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Can we simulate the biomechanical effects of exoskeletons prior to workstation implementation? Application of the Forces ergonomic method

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ABSTRACT

Increasingly, exoskeletons are becoming a valuable tool for prevention technicians to promote occupational health and reduce the risk of musculoskeletal disorders in industry. However, the effective implementation of industrial exoskeletons is a complex challenge. Deciding whether these devices are the optimal solution to the detected ergonomic risks at a specific workstation is not straightforward. This study presents the modelling of three commercial passive exoskeletons, one for lumbar and two for shoulder risk reduction, to be considered in the musculoskeletal risk assessment of industrial workstations. The presented modelling considers the forces and moments applied by exoskeletons to the body using the Forces ergonomic method, providing the musculoskeletal risk for each joint based on inertial motion capture data registered at each workstation. This approach is exemplified on simulated and actual production workstations. The results reveal that the modelling application allows an objective understanding of the biomechanical effects of exoskeletons. Modelling establishes a predictive tool to assess and make decisions regarding the suitability of the exoskeleton prior to implementation at a workstation.

1. Introduction

Recently, the Industry 4.0 approach has advanced the digitalisation of manufacturing processes, promoting such technologies as robotics, artificial intelligence, and the internet of things (Kadir et al., 2019). Nevertheless, the digital transformation of the industry should also intensively consider the health care of the people (Xu et al., 2021; Leng et al., 2022). Musculoskeletal disorders (MSDs) remain the most prevalent occupational health problem. Approximately, three out of five workers in the European Union report MSD complaints and 60% of work-related health problems are related to MSDs (European Agency for Safety and Health at Work. et al., 2019). Thus, the emerging smart ergonomics approach fosters using technology and worker-centred methodologies to support the workflow of prevention technicians to reduce the risk of MSDs (Marín and Marín, 2021).

In this context, industrial exoskeletons are becoming a tool increasingly valued by companies to prevent occupational hazards in production environments, especially when other technical actions are not feasible or sufficient (Spada et al., 2017). These wearable devices are mobile structures that adjust to the worker's body to assist them in performing specific movements in their work activity to reduce the physical load on specific anatomical areas (Sänger et al., 2022; Kong et al., 2022). Exoskeletons can be classified according to the anatomical area, usually the lower back, upper limbs, or lower limbs, where they reduce the risk of MSDs (Tiboni et al., 2022). Additionally, they can be classified as active or passive according to their mode of operation (Kong et al., 2022; Tröster et al., 2020)\Active exoskeletons are motorised and controlled by electronic activation, whereas passive exoskeletons are based on springs, elastic materials, or mechanical stops that redistribute the forces and moments in the body (Tröster et al., 2020). Active exoskeletons require batteries, are usually heavier and bulkier, and are more commonly developed for rehabilitation (Rodríguez-Fernández et al., 2021) or the military environment (Mudie et al., 2018; Crowell et al., 2019) than industrial environments. This study focuses on passive exoskeletons; although they do not present as many possibilities related to body assistance, measurement, or interconnection as the active ones (Tröster et al., 2020), their significant simplicity and lower economic cost promote their application in industrial environments (de Looze et al., 2015).

Studies have demonstrated promising results when evaluating commercial exoskeletons, such as Laevo (Rijswijk, Netherlands) or SuitX (Emeryville, US), aimed at reducing lumbar risks, with human motion

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Fig. 1. Sensor placement of the MoveHuman motion capture system for application in the industrial field.

Table 1
Interpretation of the risk at a joint throughout the entire work cycle.

Assessment	Risk per minute (%)	Interpretation
No risk	≤10	Acceptable
Low risk	>10 ≤15	
Medium risk	>15 ≤25	
High risk	>25 ≤40	Conditional
Very high risk	>40 ≤70	Unacceptable
Severe risk	>70	

capture, electromyography, heart rate monitors, or usability surveys, particularly in performing repetitive lifting and manual assembly actions (Luger et al., 2021; Madinei et al., 2020; Baltrusch et al., 2019; Bosch et al., 2016; Koopman et al., 2019). Additionally, considerable scientific attention has been focused on the study of the effects on the body of exoskeletons aimed at reducing the risk to shoulders, such as Levitate (San Diego, US), ShoulderX (Emeryville, US), Skelex (Rotterdam, Netherlands), Paexo (Duderstadt, Germany), or EksoVest (San Rafael, US), especially in static positions maintained for a long time with shoulder elevation (De Bock et al., 2021; Claramunt et al., 2019; de Vries et al., 2019, 2021; Moyon et al., 2018; Van Engelhoven et al., 2018; Van Engelhoven and Kazerooni, 2019; Maurice et al., 2020; Schmalz et al., 2019; Kim et al., 2018, 2020).

