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Biodynamic Modeling and Analysis of Human-Exoskeleton Interactions During Assisted Manual Handling

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Abstract

The objective of this study was to investigate the effects of a back exoskeleton on joint kinematics and kinetics during assisted manual handling tasks using subject-specific musculoskeletal biodynamic models and model-based analyses. We constructed these musculoskeletal models using OpenSim (Delp et al., 2007), incorporating optical motion capture, ground reaction forces (GRFs) measurements, and humanexoskeleton interactive force input. Our long-term goal is to enable digital modeling and simulation that can aid in the design and development of more effective exoskeletons and safer manual handling practices.

Introduction

Work-related musculoskeletal disorders (WMSDs) resulting from manual handling tasks have been a significant problem, especially for healthcare workers (BLS, 2020). Nursing assistants have the highest incidence rates of cases involving days away from work among the selected occupations. There are over 1.3 million nursing assistants in the US who provide basic care and help patients with activities of daily living (BLS., 2018). In 2016, 10,330 cases of back-related musculoskeletal disorders were reported among nursing assistants, accounting for 52.8% of all WMSDs suffered by this group (BLS., 2018). The repetitive bending or lifting involved in their daily work is a leading cause of low-back disorders. Moreover, manual patient-handling without assistance presents a safety risk not only to the workers but also to the patients.

Exoskeletons have been increasingly implemented to assist in manual handling tasks in the industry. Due to the lightweight design and usability, passive back-support exoskeletons have become a popular choice for various industrial environments. Previous studies have reported that back-support exoskeletons reduce back muscle activities and changes in trunk flexion angle, trunk lateral flexion angle, hip flexion and lumbar flexion (Hwang et al., 2021; Koopman et al., 2019; Yin et al., 2022). However, when there is substantial exoskeleton-related lumbar kinematic change, reduced back muscle activities do not always mean reduced spine loading (Koopman et al., 2019; Yin et al., 2023). A deeper and more unifying analysis is necessary to better ascertain the underlying mechano-physiological responses during assisted manual handling. This calls for a biodynamic modeling and model-based analysis approach.

The objective of this study was to investigate the effects of a back exoskeleton on joint kinematics and kinetics during assisted manual handling tasks using subject-specific musculoskeletal biodynamic models and model-based analyses. We constructed these musculoskeletal models using OpenSim (Delp et al., 2007), incorporating optical motion capture, ground reaction forces (GRFs) measurements, and human-exoskeleton interactive force input. Our long-term goal is to enable digital modeling and simulation that can aid in the design and development of more effective exoskeletons and safer manual handling practices.

Materials and Methods

Experiment

Twelve participants free from any musculoskeletal disorder or condition, six males (age: 27.7 ± 3.3 years, weight: 66.1 ± 5.9 kg, height: 1.71 ± 0.08 m) and six females (age: 22.7 ± 1.7 years, weight: 65.8 ± 11.8 kg, height: 1.69 ± 0.10 m), were recruited. The study protocol was approved by Texas

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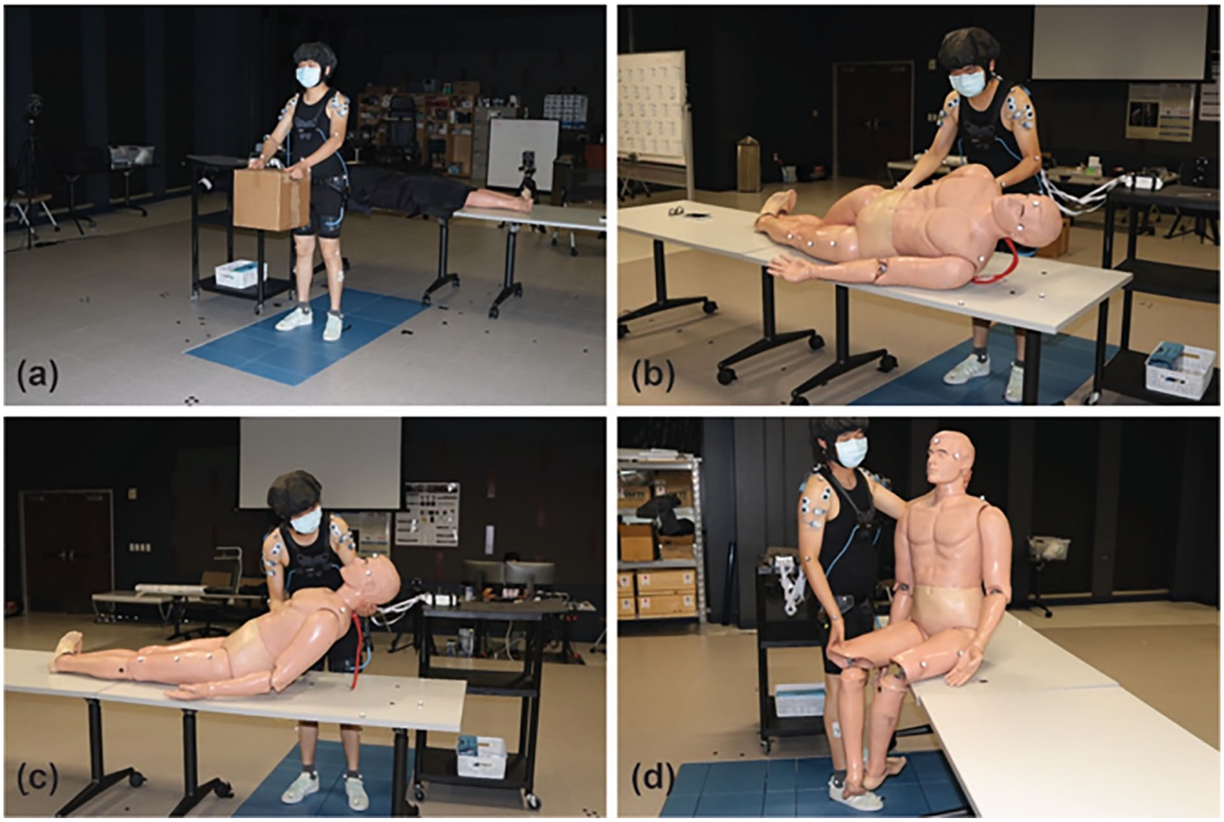

