leg (F_{rl}).

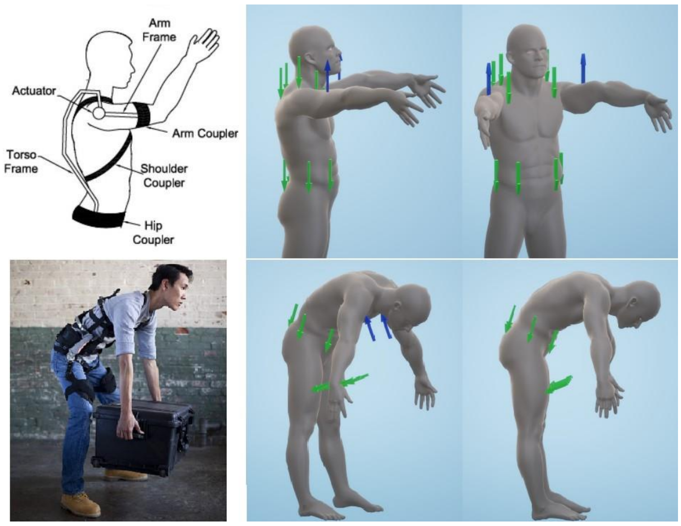

Figure 4. Exoskeletons' models; A) Upper body exoskeleton; B) Low back exoskeleton

4.4. Metrics

The physical demand of postures has been investigated without and with the two exoskeletons.
Joint torques. Santos focuses on the joint level for describing forces acting on the subject. Each joint, as a function of its angle, is characterized by an isometric torque limit, a physiological limit that the avatar is not able to exceed. Five anatomical joint torques in the sagittal plane (i.e., shoulder flexion/extension, low spine flexion/extension, hip flexion/extension, knee flexion/extension, and ankle dorsiflexion/plantarflexion) have been investigated. **Low spine shear/compression forces.** Low spine shear/compression forces act on intervertebral discs L4-L5 and L5-S1. Forces result from external (i.e., gravity) and internal elicitation (i.e., active muscle tension, passive muscle tension and passive soft tissue tension). Compression force compresses one vertebra against the other, while the anterior-posterior (A/P) shear component tends to slide the vertebra forward above the one below. In Santos, a simple polynomial equation proposed by Stuart McGill (1996) is used to predict low-back compression. A/P shear and compression forces have always to be compared with two threshold values to understand the risk to which the subject is exposed (NIOSH, 2018): Action Limit (AL) and Maximum Permissible Limit (MPL). AL represents the force value beyond which the first back problems appear. AL is 3400

N for the compression component, and 500 N for the A/P shear component. The MPL represents the value against which the risk is high in causing vertebral plate lesions. MPL is 6400 N for the compression component, and 1000 N for the A/P shear component.

4.5. Postures analysis

With the aim of assessing the effect of the assistance to the most affected joints as derived from the survey and from the literature, for each of the five postures and for each of the seven loads, three conditions have been analysed and compared: i) without exoskeleton (i.e., No Exo): condition in which Santos model is not wearing any assisting device; ii) with upper body exoskeleton (i.e., UB Exo): the Santos model is wearing the upper body exoskeleton; iii) with low back exoskeleton (i.e., *LB Exo*): the Santos model is wearing the low back exoskeleton. At first, F_{ag} has been set in each posture for each configuration of exoskeleton, and for each load supported, to completely compensate shoulder flexion torque in the *UB Exo* and low spine (L5/S1) extension torque in the *LB Exo*.

4.6. Results of the simulations

4.6.1. Neutral posture

The neutral posture is characterized by low torque values in each subject's joint and, hence, it does not overload any joint. As a result, the optimal F_{ag} for *UB Exo* and *LB Exo* and for each payload is low. It compensates 100% of the shoulder flexion torque with *UB Exo* (blue line, Figure 5 top right) and low spine extension torque with *LB Exo* (red line, Fig. 5 top left). However, *UB Exo* overloads low spine extension torque (blue line, Figure 5 top left). The three conditions return the same spine compression forces (Panel C, - Figure 5 bottom left). On the other hand, *No Exo* and *LB Exo* return very low spine shear forces, while *UB Exo* show a more marked linear increase with payload (respectively black, red and blu lines, Figure 4 bottom right) due to F_{ag} horizontal component. Then, both exoskeletons configurations do not give any relevant contribution with respect to the *No Exo* condition.

4.6.2. 90° shoulder posture

In this position, the shoulder flexion torque is at its greatest value. The F_{ag} of the *UB Exo* condition is able to compensate for 100% of the shoulder flexion torque, without inducing overload in the other joints. F_{ag} compensates a variable percentage of the low spine extension torque with *LB Exo*, for different payloads. In condition *No Exo* the shoulder flexion torque reaches the torque limit (67.0 Nm) for the payload of 23 kg (i.e., maximum weight that a subject can handle). In this posture, we can observe a clear benefit when the Santos model wears the upper body exoskeleton. For what concerns the A/P and compression forces acting on the manikin, the advantage of wearing the upper body exoskeleton is highlighted again. Therefore, the best condition in 90° shoulder posture is the *UB Exo.*

4.6.3. Squat posture

The subject with no exoskeleton (*No Exo*) reaches the highest values for low spine extension and hip extension torques (black lines - Figure 6 top). *LB Exo* noticeably reduces low spine and hip torques compared to *No Exo, UB Exo* (red lines - Figure 6 top). The spine shear and compression forces are high for the three conditions, but *LB Exo* is the only condition that remains constantly below the Action Limit, making this configuration the best candidate to address this posture.

