Influence of a passive back support exoskeleton on simulated patient bed bathing: Results of an exploratory study

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Pauline Maurice[a], Félix Cuny-Enault[a] and Serena Ivaldi[a]

[a]Université de Lorraine, CNRS, Inria, LORIA, F-54000 Nancy, France

ABSTRACT

Low-back pain is a major concern among healthcare workers. One cause is the frequent adoption of repetitive forward bent postures in their daily activities. Occupational exoskeletons have the potential to assist workers in such situations. However, their efficacy is largely task-dependent, and their biomechanical benefit in the healthcare sector has rarely been evaluated. The present study investigates the effects of a passive back support exoskeleton in a simulated patient bed bathing task. Nine participants performed the task on a medical manikin, with and without the exoskeleton. Results show that working with the exoskeleton induced a significantly larger trunk forward flexion, by 13 *deg* in average. Due to this postural change, using the exoskeleton did not affect substantially the muscular and cardiovascular demands nor the perceived effort. These results illustrate that postural changes induced by exoskeleton use, whether voluntary or not, should be considered carefully since they may cancel out biomechanical benefits expected from the assistance.

KEYWORDS

Passive exoskeletons; Healthcare ergonomics; Low back demand; Electromyography

PRACTITIONER SUMMARY

Low-back pain is a major concern among nurses, associated with bent postures. We observed that using a passive back-support exoskeleton during the typical patient bed bathing activity results in a larger trunk flexion, without changing muscular, cardiovascular or perceived physical effort.

1. Introduction

Work-related musculoskeletal disorders (WMSDs) are the first cause of occupational diseases in many countries worldwide and represent a major health issue. While many sectors are affected, the prevalence is particularly high among healthcare workers and especially nurses (Schneider, Irastorza, Bakhuys Roozeboom, & Houtman, 2010). In Europe, for instance, more that 25 % of healthcare workers reported back pain, the most common WMSD in this sector (Davis & Kotowski, 2015; Ellapen & Narsigan, 2014). Patient-handling activities, such as transfer or repositioning in bed, have been identified as a main risk factor for WMSDs because they require high force exertion when lifting or moving the patient (Andersen, Vinstrup, Villadsen, Jay, & Jakobsen, 2019; Marras, Davis, Kirking, & Bertsche, 1999). But numerous patient-handling activities requiring lower force exertion are also associated with WMSDs risks because of the awkward postures they involve. Among those, patient bed bathing is one of the most stressful: it requires prolonged static trunk forward bending which causes over-

Corresponding author: Pauline Maurice. Email: pauline.maurice@loria.fr

loading of the low back (Hoogendoorn et al., 2000; Knibbe & Knibbe, 1996; Nelson, Lloyd, Menzel, & Gross, 2003).

In the past decades, ergonomic interventions on the work equipment have been proposed to mitigate this postural risk (Knibbe & Knibbe, 1996). Medical beds with adjustable height are now common, and have been shown to reduce low back loading during patient bed bathing (Nelson et al., 2003). However, those beds alone are not sufficient to suppress the postural effort and associated WMSD risk. Trunk forward bending is still needed, *e.g.*, when reaching to the other side of the bed, or when nurses of different heights work together. For such situations, occupational exoskeletons may be a solution to physically relieve nurses by providing postural support.

Exoskeletons are wearable devices that provide physical assistance to their users through assistive torques and/or structural support. Occupational exoskeletons have recently received great interest from the industry, owing to their potential to reduce physical workload (De Looze, Bosch, Krause, Stadler, & O'sullivan, 2016) and risks of developing WMSDs (Theurel & Desbrosses, 2019). Passive (*i.e.* non-motorized) systems are currently the most common commercial exoskeletons (Voilqué, Masood, Fauroux, Sabourin, & Guezet, 2019). While they cannot generate high force and are therefore mainly dedicated to postural support (*e.g.,* back support during trunk forward flexion, arm support during overhead work), passive exoskeletons have several advantages over active ones: they are lighter, cheaper, less cumbersome, they pose no autonomy issue and present less safety risks for the user (Toxiri et al., 2019). They might therefore be easier to deploy in real world settings, especially in constrained environments such as hospitals.

Several passive back support exoskeletons are now commercially available and have been evaluated for industry-oriented activities in laboratory experiments (Baltrusch et al., 2018; Bosch, van Eck, Knitel, & de Looze, 2016; Jelti et al., 2021; Koopman, Kingma, Faber, de Looze, & van Dieën, 2019; Madinei, Alemi, Kim, Srinivasan, & Nussbaum, 2020; Picchiotti, Weston, Knapik, Dufour, & Marras, 2019; Poon, van Engelhoven, Kazerooni, & Harris, 2019; Schwartz, Theurel, & Desbrosses, 2021; Wei et al., 2020; Whitfield, Costigan, Stevenson, & Smallman, 2014), as well as in field testings (Amandels, het Eyndt, Daenen, & Hermans, 2018; Graham, Agnew, & Stevenson, 2009; Hensel & Keil, 2019). Those studies generally agree on the efficacy of back support exoskeletons in reducing metabolic cost, lumbar muscle activity or perceived back force exertion during activities involving trunk flexion in the sagittal plane. However, they also report adverse effects, such as chest discomfort (Bosch et al., 2016; Hensel & Keil, 2019; Madinei et al., 2020), increased abdominal muscle activity (Baltrusch et al., 2019; Koopman et al., 2019) and kinematics changes (DeBusk, Babski-Reeves, & Chander, 2017; Koopman, Kingma, de Looze, & van Dieën, 2020; Koopman et al., 2019). In addition, those studies show that the magnitude of the observed effects, both positive and negative, are largely task- and exoskeleton-dependent.

On the other hand, few studies have evaluated occupational exoskeletons for the healthcare sector, and most of them focus on the development or evaluation of active systems to assist patient transfer (Ishii, Yamamoto, & Takigawa, 2015; Kuber & Rashedi, 2021; Miura et al., 2021; Tröster et al., 2020). Regarding passive systems, Cha, Monfared, Stefanidis, Nussbaum, and Yu (2020) investigated the needs and barriers for the implementation of an upper-limb exoskeleton to assist surgeons in the operating room. Turja et al. (2020) conducted an acceptance study with nurses using a back support exoskeleton in a geriatric care service, analyzing both the feedback from the nurses and from the patients. While these studies provide valuable information to facilitate the deployment of exoskeletons in the healthcare sector, they do not quantify the biomechanical effects of such assistance on the users. Hwang, Yerriboina, Ari, and Kim (2021) recently reported a reduction in back muscle activity during simulated patient transfer tasks performed with three passive back support exoskeletons, but the reduction differed significantly depending on the exoskeleton and the transfer technique. Our group also observed positive trends when using a back support exoskeleton for a patient manipulation task in an Intensive Care Unit (ICU), though with a small cohort (Ivaldi et al., 2021). Importantly, this previous study indicated that passive back support exoskeletons are a readily available technology that can be deployed in a hospital service for months, with positive effects on the perceived help, both physically and mentally.