These studies highlight the possibilities of exoskeletons as preventive

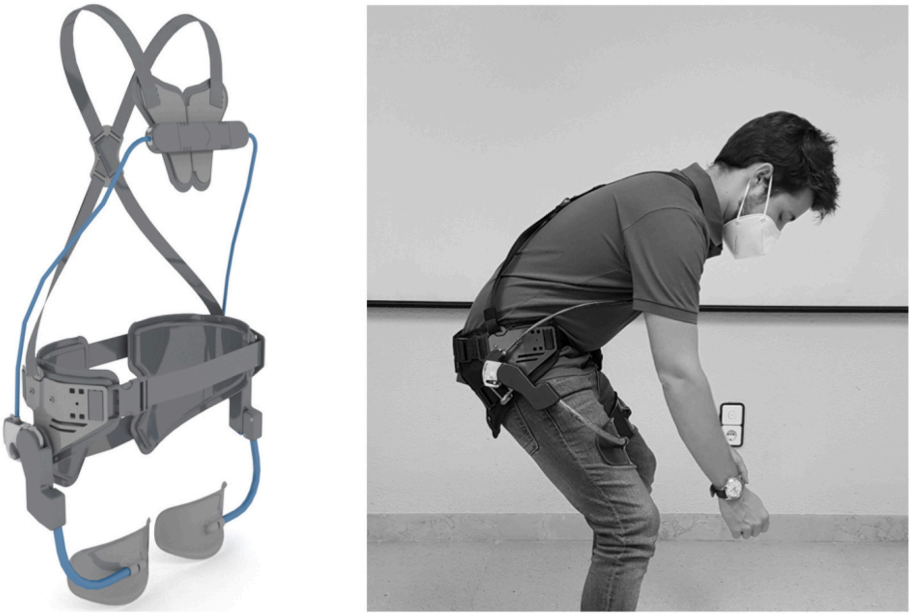

Fig. 2. Laevo placed on the user.

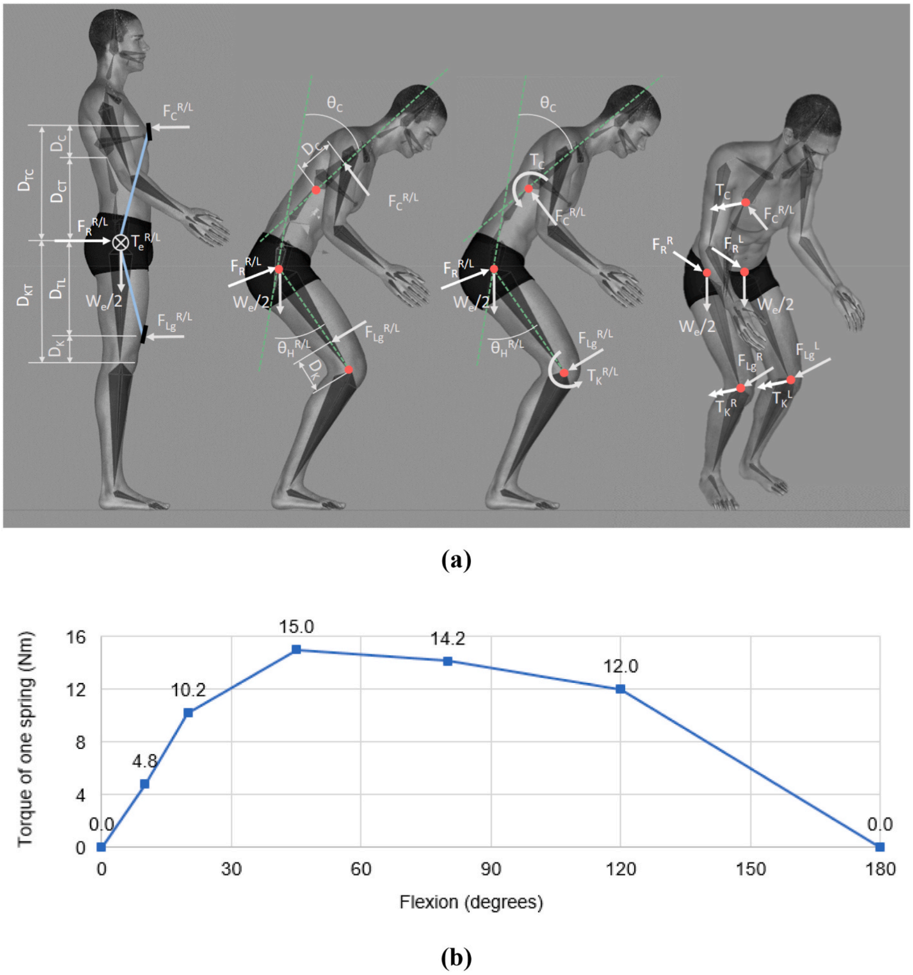

Fig. 3. (a) Free-body diagram of the Laevo exoskeleton. (b) Torque-flexion profile of one spring (right or left) of the exoskeleton.

tools to reduce the risk of MSDs and the current complexity of investigating their biomechanical effects while executing various work tasks. It is a substantial challenge to implement industrial exoskeletons effectively due to the enormous variety of work activities (Baldassarre et al., 2022). Deciding whether these devices are the optimal solution to the ergonomic risks detected in a specific workstation is not straightforward.

One approach to face this challenge is integrating the assessment of the effect of particular exoskeletons in preventive standard practices when performing ergonomic assessments of workstations (Marín et al., 2021). This integration can facilitate decision-making based on objective criteria.

Today, to conduct risk assessments, observational methods are widespread in risk prevention practice (Takala et al., 2009). However, these methods require considerable time to be applied and are dependent on the subjectivity of the assessor (ViveLab, 2019). Moreover, integrating the assessment of an exoskeleton into such methods would be an unrepresentative estimate of reality. In this regard, the Forces method, recently published by Marín and Marín (2021), can be used for this purpose. The Forces method is a digital method that provides the risks of MSD at each joint of the worker using motion capture measurements at the workstation (Marín et al., 2020). The risk scores provided by the Forces method are based on estimating all internal forces and moments in the body, which establishes an optimal framework for integrating the forces exerted by the exoskeletons on the body.