Figure 1. Experimental tasks performed by the participants: (a) symmetric load lifting; (b) patient side-turning; (c) patient upper-body lifting; (d) patient sit-up assisting.

A&M University Review Board of the Institute. After providing written informed consent, the participants were given sufficient time to become familiarized with the use of exoskeleton (Laevo V2.5, Delft, The Netherlands) and experimental tasks (Figure 1).

Subjects were instructed to perform four simulated assisted manual handling tasks (Figure 1), with and without wearing the exoskeleton. Each task was repeated four times. The order of tasks b, c, and d was completely randomized with two-minute inter-trial breaks.

Twenty-seven reflective markers were attached to the anatomical landmarks based on the plug-in gait marker set. In trials with the exoskeleton, four of these markers were placed on the hip paddings of the exoskeleton to replace the pelvis markers which would interfere with the exoskeleton. A twelve-camera Vicon system (Vicon Motion Systems, Oxford, UK) was used to record the motions of surface markers at a sampling rate of 50 Hz. The GRFs were recorded by dual AMTI force plates (Advanced Mechanical Technology, Inc., MA, USA) at a sample rate of 1000 Hz.

Modeling and Analysis

The GRFs were first filtered using a low-pass filter with a cut-off frequency of 5 Hz. The Vicon motion capture data were fed into inverse kinematics and inverse dynamics simulations in OpenSim 4.2 with Raabe's full-body lumbar spine model (Raabe & Chaudhari, 2016). The OpenSim subject-specific models were generated by scaling the generic model based on subjects' surface marker data for a static stance trial.

For the trials with the exoskeleton, the external moments generated by the exoskeleton were estimated using the Laevo angle-torque relationship measured by (Koopman et al., 2019) and the exoskeleton flexion angle calculated by markers placed on the chest pads and each leg pad.

Paired t-tests were utilized to examine the effects of the exoskeleton on lumbar joint kinematics and moment across all the tasks, with a significance level of 0.05. Additionally, we explored possible sex differences in kinematic and kinetic responses to the exoskeleton use.

Results

Significantly greater peak lumbar flexion angles ($p<0.001$) were consistently identified during all four tasks when subjects wore the exoskeleton (Figure 2, Table 1). The peak lumbar flexion angle increased by 47.8%, 47.0%, 44.9%, and 28.3% in tasks (a), (b), (c), and (d), respectively.

Significantly reduced peak lumbar flexion moments ($p<0.001$) were identified when subjects wore the exoskeleton in performing all four tasks. The peak lumbar flexion moment decreased by 27.1%, 27.8%, 22.6%, and 20.1% in tasks (a), (b), (c), and (d), respectively (Figure 3).

Discussion and Conclusion

We have identified a clear trade-off between lumbar flexion motion and flexion moment introduced by the use of back exoskeleton in manual handling tasks. Wearing the exoskeleton resulted in a decrease in peak lumbar flexion moment, indicating a reduction in the lumbar loading. However, this reduction came at the expense of an increase in peak lumbar flexion angle, suggesting a tendency to bend more when using the exoskeleton.

A significant ($p<0.001$) gender effect on peak lumbar flexion angle during lifting performance without the exoskeleton was observed, similar to what has been previously reported (Plamondon et al., 2014). Interestingly, under the exoskeleton condition, a gender effect on lumbar flexion angle was not detected ($p=0.865$). This may suggest that the use of an exoskeleton reduces the motion variability between genders and possibly across individuals in general (as indicated by a reduced SD; see Table 1) for relatively simple symmetric lifting motion performance.