Passive back support exoskeletons thus seem like a potential solution to help reduce physical fatigue, and in the long term WMSDs, among healthcare workers (O'Connor, 2021). They may be particularly beneficial in activities where fatigue is caused by postural demand, *e.g.,* patient bed bathing. However, given the task-specific efficacy and functionality of such exoskeletons, it is necessary to assess the envisioned device in relation to the specific activity. This study therefore aimed at evaluating the effects of the Laevo back support exoskeleton on the trunk posture, muscle activity, heart rate and perceived effort, during a simulated patient bed bathing task.

The Laevo was chosen as a test candidate because previous studies showed that its use is compatible with the constraints of the hospital environment (Settembre et al., 2020; Turja et al., 2020). In particular, because of its lightweight structure, it does not constrain the execution of medical gestures such as patient manipulation. The bed bathing task was selected after a 2-weeks observation period in the department of vascular surgery of the University Hospital of Nancy. One experimenter followed nurses of the department during their daily shifts, and sorted all their activities according to their duration, frequency of occurrence, and postural risk following the RULA ergonomics worksheet (McAtamney & Corlett, 1993). The bed bathing task was thereby identified as a suitable candidate to test back support exoskeleton assistance. First, the task involves prolonged trunk forward bending postures (average observed task duration: 8.6 ± 4.1 min; trunk flexion above 20 deg observed in all occurrences). Second, patient bed bathing is performed on a daily basis, in a repetitive way: the nurses visit and bath all the patients of the department one after the other. The task itself and the transfer from one patient room to the next are usually executed at a fast pace. The relevance of this selection was confirmed both by the literature (Knibbe & Knibbe, 1996) and by the nurses' subjective feedback.

2. Material and Methods

A laboratory study was conducted to evaluate the effects of using the Laevo exoskeleton during a simulated patient bed bathing task. Participants performed the task both with and without the exoskeleton, while their physical and physiological states were monitored. The study was approved by INRIA ethical committee COERLE, and was conducted in accordance to the Declaration of Helsinki.

2.1. Participants

A convenience sample of nine healthy males volunteered for the experiment. Their average age was 26.4 yrs (SD: 1.9 yrs), their average stature was 1.79 m (SD: 0.06 m), and their average body mass was 72.1 kg (SD: 9.8 kg). No participant suffered or had

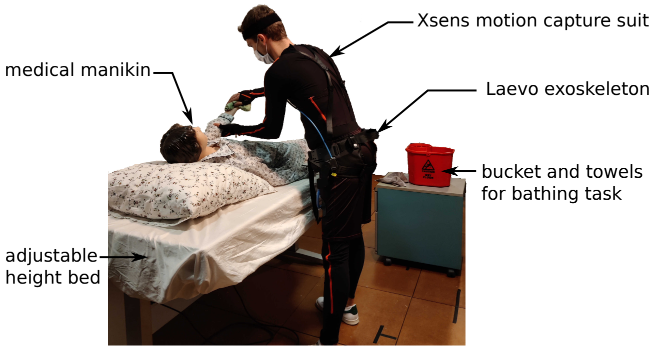


Figure 1. Experimental setup of the patient bed bathing experiment. Participants were equipped with an inertial motion capture suit to record whole-body kinematics, 14 EMG sensors to monitor muscle activity in the back, abdominal and legs, and an EKG sensor to monitor heart rate.

suffered from any musculoskeletal or neurological disease or disorder, according to self-declaration during an interview conducted prior to the experiment. The participants were not expert in the bed bathing task, and were not regular users of exoskeletons either. All were naive to the purpose of the study. Participants gave written informed consent before starting the experiment.

2.2. Patient bed bathing task

The bed bathing task was simulated in a laboratory environment (Fig. 1). The task consisted in 10 steps corresponding to washing different parts of the body in a fixed order, according to the standard bed bathing procedure: 1. prepare the material (15 sec); 2. wash and dry the face (30 sec); 3. arms (50 sec); 4. legs (60 sec); 5. torso and genitals (60 sec); 6. turn the patient on the side (15 sec); 7. wash and dry the back and buttocks (60 sec); 8. place a diaper (10 sec); 9. turn the patient on the back (15 sec); 10. attach the diaper (15 sec). The duration of each step was imposed, and guided by an audio recording. The whole task lasted 5 min and 30 sec. The patient was simulated with a manikin designed for nurse training (66fit female patient care manikin XC-401, made of washable PVC). Because of its light weight (7.6 kg), weights were added to its torso (10 kg), arms (1 kg at each wrist) and legs (4 kg at each ankle) such that the total manikin mass was 27.6 kg. While the manikin was overall lighter than a real patient, the effort required to manipulate its limbs was deemed representative of a conscious patient. The manikin was placed on a mattress set on an adjustable height table. The table height was adjusted for each participant, such that they touched the table (below the mattress) when standing straight with their arms fully extended along the body and fists closed. Participants were instructed to remain on the same side of the bed during the task, according to usual bed bathing practice. They were, however, free to choose their exact placement with respect to the bed and could move during the task.

2.3. Experimental procedures

Since participants were novice to the bed bathing task, they were asked to watch a tutorial video, made for professional nurse training, describing the task before coming to the experimental session. Upon arrival to the experimental session, participants provided their written informed consent. An experimenter with training and work ex-

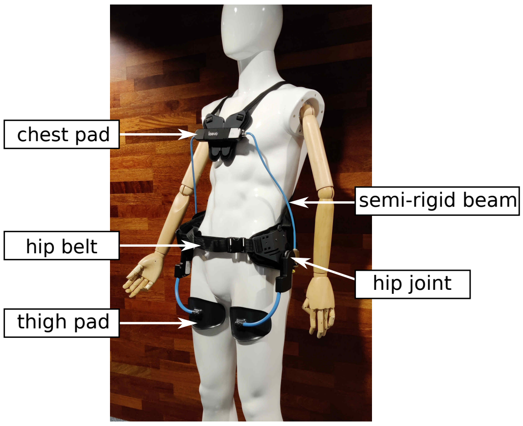


Figure 2. Laevo v2.5 passive back support exoskeleton used in the experiment. A spring embedded in the hip joint generates a supporting extension moment when the user bends forward.

perience as a nurse then demonstrated the task, and supervised participants while they practiced and familiarized with the manipulation of the manikin. Next, participants were fitted with the exoskeleton and familiarized with it. The familiarization phase with the exoskeleton lasted about 10 min, during which participants were asked to move around and manipulate the manikin similarly to what they would do during the bed bathing task. This duration was deemed sufficient to get accustomed to the device, based both on the simplicity of use of the Laevo, and on the participants' verbal feedback. Participants were then equipped with the motion capture, EMG and EKG sensors. Next, participants took a rest period during which their baseline heart rate was measured for 2 min. The experiment then started.