This study aims to answer the following research question: How can we use the Forces ergonomic method to simulate the biomechanical effects of exoskeletons? To answer this question, this study presents the modelling of three passive exoskeletons, one for lumbar and two for shoulder risk reduction. Modelling involves defining the forces and moments applied by exoskeletons on the body to be considered in the Forces risk assessment. The Forces method, including this exoskeleton modelling, was applied to actual and simulated production workstations of load-handling operations to demonstrate that the risk estimation considering exoskeletons is based on a logical and well-founded process. It is expected to demonstrate how ergonomic assessments can serve as a predictive tool for making decisions about the suitability of an exoskeleton prior to its implementation at the workstation.

2. Materials and methods

2.1. *Forces method to incorporate exoskeleton modelling*

The Forces method is based on motion capture to assess the risk of MSDs derived from repetitive tasks in industrial environments in the worker's joints (Marín and Marín, 2021). In this study, the motion capture system used to apply Forces was the MoveHuman system (Marín et al., 2020), configured to operate with inertial measurement units at 60 Hz. The MoveHuman system was described by Marín et al. (2020) and is based on 15 inertial sensors placed over the workers' clothing to translate their movement into a three-dimensional human model (Fig. 1). Previous research has demonstrated that this inertial sensor system generates reproducible results and does not require laboratory conditions, as it is portable and applicable in real working environments (de la Torre et al., 2020; Marin et al., 2017, 2020; Marín et al., 2019; Moreno et al., 2018).

Table 2
Notation of the forces and moments exerted by the lumbar exoskeleton.

Notation	Definition	Source or equation
Input		
W_e	Weight of the exoskeleton	2.8 kg, half applied to each trochanter
θ_a	Activation angle	0°–35°, selected by the user
D_{TC}	Distance: trochanter to chest pad	39 cm
D_{TL}	Distance: trochanter to leg pad	22 cm
D_{CT}	Distance: chest joint to trochanter	From human model anthropometry
D_{KT}	Distance: knee joint to trochanter	From human model anthropometry
$T_e^{R/L}$	Torque exerted by the spring	Function of the body flexion $f(\theta_C + \theta_H^{R/L})$, see Fig. 3b
θ_C	Flexion angle of the chest	Motion capture data
$\theta_H^{R/L}$	Flexion angle of the hip	Motion capture data
Output		
$F_{Lg}^{R/L}$	Leg pad force	$if\ (\theta_C + \theta_H^{R/L}) \geq \theta_a:\quad F_{Lg}^{R/L} = \frac{T_e^{R/L}}{D_{TL}},$ (1) $else:\quad F_{Lg}^{R/L} = 0$
D_K	Distance: knee joint to leg pad	$D_K = D_{KT} - D_{TL}$ (2)
$T_K^{R/L}$	Torque on the knee joint	$T_K^{R/L} = F_{Lg}^{R/L} \bullet D_K$ (3)
F_C	Total chest pad force	$F_C = F_C^R + F_C^L$ (4)
$F_C^{R/L}$	Chest pad force	$if\ (\theta_C + \theta_H^{R/L}) \geq \theta_a:\quad F_C^{R/L} = \frac{T_e^{R/L}}{D_{TC}},$ (5) $else:\quad F_C^{R/L} = 0$
D_C	Distance: chest joint to chest pad	$D_C = D_{TC} - D_{CT}$ (6)
T_C	Torque on the chest joint	$T_C = F_C \bullet D_C$ (7)
$F_R^{R/L}$	Hip reaction force	$F_R^{R/L} = F_C^{R/L} + F_L^{R/L}$ (8)

* R/L superscript indicates that the parameter exists for the right and left sides. An equation that includes this parameter must be applied for both sides.

As listed in Table 1, the risk of MSDs for various anatomical areas provided by Forces is a percentage representing the ergonomic load of the joint in relation to the maximum load obtained by experimentation (Marín and Marín, 2021). A higher percentage indicates that the joint has a higher ergonomic load.

The resulting risk depends on the *angle score*, *angular acceleration score*, *force score*, *torque score*, and *grip score*, which are calculated for all postures from the movement data (i.e. 60 times per second), as indicated in the risk per posture equations described by Marín and Marín (2021). Subsequently, to obtain the risk of the entire workstation, a sum of the risks of all postures is calculated, generating a single value called the risk per minute that summarises the risk for each joint (Table 1). Context-related factors, such as cycle time, working time, recovery time, and micro-pauses between cycles, are introduced into the equations to perform this sum (Marín and Marín, 2021). This information considers risk factors not measured by the capture.

To understand how the estimation of exoskeleton effects is integrated into Forces, it is crucial to consider that the *force score* and *torque score* factors depend on the forces and moments supported by each joint during movement, respectively. These forces and moments are calculated for each posture using the kinetic calculation described by Marín and Marín (2021). Thus, as the exoskeleton is a device that applies external forces to the body, its effect can be estimated by recalculating the kinetics considering the external forces the exoskeleton applies on the body. This concept is the core of the simulations of exoskeletons with the Forces ergonomic method.