4.6.4. Stoop posture

In the *No Exo* condition, the avatar has to exert greater torque values in each joint compared to the squat posture. However, considering the *UB Exo*, the avatar has to exert torque values in the low spine extension and hip extension higher than the condition *No Exo*. In the condition *LB Exo*, instead, there is a clear reduction of the torque values in each joint compared to the other conditions. The results in terms of spine shear/compression forces are similar to the previous posture. However, in stoop posture also the *UB Exo* reaches the compression Action Limit for a mass of 23 kg. According to this reasoning, the best condition in the stoop posture is the *LB Exo.*

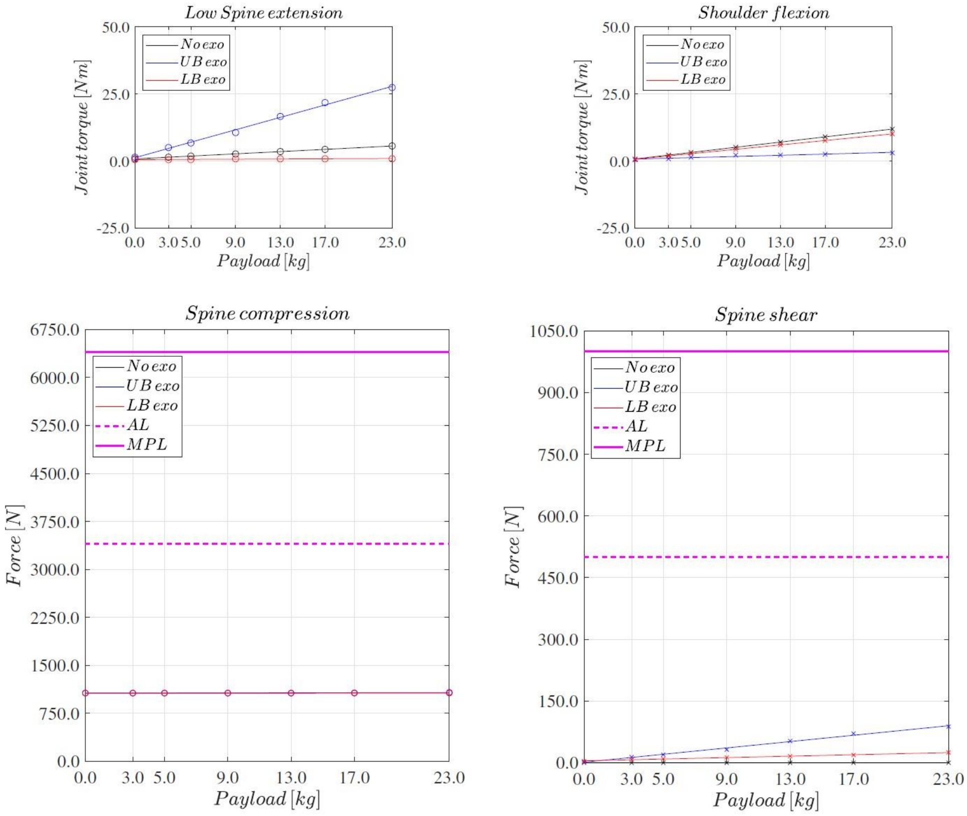

Figure 5. Joint torque and force - neutral posture with and without exoskeleton

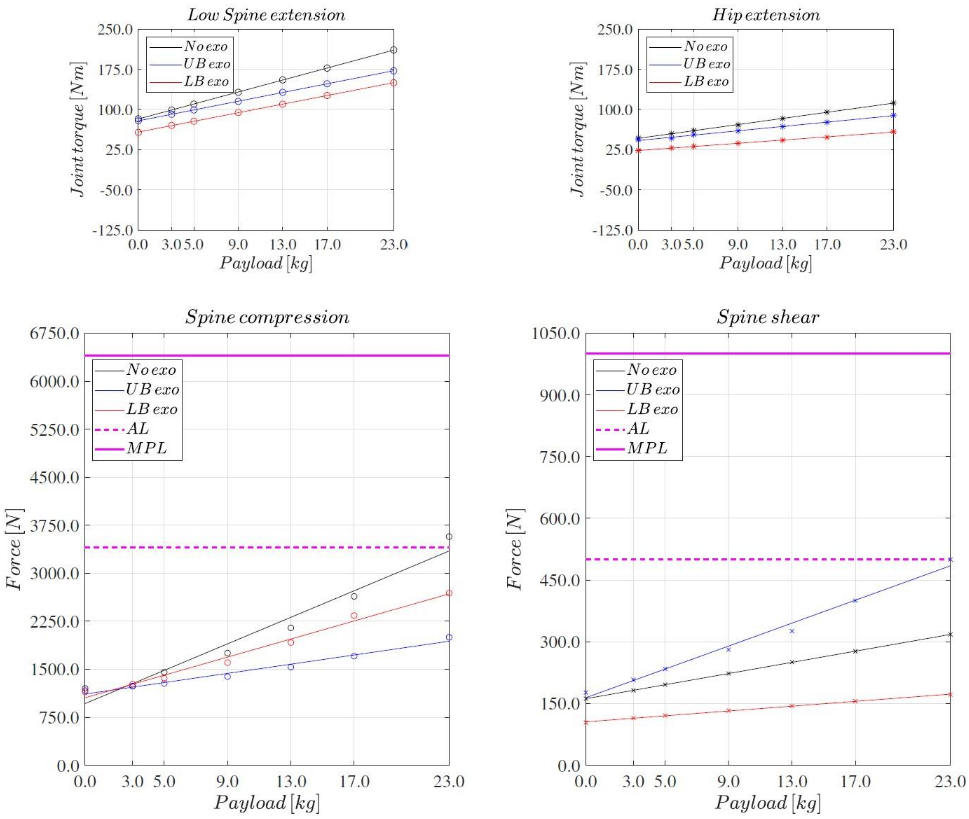

Figure 6. Joint torque and force - squat posture with and without exoskeleton

5. Discussion and conclusion

In this contribution, we showed an exemplary application of an approach to identify and characterize design requirements during the product planning phase. This integrates a user-centred perspective with the opportunities enabled by simulation technologies. While the former is used to collect the so-called voice of the customer, the extracted qualitative requirements receive a quantitative attribute by means of the latter. This set the target values for the requirements to achieve, to populate a well-defined design specification (Altavilla et al, 2022). The exemplary application presented in this paper concerns the development of an exoskeleton to support body movements in repetitive tasks. We estimated the effect of the assistance of wearable devices in supporting the most affected joints in the most critical positions noted in the survey. More than 100 subjects voluntarily participated providing data for the research, mostly employed as health-related workers. These highlighted that the most fatiguing actions are handling weights, sitting, staying in uncomfortable positions, and standing or walking for a long time. The most affected joints have been reported to be the back and shoulders, confirming results reported in the literature concerning the most exhausting activities potentially leading to Work-related Musculoskeletal Disorders (WMSD). The design-relevant aspect of the described approach is to be able to improve and test the assistive technology in a simulation environment before going in situ, for a given target population. A further extension may foresee simulations on mannequin derived from single user scanner, to further deepen single-subject specific requirements definition.