All participants performed the bed bathing task both wearing the exoskeleton (WE session) and without wearing it (NE session), in random order. Five participants started with the NE session, and the four others started with the WE session, to counter-balance potential effects of residual fatigue from one condition to another. Each session consisted in 5 trials. Between each trial, participants performed 10 back and forth walking motions (15 m between the start and end points). This side task was added to replicate the operating conditions of the bed bathing task realized during the nurses' shifts, where they walk from one patient's room to another between consecutive bed bathing tasks. Between the two sessions, participants took a 10-minute break. The overall duration of the experimental session (including equipment) was about 3 hours.

2.4. Exoskeleton

The Laevo v2.5 (Laevo, Rijswijk, Netherlands) passive back support exoskeleton was used in this study. The Laevo is a commercially available exoskeleton designed to provide postural support in postures involving trunk forward bending, initially for applications in the industrial sector. The Laevo consists of 2 semi-rigid beams (one on each side) attached at one end to a chest pad, and at the other end to the upper part of the exoskeleton hip joint (Fig. 2). The lower part of the hip joint is connected to a thigh pad. A gas spring embedded in the hip joint generates a supporting extension moment at the low back when the user bends forward, which results in a support force applied on the chest and reported on the thighs. The Laevo is attached to the user's body with shoulder straps and a hip belt. The total mass of the system is 2.5 kg.

Different sets of beams designed for different human heights were used to fit the exoskeleton to each participant's morphology. The engagement angle of the Laevo (trunk flexion angle at which the assistance starts) was set to its minimal value for all participants. The Laevo v2.5 includes a button to manually disengage the assistance by unlocking the thigh pads. This facilitates walking with the exoskeleton, and was used for the walking phases between each bed bathing trial.

2.5. Instrumentation

Participants were equipped with several sensors described hereafter to record their trunk posture, back, abdominal and leg muscle activities, and heart rate. Questionnaires were also used to collect subjective data. Participants wore the sensors throughout the whole experimental session, but data were recorded only during the bed bathing trials, and not during the walking phases.

2.5.1. Electromyography

Muscle activity of abdominal, back and leg muscles was monitored with a Delsys Trigno Wireless surface electromyography (sEMG) system (Delsys Inc., Natick, MA, USA). Surface electrodes were placed following the SENIAM recommendations (Hermens et al., 1999), bilaterally over the erector spinae longissimus lumborum (LL), erector spinae longissimus thoracis (LT), erector spinae iliocostalis lumborum (IL), latissimus dorsi (LD), rectus abdominis (RA), external oblique (OE) and biceps femoris (BF). Medical strap was placed around the electrodes to make sure they would not move. EMG signals were recorded at 1111 Hz with the Delsys EMGworks software. EMG signals were subsequently band-pass filtered (4^{th} order Butterworth filter with 20-450 Hz cut-off frequencies), detrended and rectified. The envelop of the signal was then extracted using a low-pass filter (4^{th} order Butterworth filter with a 10 Hz cut-off frequency). Finally, the signal was normalized by the maximum value reached during the experiment (including both sessions) for each participant. This allowed to work with normalized EMG data without a maximum voluntary contraction (MVC) calibration, which could not be performed due to time constraints.

2.5.2. Kinematics

Participants were equipped with an Xsens MVN Link inertial motion tracking system consisting of 17 IMUs to record whole-body kinematics (Xsens, Enschede, The Netherlands). IMUs were attached to the body with the provided straps and T-shirt. Data were recorded with the MVN software at 240 Hz (version 2021.0.0). For each participant, the system was calibrated at the beginning of the experimental session following the MVN calibration procedure. The trunk forward flexion, lateral flexion and twisting angles were extracted from the Xsens data, using the Cartesian orientation of the Xsens avatar T8 segment (upper back). The T8 segment was chosen because it is the only segment of the Xsens trunk model to which an IMU is directly attached, hence its orientation was deemed more reliable.

2.5.3. Heart rate

A Delsys Trigno EKG Biofeedback sensor was placed on the participants' chest to monitor their heart rate (Delsys Inc., Natick, MA, USA). Data were recorded at 1925 Hz with the Delsys EMGworks software. The instantaneous heart rate was subsequently computed offline with the Delsys EMGwork software. Finally, the heart rate signal of each participant was normalized by the participant's average heart rate value measured during the baseline rest condition.

2.5.4. Perceived effort

After each trial, participants answered a Borg CR10 questionnaire (Borg, 1998) to estimate their perceived level of exertion in the 7 following body parts: neck, back, right/left shoulder and upper-arm, right/left forearm and hand, legs. These body parts were selected to check if i) the Laevo had a positive effect on the back where the assistance is provided, and ii) the Laevo did not cause detrimental effects on other body parts, due either to the force transfer imposed by the exoskeleton design, or to a postural modification induced by its use. The questionnaire was filled before starting the walking phase between trials.

2.6. Statistical analysis

The independent variables of the study were the *intervention* (WE/NE) and the *trial* number. The dependent variables were the 3 trunk angles, the normalized heart rate, the normalized activities of the 14 recorded muscles, and the 7 scores of the Borg CR10 questionnaire. Root mean square (RMS) (resp. mean) values of the time-series of each trial were used in the statistical analyses for the kinematics and EMG (resp. heart rate) data. In addition, the EMG data were further analyzed for each step of the bed bathing task separately (i.e., computing an RMS value for each of the 10 steps of the task). The bed bathing task is indeed dynamic with several steps involving different postures and motions. Muscle activity, and consequently the effect of the exoskeleton, might therefore vary from one step (subtask) to another. The heart rate data of 3 out of 9 participants were corrupted, due to a defect in the sensor. Those 3 participants were therefore excluded from the subsequent heart rate analysis. No other data were excluded.