The kinetics recalculation considering the exoskeleton forces and moments generates different *force score* and *torque score* factors for a given capture. All other factors remain fixed regarding the initial calculation without the exoskeleton, as they do not depend on kinetics. Therefore, modelling an exoskeleton for this paper involves defining the direction and magnitude of the external forces exerted by the exoskeleton and their application points on the body.

In order to determine these forces and the points of application on the body the following data sources were assessed: exoskeleton manuals, and device measurements. Regarding the measurements, we took the exoskeleton dimensions with a calliper and flexometer. Additionally, we measured their weight and spring forces using a calibrated 100-kg S-type load cell connected to a PhidgetBridge 4-Input. The measurements obtain reference values to create the model and establish the equations related to the forces applied to the body. Nevertheless, as detailed in the discussion section, more quality measurements could improve the precision of estimating this or other exoskeletons in the future.

2.2. *Modelling exoskeletons to reduce lumbar risk*

The exoskeleton for lumbar risk reduction selected in this study was the Laevo V2.56 lumbar exoskeleton (Fig. 2). This exoskeleton includes two springs located just above the worker's trochanter, which produces torque under trunk flexion between the bars that go towards the chest pad and those that go down towards the leg pads. The exoskeleton allows configuring the size to the worker anthropometry and the activation angle, enabling the force only when the trunk flexion exceeds the selected angle (0°–35°).

The free-body diagram of the exoskeleton, including the forces and moments applied by the exoskeleton to the body and their notation is presented in Fig. 3a. As illustrated in this figure, the forces and moments were sequentially translated to the joint centres to be considered in the kinetic calculation of the Forces method (Marín and Marín, 2021). The three-dimensional force distribution finally considered in the modelling is depicted on the rightmost human model in Fig. 3a.

The notation definition and equations necessary for the kinetic calculation at each instant are described in Table 2. As described in this table, the torque exerted by the exoskeleton is a function of the body flexion ($T_e^{R/L}, f(\theta_C + \theta_H^{R/L})$). To stabilise the torque and flexion dependency, we measured the force exerted by the exoskeleton with the described load cell at various angles. This toque-flexion profile is presented in Fig. 3b, indicating a profile similar to that characterised by Koopman et al. (2019) and van Harmelen et al. (van Harmelen et al., 2022). In this regard, the torque-flexion profile is represented for one side, and its maximum value is 15 Nm, half of the total exerted by the whole exoskeleton (30 Nm), according to the device manual and measurements. Additionally, although the last measurement was 120°, the curve was set to zero at 180° to ensure a torque exists to apply to the model.

According to equations in Table 2, depending on the activation angle, the exoskeleton exerts forces on the leg and chest pads following the bone perpendicularly, coplanar to the sagittal planes of the bone (Eqs. (1)–(7)). In addition, a reaction force is exerted by the exoskeleton on the body, translating to a forward effort in the hip area, consistent with the vector $F_R^{R/L}$ (Eq. (8)).

2.3. *Modelling of exoskeleton to reduce shoulder risk*

The exoskeletons for shoulder risk reduction selected in this study were the Skelex 360 (Fig. 4a) and Levitate Airframe (Fig. 4b). These devices provide arm support between the elbow and shoulder when the worker performs tasks that require raising the arms.

The free-body diagram of the shoulder exoskeletons is presented in Fig. 5a. As in the lumbar exoskeleton, the forces and moments were sequentially translated to the joint centres to be considered in the kinetic

Fig. 4. (a) Skelex placed on the user; force measurement using a load cell attached to the arm pad (100-kg S-type load cell). (b) Levitate placed on the user.

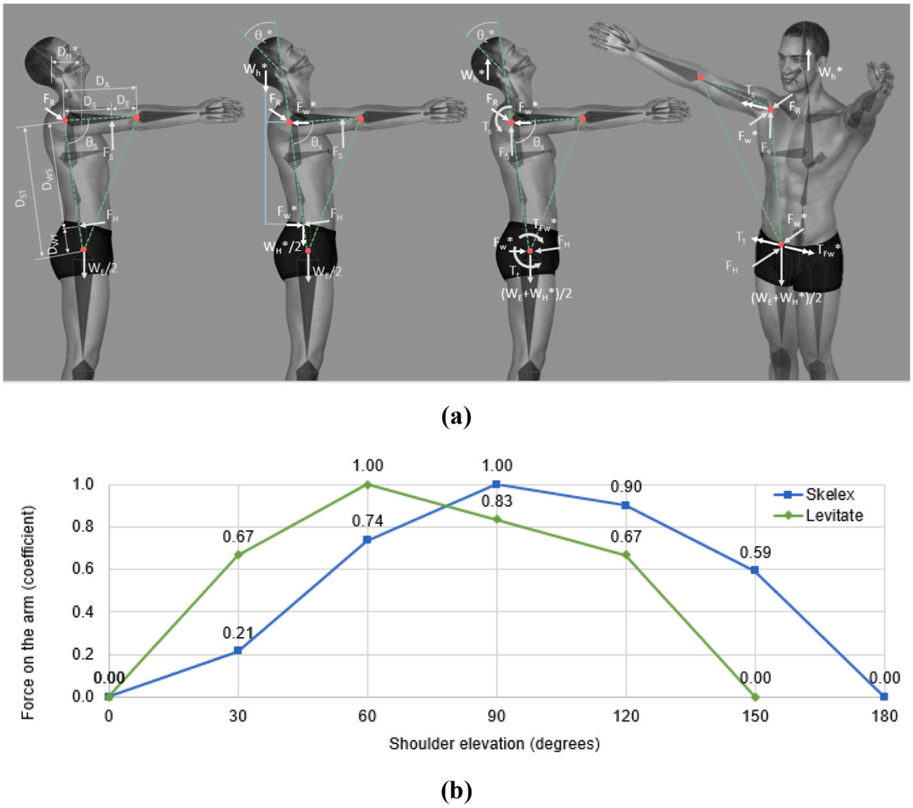

Fig. 5. (a) Free-body diagram of Skelex or Levitate exoskeletons. (b) Force-elevation profile of the Skelex and Levitate exoskeletons.