The impact of an exoskeleton being task-dependent (Kuber et al., 2022) was also evidenced. For instance, the percent decrease in lumbar flexion moment and thus the spine loading was greater in more symmetric handling tasks (a & b) and less in more asymmetric, complex handling tasks (c & d). As Laevo was designed mainly for assisting repeated load lifting (Baltrusch et al., 2019), its biomechanical benefits could be curtailed for more complex, asymmetric handling tasks (Zhu

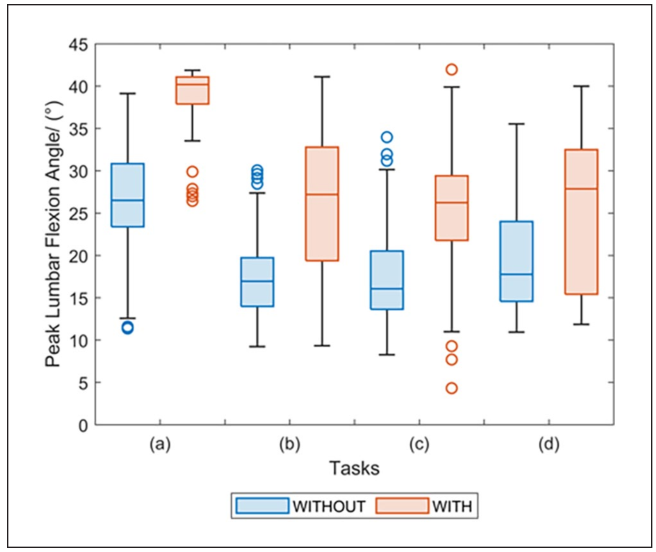

Figure 2. Peak lumbar flexion angles under WITH and WITHOUT exoskeleton conditions during four manual handling tasks.

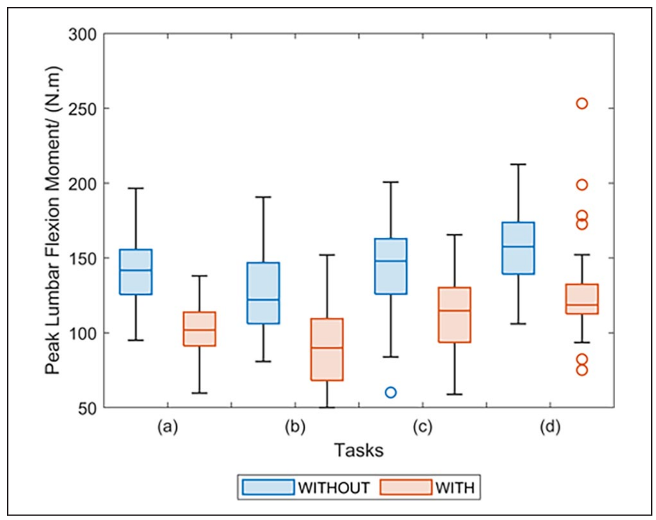

Figure 3. Peak lumbar flexion moments under WITH and WITHOUT exoskeleton conditions during four manual handling tasks.

Table 1. Mean (standard deviation) peak lumbar flexion angles and moments comparing WITH and WITHOUT exoskeleton conditions.

Variables	Tasks	WITHOUT	WITH	p-value
Peak Lumbar Flexion Angle (°)	a	26.21(6.81)	38.74(3.90)	<0.001
	b	17.74(5.02)	26.07(8.54)	<0.001
	c	17.78(6.31)	25.77(8.00)	<0.001
	d	19.72(6.36)	25.30(9.10)	<0.001
Peak Lumbar Flexion Moment (Nm)	a	141.09(21.85)	102.90(17.99)	<0.001
	b	126.29(27.40)	91.17(24.33)	<0.001
	c	145.74(27.48)	112.81(25.49)	<0.001
	d	156.22(24.21)	128.07(27.59)	<0.001

et al., 2021). This raises issues such as whether back exoskeletons should be made to better suited for different types of manual handling and what the typology should be.

One limitation that should be noted is the Laevo angle-torque relationship was a "one-size-fits-all" representation from the literature (Koopman et al., 2019). This relationship is believed to be under the influence of a multitude personal and possibly task factors. It can be more personalized as an improvement in the modeling approach or in the design of adjustability into the exoskeleton.

In conclusion, this study assessed the effects of a back-support exoskeleton on joint kinematics and kinetics experimentally and through subject-specific biodynamic modeling. The study found significant exoskeleton effects of increasing the peak lumbar flexion angle and reducing peak lumbar flexion moment, as well as some gender difference and task dependency in the effects.

Disclaimer

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health (NIOSH), Centers for Disease Control and Prevention (CDC). Mention of any company or product does not constitute endorsement by NIOSH/CDC.

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