Kinematics, heart rate and EMG data were checked for normality with the Shapiro-Wilk test. All distributions except the trunk flexion matched the normality assumption. The trunk flexion data were transformed using a logarithmic transformation to obtain a distribution matching the normality assumption. The transformed data were then analyzed in the same way as the normal data. A two-way repeated-measures analysis of variance (ANOVA) was conducted on kinematics, heart rate and EMG data to evaluate the main effect and interaction of the exoskeleton and the trial number. *Intervention* (WE/NE) and *trial* were therefore set as fixed factors, and *participant* as a random factor. The Greenhouse-Geisser correction for sphericity was applied when needed. The effect size is reported using the ω^2 coefficient. When the ANOVA revealed a significant effect, pairwise multiple comparison post-hoc tests with Bonferroni corrections were conducted. Data from the Borg CR10 questionnaires were analyzed with non-parametric tests due to their ordinal nature. The effects of each of the 2 factors *intervention* and *trial* were analyzed separately. Friedman tests were performed separately for the WE and NE conditions, to assess the effect of *trial* within each condition. When a significant effect was detected, post-hoc multiple comparison tests were conducted. The effect of *intervention* was assessed with a Wilcoxon signed-rank test performed for each of the 5 trials separately. A significance level of 5% was adopted for all statistical tests. Analyses were performed with the R software.

3. Results

3.1. Muscle activity

Fig 3 displays the distribution across participants of the activity of the 14 muscles that were recorded, for both conditions WE and NE and for all trials. The ANOVA results are summarized in Table 1. The ANOVA revealed a significant main effect of *intervention* on muscle activity only for the right LL muscle. The muscle activity was reduced by 16 % in average when using the exoskeleton compared to without it. The effect size is however small ($\omega^2 = .023$).

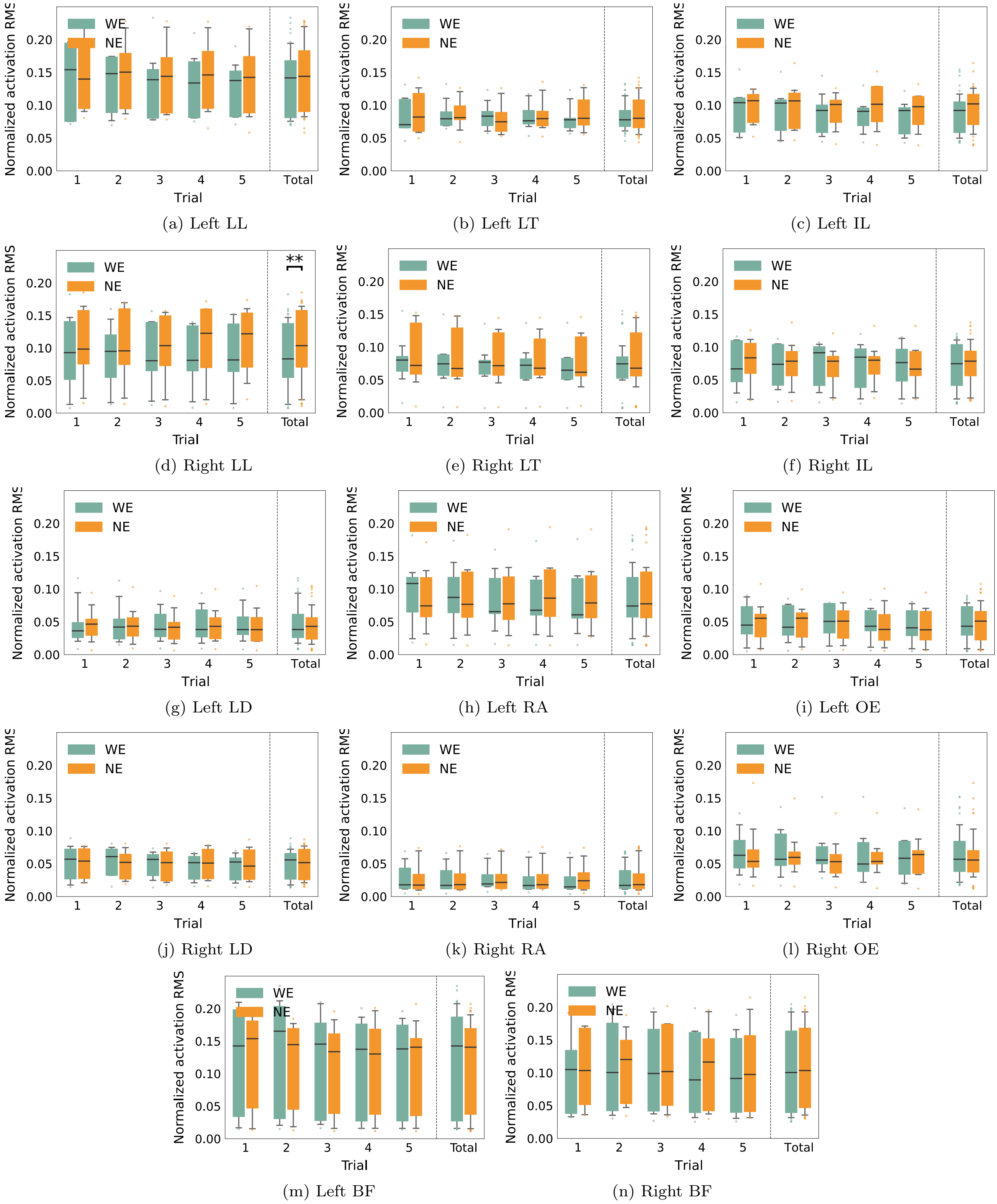
The ANOVA also revealed a main effect of *trial* for the left LL, right LT, right LD and left and right OE muscles, as well as an interaction effect for the right LD. Post-hoc tests revealed a statistically significant difference between trials 1-5 ($p < .001$) and 2-5 ($p = .007$) for left LL; trials 1-3 (p=.020), 1-4 ($p = .009$), 1-5 ($p < .001$) and 2-5 ($p = .026$) for right LT; trials 1-5 ($p = .046$) for right OE; and trials 2-5 WE ($p = .029$) for right LD. No statistically significant difference was observed in the post-hoc pairwise comparison for the *trial* factor of left OE and right LD muscles, despite the effect revealed by the ANOVA. All main and interaction effects of *trial* in the ANOVA are, however, associated with very small effect sizes ($\omega^2 < .01$).