calculation of the Forces method (Marín and Marín, 2021). The notation definitions and equations necessary for the kinetic at each instant are described in Table 3.

Regarding the arm support force, F_S, a key parameter in the equations, both exoskeletons are characterised by a maximum arm support force. In the case of Skelex, the maximum arm support force is adjustable with a tensor. According to the user's weight, the support force must be adjusted between 0.5 and 3.5 kg following a recommendation table included in the user manual. For Levitate, the maximum arm support force is 3.0 kg.

Nevertheless, in both cases, the arm support force varies with the shoulder elevation (de Vries et al., 2019; Van Engelhoven et al., 2018). Therefore, we measured the force-elevation profile of both exoskeletons (Fig. 5b) using the described load cell (Fig. 4a) at various elevation angles. The values were translated as coefficients relative to the maximum arm support values, 0.5–3.5 kg for Skelex and 3.0 kg for Levitate. Therefore, the support force, F_S, included in the equations can be obtained by multiplying the maximum arm support force for each exoskeleton by the coefficients corresponding to the shoulder elevation.

The equations described in Table 3 are applied independently for the right and left sides. Likewise, the forces and torques generated by the exoskeleton are coplanar in the plane formed by the anthropometric points of the shoulder, elbow, and trochanter, except for weights that follow the gravity direction.

Finally, the Levitate exoskeleton has optional cervical support. When the cervical extension θ_c reaches the cervical support at 25°, this accessory sustains the weight of the head, W_H, so that the exoskeleton exerts an equal force on the head in the opposite direction. The effect of the cervical support, $(W_E + W_H)/2$, was added to each hip to maintain the balance of the forces in the vertical direction. Additionally, the head produces a torque on the device, transmitted as a force, F_w, at the shoulders towards the back and the same at the waist towards the front.

2.4. Experimentation

The exoskeleton estimations were applied in 24 specific work activities recorded using motion capture with the described system (Marín et al., 2020). This process allows showing the result that a prevention technician would observe to make decisions about including a real exoskeleton.

The Forces method provides lumbar, cervical, shoulder, elbow, wrist, and knee risks from the human capture data. Nevertheless, for this study, we provide those risks affected by the biomechanical recalculation because the other risks remain constant with or without applying exoskeleton simulations in the capture.

The selected work activities were repetitive tasks with a cycle time between 32.7 and 85.5 s, which were chosen according to the characteristics of each exoskeleton. For Laevo, we selected tasks with lumbar requirements caused by manual handling or sustained back bending. For Skelex and Levitate, we selected tasks with shoulder requirements caused by working positions above the shoulders.

Activities 1 to 6 and 13 to 18 were performed in a laboratory environment by the authors of this article. Captures 7 to 12 and 19 to 24 were performed in the automotive industry. In these captures in industrial environments, experienced workers were selected, and the production manager supervised them to ensure that the operations were accomplished according to work procedures. In both cases, there was one participant for each task, and captures were taken without wearing the exoskeleton, which, as mentioned in the discussion, represents the actual application of the modelling. Additionally, a concise description of each activity, including the loads handled, is included with the results and a video of the human model of each work activity is included as supplementary material.

3. Results

This section quantitatively presents the risk of MSD values resulting

Table 3
Notation of the forces and moments exerted by the shoulder exoskeletons.

Notation	Definition	Source or equation		
Input		**Skelex**	**Levitate**	
W_E	Weight of the exoskeleton. Half applied to each trochanter	2.7 kg	3.0 kg, 2.8 kg without cervical support	
$F_{S/s}$	Arm pad force. Function of the shoulder elevation angle $f(\theta_S)$, see Fig. 3b	Adjustable maximum 0.5–3.5 kg	Maximum 3.0 kg	
$\theta_{S/s}$	Shoulder elevation angle	Motion capture data		
D_E	Distance: elbow joint to arm pad	10 cm		
D_{WT}	Distance: waist pad to trochanter joint	15 cm		
D_A	Distance: shoulder to elbow joints	From human model anthropometry		
D_{ST}	Distance: shoulder to trochanter joints	From human model anthropometry		
D_H[a]	Horizontal distance: head centre of mass to waist pad	-	From human model anthropometry and motion capture data	
θ_{CS}[a]	Cervical support angle	-	25° of cervical extension	
$\theta_{C/c}$[a]	Cervical flexo-extension angle	-	From motion capture data	
$W_{H/h}$[a]	Weight of the head	-	From human model	
Output				
D_S	Distance: shoulder joint to arm pad	$D_S = D_A - D_E$		(9)
D_{WS}	Distance: waist pad to shoulder joint	$D_{WS} = D_{ST} - D_{WT}$		(10)
$T_{S/s}$	Torque on the shoulder	$T_S = T_T$		(11)
		$T_S = F_S \cdot D_S$		(12)
$T_{T/t}$	Torque on the trochanter	$T_T = F_T \cdot D_{WT}$		(13)
F_H	Hip force	$F_H = \frac{F_S \cdot D_S}{D_{WT}}$		(14)
F_R	Reaction force on the shoulder	$F_R = F_S + F_H$		(15)
F_w[a]	Force on the shoulder joint and waist pad by the head weight	-	$if\ \theta_C \geq \theta_{CS}: F_w = \frac{W_H \cdot D_H}{D_{WS}},\ else: F_w = 0$	(16)
T_{Fw}[a]	Torque on the trochanter by the translation of F_w	-	$T_{Fw} = F_w \cdot D_{WT}$	(17)