Regardless of the specific application presented in this paper, we think that the proposed approach holds sufficient versatility to find application in different contexts. Obviously, it can trigger the largest benefits where the standard design and development practice still requires experiments with subjects that are complicated to organize, manage and run. The portability of the approach also requires the investigators to develop and validate a tailored questionnaire to address and surface the problems that design should be able to solve. Finally, yet importantly, the ultimate condition for the approach to be successful concerns the availability of simulation technologies that provide data for post-processing, as these will fully characterize the qualitative requirements with quantitative targets for their fulfilment.

This example of application also generated interesting results that were unexpected at the beginning of the research. Two of them are worth of noticing.

First, the simulations carried out with the models of two existing exoskeletons did not just provide elements that characterize better the design specification by assigning target values; these also made it possible to highlight more adequate product design, layout, architecture depending on the specific conditions the product should work in. Analyses of different postures with different devices highlighted that there is no dominant design. There are different adequate designs for exoskeletons, which depend on the task the device aims at providing support for. Second, but not less important, the running of simulations using existing skeletons model enables the benchmarking of different market products. This is one of the essential elements of Quality Function Deployment (e.g., Chan et al, 2002) to define new product characteristics. Within the framework of the House of Quality (Hauser et al, 1988), Phase 1 (survey) supports the definition of customer attributes, while the Phase 2 (simulation) enables more objective estimation of performance and achievements for the subjective benchmarking/preference analysis, which is essential to steer product differentiation.

This research, however, also suffered some limitations that is necessary to point out for the proper interpretation of the results. With the purpose to involve a relevant set of subjects, the authors exploited their own networks to administer the survey to the largest set of possible respondents. On the one hand, this facilitated the circulation of the survey, which now counts more than 100 respondents. On the other hand, its diffusion by word-of-mouth does not make sure that the sample is sufficiently free from biases.

The research now proceeds according to two different streams. On the one hand, the proposed approach will be tested also in different industrial contexts to confirm its expected flexibility of application. On the other hand, the specific findings emerged for the new exoskeleton design have already given birth to a set of ideas that are already prototyped, which will be pilot tested also to have empirical backing of the experimental results on the results obtained with the present study.

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