Table 2 summarizes the results of the ANOVA conducted on the EMG data for each step of the bed bathing task separately. Only the effect of the *intervention* factor is reported, for the sake of readability and because it is the main focus of the study[1]. The ANOVA revealed a significant effect of *intervention* on muscle activity of several of the erector spinae muscles (LL left, LL right, LT left and/or IL left depending on the step), but only during the second half of the task starting from when the manikin is turned on its side. Left erector spinae muscles were affected at different levels (longissimus lumborum, longissimus thoracis and iliocostalis lumborum), while on the right side only the longissimus lumborum was affected. In all cases, the muscle activity was reduced when using the exoskeleton compared to without it, by 12 to 17 % in average for LL left, 13 to 19 % for IL left, 8 % for LT left, and 32 to 44 % for LL right. No significant effect of the exoskeleton was detected on any other muscle, except on the right BF in the first step of the task. Effect sizes are however small for all muscles and steps ($\omega^2 \leq .052$).

3.2. Kinematics

Fig 4 displays the distribution across participants of the trunk angles, for both conditions WE and NE and for all trials. The ANOVA results are summarized in Table 1. The ANOVA did not reveal any significant effect of *trial* nor any interaction for any of the 3 trunk angles. Conversely, the ANOVA revealed a main effect of *intervention* on all 3 trunk angles. This effect is associated to a large effect size for the forward flexion ($\omega^2 = .53$) and twisting ($\omega^2 = .32$) and a medium effect size for the lateral

[1] A main effect of the *trial* factor and/or an interaction effect were detected for some muscles and some steps, however the effect sizes were all very small.



(a) Left LL (b) Left LT (c) Left IL

(d) Right LL (e) Right LT (f) Right IL

(g) Left LD (h) Left RA (i) Left OE

(j) Right LD (k) Right RA (l) Right OE

(m) Left BF (n) Right BF

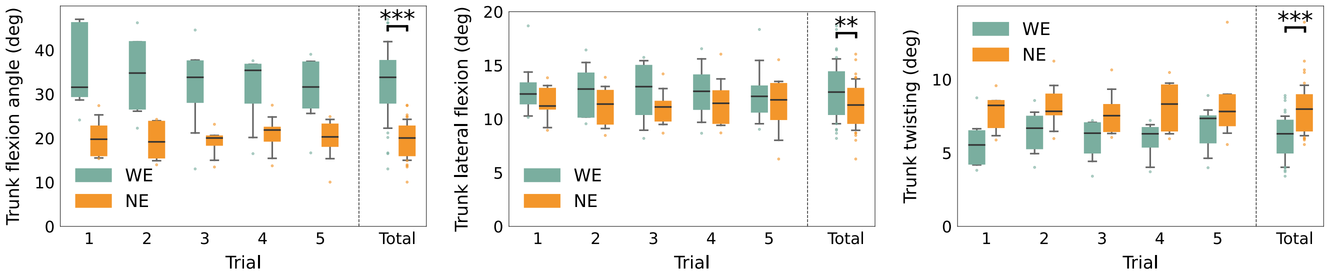
Figure 3. Distribution across participants of the RMS (root mean square) value of the normalized activity of the 14 recorded muscles, for the two conditions WE (with exoskeleton) and NE (no exoskeleton), by trial (trial 1 to 5) and for all trials together (total). Limits of the boxplots correspond to the 10th and 90th percentiles. Significant differences between the NE and WE conditions are indicated on the graphs. LL: erector spinae longissimus lumborum, LT: erector spinae longissimus thoracis, IL: erector spinae iliocostalis lumborum, LD: latissimus dorsi, RA: rectus abdominis, OE: external oblique, BF: biceps femoris.

Table 1. Summary of ANOVA results (F-value, p-value and effect size ω^2) for trunk kinematics (top rows) and for muscle activity of the 14 recorded muscles (bottom rows), in terms of main and interaction effects of the *intervention* and *trial* factors. Degrees of freedom are reported in the F-value column headers. Significant effects are highlighted in bold font. LL: erector spinae longissimus lumborum, LT: erector spinae longissimus thoracis, IL: erector spinae iliocostalis lumborum, LD: latissimus dorsi, RA: rectus abdominis, OE: external oblique, BF: biceps femoris.

	intervention		*trial*		*intervention*trial*	
	F-value(1,8)	p-value (ω^2)	F-value(4,32)	p-value (ω^2)	F-value(4,32)	p-value (ω^2)
Forward flexion	**125.1**	**< .001 (.53)**	2.03	.18 (.017)	2.16	.16 (.017)
Lateral flexion	**14.3**	**.005 (.078)**	.32	.86 (< .001)	.12	.97 (< .001)
Twisting	**23.7**	**.001 (.32)**	2.13	.10 (.023)	.43	.65 (< .001)
LL left	5.22	.052 (.011)	**6.04**	**< .001 (.007)**	1.64	.19 (.001)
LL right	**15.6**	**.004 (.023)**	1.01	.42 (< .001)	1.09	.38 (< .001)
LT left	.56	.48 (< .001)	1.18	.34 (< .001)	.85	.44 (< .001)
LT right	1.70	.23 (.005)	**7.58**	**< .001 (.007)**	.36	.83 (< .001)
IL left	4.70	.062 (.019)	2.47	.12 (.005)	.87	.44 (< .001)
IL right	.46	.52 (< .001)	.69	.60 (< .001)	.59	.51 (< .001)
LD left	.23	.65 (< .001)	.92	.47 (< .001)	.30	.87 (< .001)
LD right	.083	.79 (< .001)	**2.91**	**.037 (.003)**	**2.72**	**.047 (.004)**
RA left	.86	.38 (< .001)	.72	.59 (< .001)	2.47	.13 (.002)
RA right	1.74	.22 (< .001)	.53	.72 (< .001)	.87	.49 (< .001)
OE left	.22	.65 (< .001)	**2.74**	**.046 (.002)**	.025	.99 (< .001)
OE right	.91	.37 (< .001)	**3.55**	**.017 (.003)**	.91	.41 (< .001)
BF left	2.38	.16 (.001)	2.19	.093 (< .001)	3.08	.064 (.001)
BF right	.42	.54 (< .001)	.91	.42 (< .001)	.75	.47 (< .001)

Table 2. ANOVA results for muscle activity for each of the 10 steps of the bed bathing task, in terms of main effect of the *intervention* factor (the steps are defined in Section 2.2). Only muscles for which a significant effect was detected for at least one of the steps are listed. Results are reported as F-value(1,8), p-value and effect size (ω^2) only for significant effects, and in parentheses for effects close to the significance level of .05. LL: erector spinae longissimus lumborum, LT: erector spinae longissimus thoracis, IL: erector spinae iliocostalis lumborum, BF: biceps femoris.