[a] Related to the optional cervical support of the Levitate exoskeleton.

from applying the Forces method to 24 occupational activities. Table 4 presents the results for the exoskeleton Laevo, and Table 5 displays the results for Skelex and Levitate. For a given work activity (ID 1 to 24), the first row lists the initial risk without considering the exoskeleton (base risk), and the following rows list the risk of applying the forces that the exoskeleton would exert. In those activities where Levitate was tested and had a cervical extension greater than 25° at any time, cervical support was considered. Additionally, Laevo was configured with an activation angle of 10°, as it is an intermediate regulation.

4. Discussion

This study presents the modelling of various exoskeletons, integrating them into the Forces ergonomic assessment method to analyse their influence on MSD risk reduction when workers perform repetitive tasks. This section discusses the applicability, benefits, and limitations of the presented models according to the results.

First, in response to the research question, this article demonstrates that it is possible to use the Forces ergonomic method (Marín and Marín, 2021) to estimate the biomechanical effects of exoskeletons before implementation. To undertake this process, it is necessary to (1) capture the movement at the workstation, (2) apply the Forces method to obtain the initial risk, and (3) reapply the Forces method on the same capture, recalculating the kinetics considering the external forces applied by the exoskeleton on the body. This workflow can be used in actual prevention practice because, as demonstrated by Marín and Marín (2021), it is possible to conduct motion capture in the field with inertial sensors in a few minutes without interfering with production. Additionally, the Forces method is designed to be software-automated, making the result generation agile.

In this study, we applied the models developed for the lumbar exoskeleton and shoulder exoskeletons to 24 repetitive work activities. This application proves that practical information can be provided to prevention technicians to make decisions to integrate a specific exoskeleton in a particular workstation. Specifically, the initial risks of the joints and the risks considering the specific exoskeleton (Table 4 and Table 5).

Concerning the Laevo exoskeleton modelling results, a general reduction in risk in the lumbar area of −11.6% ± 5.8% and a slight increase in risk in the knees of 0.7% ± 3.0% (Table 4) were observed. This behaviour is consistent with the new kinetic distribution, which transfers the weight from the torso to the legs. In the Skelex and Levitate exoskeletons, the risk was reduced in the shoulders (Skelex: 7.9% ± 7.3%, Levitate: 5.7% ± 5.7%) and the lumbar area (Skelex: 1.3% ± 1.0%, Levitate: 2.0% ± 1.6%), and slightly increased in the knees (Skelex: 0.8% ± 0.7%, Levitate: 0.3% ± 0.4%), which is also consistent with the new kinematic distribution. Last, in the three captures where the Levitate cervical support was used, the risk in the cervical area was considerably reduced (−20.9% ± 8.0%, Table 5).

These average results summarise what happened in these workplaces at a general level. Nevertheless, the risk reduction detected in each individual work activity and whether this reduction decreases a high risk to a lower level (Table 2 of risks levels) are the most relevant finding for the practical application of this model in decision-making. Therefore, according to results, an exoskeleton could be potentially selected for those work activities that reduced the risk from a high lumbar risk (IDs: 1–6, 9, 12) or from a high shoulder risk (IDs: 14, 15, 17).

In this manner, the modelling of exoskeletons presented with the Forces method can favour the work practice and decision-making of prevention technicians, who can obtain objective information about the suitability of a specific exoskeleton. Likewise, the modelling process can be extrapolated to other exoskeletons launched on the market. The challenge is focused on determining the forces and the application points on the body for the exoskeletons.

However, the model has limitations that should be considered. First, regarding the force-angle curves of the exoskeletons, a measurement was made with each exoskeleton using a load cell to determine these forces. These measurements were useful for the scope of this study to present how the model works; however, if this curve were measured with ad hoc setups, better characterisation could be achieved. The study by van Harmelen et al. (van Harmelen et al., 2022) presents an advanced measurement setup.

In this line, in the performed measurement, the energy loss in the exoskeletons due to friction was not considered. This phenomenon is known as hysteresis, which affects exoskeletons (Koopman et al., 2019; van Harmelen et al., 2022), causing the device not to apply the same force when the torso or arms move up or down. Including this effect in the model would be an interesting future direction. However, it seems

Table 4
Work activities with and without considering the Laevo exoskeleton.

ID		Lumbar [%]	Knee L [%]	Knee R [%]	Cycle time [s]	Gender [M/F]	Height [cm]	Description
1	B	39.2	6.9	14.6	52.5	M	171	Handle two boxes (2.0 and 5.0 kg). Open one box. Take a piece (1.0 kg) and a bag (10.0 kg) out of one box.
	V	20.8	8.3	19.3				
2	B	36.8	8.8	10.7	85.5	M	171	Handle two boxes (2.0 and 5.0 kg). Open one box. Take a piece (1.0 kg) and a bag (10.0 kg) out of one box. Push a trolley (4.0 kg). Handle three workpieces (3.0, 3.0, and 2.5 kg).
	V	20.2	8.8	13.4				
3	B	44.3	7.7	7.2	83.1	M	171	Handle two boxes (2.0 and 5.0 kg). Push a trolley (4.0 kg). Open one box. Take two workpieces (1.0 and 3.0 kg) and a bag (10.0 kg) from one of the boxes.
	V	25.6	10.0	8.3				
4	B	47.2	11.5	8.1	40.4	M	171	Lumbar flexion forward, right side and left side with and without squatting.
	V	30.8	13.0	8.4				
5	B	40.8	28.2	9.5	46.2	M	171	Lumbar flexion with squatting with different feet openings.
	V	25.0	18.3	10.1				
6	B	28.8	19.2	2.3	35.1	M	171	Lumbar flexion with squatting with different feet openings.
	V	18.4	17.4	2.6				
7	B	29.7	19.7	14.3	47.0	F	170	Handle six workpieces (4.8, 1.4, 1.5, 1.0, 1.1, and 7.5 kg) and use an automatic screw tool.
	V	20.7	26.2	16.3				
8	B	24.4	7.0	8.4	80.0	F	170	Handle five workpieces (1.7, 1.7, 3.8, 3.5, and 1.9 kg) and use an automatic screw tool.
	V	20.8	6.3	9.0				
9	B	32.0	10.3	9.7	70.0	F	170	Handle two workpieces (3.5 and 3.8 kg) and use an automatic screw tool.
	V	22.3	9.1	11.5				
10	B	20.8	16.4	17.2	80.0	F	170	Handle four workpieces (4.3, 4.3, 4.7, and 4.7 kg) and place in tooling for cutting operation.
	V	18.7	19.7	19.0				
11	B	19.3	9.6	8.7	38.0	F	170	Handle three workpieces (2.7, 1.2, and 1.2 kg) and place in tooling for cutting operation.
	V	13.6	8.4	9.0				
12	B	34.5	4.0	7.0	35.0	F	170	Handle one workpiece from a conveyor belt (10.3 kg).
	V	22.1	6.3	4.9				

* B: Base risk, V: Risks considering Laevo, L: Left side, R: Right side, M: Male, F: Female.

complex to consider two different force curves when moving up or down because work movements are not continuous; from one instant to the next, the torso or arms may change direction. In addition, spline interpolation between the points could be used instead of linear interpolation to increase the realism of the model.

As a further note on the application of forces on the body, the exoskeletons allow for deactivation. That is, Laevo allows the pads to be removed from the legs for walking and Skelex and Levitate allow the pads to be removed from the arms to lower the arms comfortably. At the biomechanical level, this effect can be considered directly with the presented models, considering the weight of the device and no other forces on the body in the specific periods selected by the technician.

Another matter to be discussed is the effect of exoskeletons on human movement. It is well-known that these devices affect a worker's movements (Spada et al., 2017; Sänger et al., 2022; Kong et al., 2022). Indeed, besides the device itself, the postural training required for its use may also affect movement. Nevertheless, the captures were performed without the exoskeleton, as this is how this model is intended to be applied in practice, that is, as a decision tool before using the device physically. This approach does not exclude the possibility of re-evaluating and recapturing movement after integrating the exoskeleton to consider new movements. Modelling can be applied to any capture independently if the exoskeleton is worn in reality.

Similarly, a limitation of the Forces method or any assessment method based on motion capture is that each worker may move differently. The prevention technicians must choose how many workers to assess, depending on the required level of precision. In this case, to approximate the modelling to the actual practical application in industrial environments, the movement of one experienced worker was captured for each task under the supervision of the production manager. This approach provides rapid risk mapping, reducing the time required to assess each workstation, a critical barrier to using motion capture technology in practice (Marín and Marín, 2021). Furthermore, digitisation allows changing the size, shape, or weight of the human model to consider other situations without recapturing.

Given the above, the model provides information on whether a workstation could be selected to use an exoskeleton to reduce risks. Indeed, in this study, IDs 1–6, 9, 12, 14, 15, and 17 could be selected. However, for the effective implementation of the device in the workstation, as Luger et al. (2021) indicates, other factors must be considered in addition to the biomechanical effects assessed with this or other methods. Regarding the technical feasibility, is it possible to solve the problems detected more straightforwardly? Is there available time to adjust the device? Is it safe in that workstation? Regarding human viability, will these workers adapt to wearing it? Will they actively participate in postural training? The presented model should become a first objective filter of a broader methodology for device integration in the industry.

Concerning future actions, no specific regulations currently apply to these devices, except three related standards: ISO 13482:2014 for medical robots, ISO/TS 15066:2016 for collaborative robots, and ISO/FDIS 18646–4:2021 for lower-back support robots. It is crucial that regulations consider exoskeletons and motion capture-based ergonomic assessments to study exoskeleton effects.