		1.prepare	2.face	3.arms	4.legs	5.torso	6.turn	7.back	8.diaper	9.turn	10.attach
LL left	F						12.7	9.16	6.53		-
	p	-	-	-	-	-	.007	.016	.034	-	-
	ω^2						.022	.015	.042		
LL right	F					(4.91)			19.5	8.50	(5.13)
	p	-	-	-	-	(.058)	-	-	.002	.019	(.053)
	ω^2					(.047)			.052	.022	(.017)
LT left	F						9.91				
	p	-	-	-	-	-	.014	-	-	-	-
	ω^2						.007				
IL left	F						7.25	6.13		5.70	6.28
	p	-	-	-	-	-	.027	.038	-	.044	.037
	ω^2						.050	.028		.031	.043
BF right	F	8.22									
	p	.021	-	-	-	-	-	-	-	-	-
	ω^2	.045									



(a) Forward flexion (b) Lateral flexion (c) Twisting

Figure 4. Distribution across participants of the RMS (root mean square) value of the three trunk angles, for the two conditions WE (with exoskeleton) and NE (no exoskeleton), by trial (trial 1 to 5) and for all trials together (total). Limits of the boxplots correspond to the 10th and 90th percentiles. Significant differences between the NE and WE conditions are indicated on the graphs.

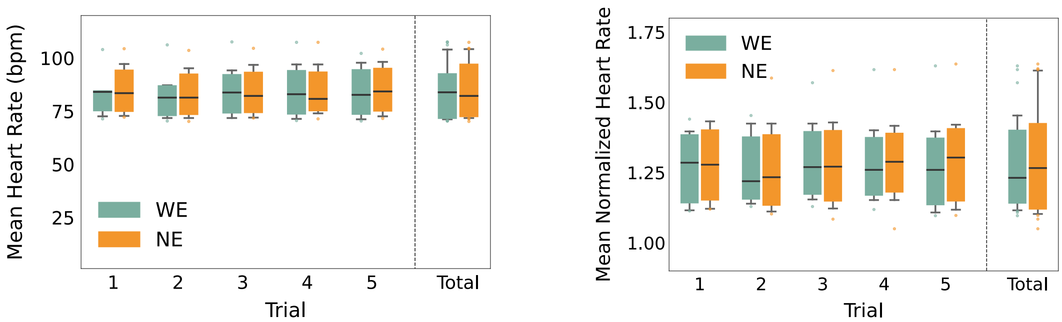
(a) Participant 1 (b) Participant 2 (c) Participant 3 (d) Participant 4

Figure 5. Four participants performing the bed bathing task without (left of each subfigure) and with (right of each subfigure) the exoskeleton. Pictures represent different phases of the bathing task across participants, but for a same participant the pictures WE (with exoskeleton) and NE (no exoskeleton) correspond to the same moment in the task. Participants tended to adopt a posture with larger trunk flexion when using the exoskeleton.

flexion ($\omega^2 = .078$), according to Kirk's effect size recommendations (Kirk, 1996). The trunk forward and lateral flexion angles were both larger when using the exoskeleton, respectively by $13.4\,deg$ and $1.3\,deg$ in average (Fig. 5) (average and SD for forward flexion NE: $19.8\pm4.0\,deg$, WE: $33.2\pm9.2\,deg$; for lateral flexion NE: $11.3\pm2.0\,deg$, WE: $12.7\pm2.6\,deg$). Conversely, the trunk twisting angle was smaller by $1.9\,deg$ in average when using the exoskeleton (average and SD NE: $8.0\pm1.7\,deg$; WE: $6.1\pm1.4\,deg$).

3.3. Heart rate

Fig. 6 displays the distribution across participants of the heart rate values (raw and normalized by the baseline rest value), for both conditions WE and NE and for all trials. The ANOVA did not reveal any significant main effect on the normalized heart rate for any of the 2 factors (*intervention:* $F(1,5) = .89$, $p = .39$, $\omega^2 < .001$; *trial:* $F(4,20) = 1.10$, $p = .39$, $\omega^2 < .001$), nor any interaction effect ($F(1.3,6.3) = .72$, $p = .46$, $\omega^2 < .001$).



(a) Heart rate (b) Normalized heart rate

Figure 6. Distribution across participants of the mean value of the raw (left) and normalized (right) heart rate, for the two conditions WE (with exoskeleton) and NE (no exoskeleton), by trial (trial 1 to 5) and for all trials together (total). Limits of the boxplots correspond to the 10th and 90th percentiles.

Table 3. Median and IQR (Interquartile Range) values of the Borg scores for the two conditions WE (with exoskeleton) and NE (no exoskeleton) (all trials are considered).

	NE Median (IQR)	WE Median (IQR)
Back	3(1–4)	2 (0.5–3)
Neck	1 (0–2)	1 (0–2)
Legs	1 (1–3)	2 (1–3)
Right arm	1 (0.5–2)	2 (0.5–2)
Right forearm	1 (0.5–2)	2 (0.5–2)
Left arm	1 (0.5–2)	0.5 (0.5–2)
Left forearm	1 (0.5–2)	1 (0.5–2)

Table 4. Results of the Friedman tests performed to assess the effect of *trial* on the perceived effort, in the two conditions WE (with exoskeleton) and NE (no exoskeleton) separately. Degrees of freedom are reported in the χ^2 column header. Significant effects are highlighted in bold font.

	NE		WE	
	$\chi^2(4)$	p-value	$\chi^2(4)$	p-value
Back	**20.55**	**< .001**	**18.68**	**< .001**
Neck	**10.22**	**.037**	7.16	.13
Legs	**11.32**	**.023**	8.41	.078
Right arm	2.40	.66	7.08	.13
Right forearm	2.40	.66	6.07	.19
Left arm	2.54	.64	9.75	.051
Left forearm	2.86	.58	7.29	.12

3.4. Perceived effort

The Wilcoxon tests did not reveal any significant effect of *intervention* on any of the perceived efforts, for any of the 5 trials ($p > .1$ for all tests). There is however a small –though not significant– trend to reduced perceived effort in the back when using the exoskeleton (Table 3).

Table 4 summarizes the results of the Friedman tests. A significant effect of *trial* was detected for the back effort, both with and without exoskeleton. For both conditions WE and NE, post-hoc tests revealed a significant difference between trials 1-5. The perceived effort was always higher in the late trials compared to the early trials (median and IQR: trial 1-NE: 3(1–3), trial 5-NE: 4(3–4), trial 1-WE: 2(.5–2), trial 5-WE: 3(2–

4)). The Friedman tests also revealed a significant effect of *trial* on the neck and legs efforts, in the NE condition. However, no statistically significant difference was observed between any of the trials in the post-hoc comparisons.

4. Discussion

This study investigated the effects of the Laevo during a simulated patient bed bathing task. The Laveo is a passive back support exoskeleton designed to provide postural support during forward bent postures, which are frequent in bed bathing. Neither heart rate, nor activity of back (except for right LL), abdominal and leg muscles, nor perceived effort were substantially affected by the use of the exoskeleton. Conversely trunk kinematics was strongly modified when performing the task with the exoskeleton. Participants flexed their trunk more when using the Laevo, while they reduced trunk twisting. These results are further discussed hereafter.

4.1. Effects on physical strain

Muscle activity was largely unaffected by the use of the Laevo when considering the overall bed bathing task. Only the right LL muscle showed reduced activity by about 16 % with the exoskeleton. Analyzing separately each step of the task revealed that the Laevo actually reduced muscle activity of several of the erector spinae muscles in various steps of the bed bathing task, by up to 19 % for the left side and up to 44 % for the right side. The relatively short duration of the steps where activity was reduced, combined with the moderate value of the reduction, however explain the absence of significant effect on the left side erector spinae muscles at the whole task level. Significant reductions in back muscle activities were observed only in the second half of the task, starting at step 6. This may be due to the fact that the manikin was then lying on its side at the far edge of the bed (in steps 6, 7, 8, and partly 9), hence participants had no choice but to bend forward to reach the manikin. Conversely, in steps 1 to 5, the manikin was closer to the participant who therefore did not necessarily have to bend forward significantly. Given its design, the Laevo is more likely to have an effect when the torso is further inclined, since the support it provides increases with the torso inclination angle (up to a limit) (Koopman et al., 2019).

The different trends between the right and left side muscles may be explained by the asymmetry of the task: all participants were right-handed and manipulated the washcloth and towel with their right hand, hence having to extend forward their right side more in most of the steps, while the left hand was used to maintain the manikin's manipulated limb. This may explain the significant effect observed only on a right-side back muscle (LL) at the whole task level. Conversely, in steps *6.turn* and *7.back* where only the activity of the left side erector spinae muscles was significantly reduced, participants had to maintain the manikin on its side with their left hand while working with their right hand, which required a slightly larger extension of their left side. The small reduction in trunk twisting induced by the use of the Laevo might also have played a role in the unilateral reduction of back muscle activity during asymmetrical steps. In step *8.diaper*, both LL muscle activities were reduced when using the Laevo, likely because this step required a large and symmetrical forward flexion of the trunk to place the diaper below the manikin with both hands. Overall, the EMG results are in agreement with the perceived effort reported by participants: no significant change was observed between the two conditions, but a trend towards reduced effort in the back when using the exoskeleton exists, consistent with the reduction in erector spinae –and mainly right LL– activity.

Other studies reported an absence of systematic effect of the Laevo on muscle activity, such as Baltrusch *et al.* in a lifting task (Baltrusch et al., 2018), and Koopman *et al.* in a static holding task with bending range and exoskeleton settings matching ours (Koopman et al., 2019) Madinei *et al.* also observed no effect when considering only male participants, as is the case here (Madinei et al., 2020). Conversely, several studies did report a reduction of back muscle activity when using the Laevo in various tasks (Koopman et al., 2020; Madinei, Kim, Alemi, Srinivasan, & Nussbaum, 2019), sometimes associated with lower perceived discomfort (Bosch et al., 2016). A reduction in muscular demand was also achieved with other back support exoskeletons, such as the MeBot-EXO (Wei et al., 2020) or the PLAD (Graham et al., 2009). The diversity in tasks and experimental conditions is a plausible explanation to the lack of consistency in the results across studies. But most importantly, in the aforementioned studies, the trunk posture –when monitored– was generally similar with and without exoskeleton. Therefore, their results cannot directly be compared with ours, as lumbar flexion has a major effect on back muscle activity.

In the present study, the trunk forward flexion was larger by about $13\,deg$ when using the exoskeleton (while always remaining smaller than $90\,deg$). This kinematic change generates a larger gravity-induced torque at the L5/S1 joint, which should increase back extensor muscle activity if no assistance is provided. Increased trunk flexion can be associated with a decrease in back muscle activity when the flexion-relaxation phenomenon occurs: when muscles are stretched beyond a limit, the passive structures take over and generate the force, such that the active force –hence the muscle activity– decreases (Floyd & Silver, 1955). However, this explanation can be ruled out here, because the trunk flexion was not sufficient to trigger the flexion-relaxation phenomenon (Koopman et al., 2019). In addition, the increase in gravity-induced torque at the L5/S1 joint associated with a change in trunk forward flexion from $20\,deg$ (NE) to $33\,deg$ (WE) is of the same magnitude as the support torque provided by the Laevo for a $33\,deg$ flexion angle (according to the calibration curve published by Koopman et al. (2019)). Hence the absence of increase in back muscle activity despite a larger trunk flexion is consistent with the assistive effect of the exoskeleton.

4.2. Effects on cardiovascular strain

Heart rate was not affected neither positively nor negatively by the use of the Laevo. Those results are in line with those of Luger *et al.*, who observed no influence of the Laevo on heart rate in three different tasks (Luger, Bär, Seibt, Rieger, & Steinhilber, 2021). They are also consistent with the very limited changes we detected in muscle activity. However, it must be noted that the duration of the experimental session was shorter than a real work shift (the number and duration of the repetitions in the simulated task were chosen as a compromise to best match the values observed at the hospital, while keeping the overall duration of the experiment reasonable for participants). In addition, the study was conducted on a cohort of young and healthy participants. Since the activity was of low to moderate intensity, fatigue might not have developed significantly, as suggested by the absence of change in heart rate across repetitions. Yet, the slight increase in back perceived effort at the end of the experimental session (both with and without exoskeleton) suggests that fatigue might have developed with a longer session, since perceived effort has been showed reliable to assess fatigue (Sood, Nussbaum, & Hager, 2007).

4.3. Effects on kinematics

Trunk posture was affected in several ways by the use of the Laevo during the bed bathing task. Trunk twisting was reduced by about 2 *deg* when using the exoskeleton. This may be due to the rigidity of the Laevo along this direction, which makes twisting harder and prevents the user from doing large twisting motions. Reduced twisting is positive, since excessive twisting can damage the spine structures (Bogduk, 2005) and should be avoided according to ergonomics guidelines (McAtamney & Corlett, 1993). The magnitude of reduction is however small, and twisting motions are not extreme during the bed bathing task. The impact of such postural change on the user's health is therefore questionable.