Considering all the above, ergonomic assessments can provide high value to simulate exoskeletons in actual practice. Integrating exoskeletons in ergonomic evaluations could allow companies to determine the most suitable workstations for using these devices before physically obtaining them. Exoskeletons should become a real and accessible solution for prevention technicians as an additional working tool contributing to the overall objective of improving occupational health.

5. Conclusions

The biomechanical effects of one lumbar and two upper limb exoskeletons were modelled and applied using the Forces ergonomic method for an MSD risk assessment. This model considers the forces and moments applied by exoskeletons to the body in work activities recorded

Table 5
Work activities with and without considering Levitate and Skelex exoskeletons.

ID		Lumb. [%]	Cervical [%]	Shoul.L [%]	Knee L [%]	Shoul.R [%]	Knee R [%]	Cycle time [s]	Gender [M/F]	Height [cm]	Description
13	**B**	2.8	3.8	17.4	4.4	17.3	3.5	56.7	M	185	Handle five workpieces (1.0, 2.0, 2.0, 2.0, and 3.0 kg) overhead in the frontal plane.
	T	1.9	3.8	9.2	4.7	9.1	3.8				
	S	1.9	3.8	7.9	4.8	7.9	4.0				
14	**B**	3.7	5.3	32.7	1.6	31.3	1.1	55.7	M	185	Handle a tool in each hand (2.0 kg) to operate with shoulder elevation movements.
	T	2.5	5.3	15.8	1.7	15.7	1.2				
	S	2.3	5.3	12.6	1.7	12.3	1.2				
15	**B**	3.0	0.9	38.3	1.7	35.3	1.9	66.0	M	185	Handle a tool in each hand (2.0 kg) to operate with shoulder elevation movements.
	T	1.6	0.9	20.0	1.8	18.2	2.0				
	S	1.3	0.9	14.3	1.8	13.2	2.0				
16	**B**	6.1	24.9	25.2	13.4	25.8	12.2	35.0	M	185	Overhead, handle a box (0.5 kg) and a tool to operate (0.5 kg).
	TC	4.6	9.3	22.9	14.2	19.7	13.0				
	S	5.4	24.9	13.0	15.4	12.7	13.7				
17	**B**	5.2	35.3	18.7	14.4	21.4	11.8	35.0	M	185	Overhead, handle a box (0.5 kg) and a tool to operate (0.5 kg).
	TC	3.8	5.2	18.2	15.4	17.5	12.4				
	S	4.8	35.3	11.0	17.1	11.1	14.2				
18	**B**	2.2	23.1	14.4	4.6	22.2	5.3	35.0	M	185	Overhead, handle a box (0.5 kg) and a tool to operate (0.5 kg).
	TC	1.2	6.0	13.4	4.9	17.5	5.7				
	S	2.0	23.1	10.4	5.0	11.2	6.2				
19	**B**	19.3	14.1	20.0	7.5	21.6	5.8	32.7	M	178	Handle and place a workpiece (6.3 kg) on a conveyor belt and use an automatic screw tool.
	T	17.0	14.1	13.1	8.0	17.1	6.0				
	S	17.4	14.1	13.8	8.1	16.6	6.0				
20	**B**	23.1	14.5	25.9	4.7	14.3	6.8	32.7	M	178	Handle and place a workpiece on an overhead horizontal plane; use an automatic screw tool and two push insertions (11.8 kg).
	T	19.8	14.5	23.1	4.9	11.9	7.1				
	S	20.3	14.5	23.4	5.0	12.3	7.1				
21	**B**	15.0	18.0	4.1	12.8	25.2	3.6	32.7	F	163	Handle and place a workpiece on an overhead horizontal plane; use an automatic screw tool and two push insertions (13.1 kg).
	T	13.6	18.0	3.7	13.1	24.2	3.5				
	S	14.1	18.0	3.8	13.8	24.8	3.9				
22	**B**	32.3	20.5	20.4	20.5	19.6	6.7	32.7	F	163	Handle and place a workpiece (6.3 kg) on a conveyor belt and two push insertions (10.1 and 13.2 kg).
	T	25.6	20.5	12.9	19.9	14.3	7.4				
	S	28.7	20.5	16.3	21.5	16.2	7.5				
23	**B**	15.8	12.3	5.3	13.1	22.3	14.3	47.4	M	172	Use an automatic screw tool twice on an engine.
	T	14.7	12.3	4.6	13.7	20.5	14.2				
	S	15.2	12.3	4.8	14.0	20.5	14.6				
24	**B**	8.9	12.7	15.7	10.5	29.2	13.0	33.8	M	170	Use an automatic screw tool twice with horizontal pushing (19.3 kg) and place a workpiece with one screw using an automatic tool with horizontal pushing (12.5 kg).
	T	7.4	12.7	14.8	10.8	28.3	14.0				
	S	7.9	12.7	15.0	11.2	28.5	14.2				

* T: Risks considering Levitate, S: Risks considering Skelex, C: Cervical support.

with motion capture.

It is concluded that the model is applicable in actual practice when conducting ergonomic assessments to provide simple information to reach an objective understanding of the biomechanical effects of exoskeletons. Ergonomic assessments can be a predictive tool to make better decisions for companies. Additionally, although the model has limitations, it establishes a framework that can be extrapolated to other exoskeletons. Thus, this study adds value to the risk prevention workflow and supports exoskeletons as a real solution to reduce MSDs.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ergon.2023.103409.

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