More importantly, the use of the Laevo induced a large increase in trunk forward flexion, from 20 *deg* in average without the exoskeleton to 33 *deg* with it. While postural changes are not systematically observed (e.g., Madinei et al. (2020)), this finding is aligned with those reported by several other studies on the Laevo, in a patient transfer task (Hwang et al., 2021), in lifting tasks (Koopman et al., 2020; Schwartz et al., 2021), and in a manual assembly task (Bosch et al., 2016). Those studies consistently observed an increase in trunk forward flexion when wearing the Laevo, often around 5 *deg* but the magnitude varies (in some studies, the trunk inclination was loosely constrained, which might have limited the extent of the postural change). A similar phenomenon was reported with other back support exoskeletons (Hwang et al., 2021). Postural adaptation in a way that seemingly contradicts ergonomics guidelines was also observed with other types of exoskeletons. Studies on arm support exoskeletons reported increased shoulder abduction (Maurice et al., 2019) and elevation (McFarland, McDonald, Whittaker, Callaghan, & Dickerson, 2022) when using an exoskeleton.

The reason underlying those postural changes remains, however, unclear. In the present study, the increased trunk flexion may result from a structural constraint of the exoskeleton. Specifically, the thigh pads of the Laevo might have prevented the participants to lean against the bed, forcing them to stand further away from the manikin, and hence to bend forward further. But the postural change may also be a choice (not necessarily conscious). With the assistance provided by the exoskeleton, the user can bend forward further without additional effort, as the support torque increases –up to a limit– with the flexion angle (Koopman et al., 2019). Postures that were avoided without the exoskeleton because they required too much physical effort may then be adopted if they are more favorable with respect to other criteria. For instance, being further bent may enable participants to manipulate more easily and comfortably the patient. In particular, a further bent posture allows participants to reduce their elbow extension during the bathing gestures, since the shoulder-patient distance is reduced. This should increase the hand manipulability, thereby resulting in more efficient and comfortable arm postures (Jacquier-Bret, Gorce, & Rezzoug, 2012). The fact that increased trunk flexion was observed in several other studies where the environment was less constrained suggests that it is rather the result of a choice due to the more favorable mechanical demand created by the exoskeleton, as suggested in Schwartz et al. (2021) and Bosch et al. (2016). However, the present study does not allow to conclude with certainty.

Yet, even if the postural change is a choice, its biomechanical consequences on health and WMSDs risks remain to be investigated (Theurel & Desbrosses, 2019). Trunk forward flexion is considered a risky posture from an ergonomics standpoint, because it causes spine loading (Hoogendoorn et al., 2000). But ergonomics guidelines were not designed with robotic and exoskeletal assistance in mind. Is extra trunk flexion harmful if it is associated with postural support from an exoskeleton? In the present study, the increase in trunk flexion did not cause any significant increase in back muscle activity, which is closely related to spinal compressive forces. Nevertheless, muscular effort may not be the sole cause of back WMSDs. For instance, in the case of arm support exoskeletons, arm elevation itself is risky because it causes subacromial impingement and tendon damage due to the motion of the humeral head. But how the effects of increased arm elevation combines with reduced muscular effort in terms of WMSDs risks remains unknown (McFarland et al., 2022). Given the growing interest in occupational exoskeletons and the availability of commercial products, there is a strong necessity to analyze the ergonomics consequences of postural changes associated with exoskeleton use, and provide updated ergonomics standard.

4.4. Limitations

Our results suggest that using the Laevo during the bed bathing task induces strong changes in the trunk posture, but limited changes in terms of physiological effort. Nevertheless this study presents some intrinsic limitations. Most importantly, participants were not nurses, but engineers and graduate students novice to the bed bathing task[2]. Though participants watched a video tutorial showing the task prior to participating in the experiment, it is possible that professional nurses would perform the technical gesture differently, resulting in different postures. For instance, we cannot guarantee that the posture adopted by participants allowed a manipulation that would be both efficient and comfortable for a real patient, even more so since the patient was in fact a manikin.

Aside from the expertise, our participants also differed from professional nurses in that they were males, whereas the vast majority of nurses are females. This cannot be ignored, since gender-differences in exoskeleton effects have been previously reported. For instance, Madinei *et al.* observed a larger reduction in back muscle activity for women, during a lifting task with the Laevo (Madinei et al., 2020). Most importantly, several studies reported significant chest discomfort when using the Laevo, due to the pad pressing against the chest when assistance is provided (Bosch et al., 2016; Hensel & Keil, 2019). This effect is more prominent for women (Madinei et al., 2020), which might affect the acceptance within the nurses population, but also lead to the adoption of different postures to minimize discomfort. A recent study by Schwartz *et al.* indeed suggested that the discomfort caused by the exoskeleton may explain why trunk flexion was larger among male users compared to female users (Schwartz et al., 2021).

Lastly, the current study focused on short-term effects of the Laevo. Long-term effects should be investigated, though seldomly done for occupational exoskeletons so far. Muscle weakness due to prolonged use of exoskeletons or orthoses is often raised as a concern (Azadinia et al., 2017). But on a shorter timescale, motor adaptation related to familiarization with the exoskeleton may also happen and affect the mea-

[2]For Covid-19 related sanitary reasons, we were not allowed to invite participants from the hospital to participate in the lab study, despite the ethical approval of the study. Hence, we had to recruit participants locally within the limited population authorized to access the lab premises, which strongly constrained the participants' profiles.

sured biomechanical effects (Bastide, Vignais, Geffard, & Berret, 2019). Though the participants in the current study did practice with the Laevo for a few minutes prior to the experiment, the duration of the familiarization process for such exoskeletons remains unclear, and might involve different time scales.

Owing to the aforementioned limitations, the present results should be considered carefully. But this study is a first step in the evaluation process. It needs to be followed by field testing with real end-users, to assess not only biomechanical effects on experts, but also acceptability and feasibility in hospital settings. In this context, a preliminary lab study is a strong asset to gain access to hospitals for field testing.

5. Conclusion

This study presented an assessment of the Laevo passive back support exoskeleton to assist nurses during patients' bed bathing. A lab study was conducted in which novice participants performed the bed bathing task on a medical manikin, both with and without the exoskeleton. When using the Laevo, participants adopted a posture with significantly larger trunk forward flexion, whereas effort remained mostly unchanged thanks to the support provided by the exoskeleton. Whether the postural change is a voluntary choice offered by the exoskeleton, or a constraint imposed by it remains an open question. In addition, the long term consequences of such a change in terms of WMSDs are yet to be investigated. Nevertheless, these results shed light on an important phenomenon associated with exoskeleton use: postural changes, which may cancel out biomechanical benefits expected from the assistance.

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Disclosure statement

The authors report there are no competing interests to declare.

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Data availability statement

The data collected for our study are available for reviewers upon request (to preserve the reviewers anonymity we will send the link of the data container to the Editors request).

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