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EFFECTS OF EXOSKELETON ROBOT ON HUMAN POSTURE AND LUMBAR PRESSURE DURING MANUAL LIFTING TASKS

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Abstract. *This study analyzed the effects of exoskeleton robot on human lumbar spine load during manual lifting tasks. Participants were asked to perform two tasks: a typical manual lifting and a lifting with exoskeleton robot. Lumbar spine loads were analyzed in terms of biomechanical models. In the case of lifting with the robot, additional analysis for confirming the posture effect was applied by neglecting the weight and force of the robot. The results revealed that the use of the exoskeleton robot reduced the lumbar spine load by 155.7 N on average. Additionally, they also showed that the effect of posture correction of the exoskeleton robot was 90.5 N on average, compared with the lifting tasks without the robot. The key finding of this study is that the use of the exoskeleton robot during manual lifting can provide lumbar load relief to the users and correct their posture. Although extensive experimental evidence is needed for confirmation of the results in practical scenarios, it is very likely that exoskeleton robot would be used in future industries.*

Keywords: Exoskeleton robot, Lumbar spine load, Manual lifting, Biomechanical models

1. **Introduction.** Manual handling tasks are common in most industries. The effort required for such tasks often results in injuries and disabilities, especially those related to the lower back [1], owing to the possibly awkward posture of the workers during task execution. According to biomechanical studies, the key risk factor for musculoskeletal problems is lumbar spine compression. A study of 217 workers performing at least 25 lifts per day found a 58% pervasiveness of lower back symptoms compared to a 33% pervasiveness of upper back symptoms [2]. Workers are often instructed to lift a load with squat lifts (back upright and knees bent) and stoop lifts (back bent and knees straight); however, even during such lifts, lower back injuries cannot be prevented [3]. Squat lifting is often considered to be a 'correct' way to lift loads; however, most studies have found lower back compressive forces during squat and stoop lifting of loads [4]. Lowering and

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lifting actions can significantly affect the lumbar spine and increase the worker's risk of lower back injuries [5].

Chaffin (2005) suggested a method to consider risk factors during job design [6]. In this method, computerized human simulation models were used to gauge the stress on lower back tissues and other musculoskeletal system areas, considering different population groups, gender, and human anthropometry [6]. According to the US National Institute of Occupational Safety and Health (NIOSH), during the design of a two-handed load lifting task, the major factors that must be considered are: weight of the load, horizontal distance of the load from the feet, vertical distance of the load from the ground, and frequency and duration of lifting [7]. Furthermore, several national standards already exist to define the maximum weight that a person can lift without any physical problem [8].

Exoskeletons are wearable devices (external to the body) that are placed on the worker's body to increase their efficiency and reduce the lumbar spine load. The use of the exoskeleton robot increases the worker's alertness, productivity, and work quality. Several exoskeleton prototypes have been developed to assist load carrying and back support, e.g., the MK2 [9-12], WSAD [13], PLAD [14,15], HAL Lumbar Support [16], backX [17], HuMan [17], and Hyundai H-WEX 2 back support exoskeleton [5]. According to biomechanical modeling and analysis, exoskeleton robots reduce both muscle activity and lower back compression in load handling activities [18-20]. De Looze et al. [5] discussed a total of 26 different industrial exoskeletons which are developed to support back compression during stoop working posture, bending posture and static lifting posture and they reduce the back compression during task performance.

There are various types of tasks such as pulling, pushing, turning, and lifting of heavy objects. In this study, we analyzed the effect of the use of the exoskeleton robot on lumbar spine load and posture during manual load lifting. The actual weight of the exoskeleton robot is 4.6 kg (45.08 N), and the maximum assistive force when the participant is lifting is 54.88 N.

2. **Method.** Among the 10 participants in this study, 7 were males and 3 were females. Their average height and weight was 157 cm (± 10.0) and 72.2 kg (± 14.7), respectively. According to De Looze et al. [5], the average number of participants of ten studies regarding active exoskeleton is 3 whereas in our study the number of participants is ten. Random hand loads of 5, 10, and 15 kg were applied to the participants according to their tasks. The load is assumed to be equally distributed to both the hands.

The experiment was performed in two workspaces. The participants were instructed to lift the load from the ground in their normal and comfortable posture with and without the exoskeleton robot. Their postures during the tasks were captured with the help of a camera (Figure 1). The anthropometric data of the participants is listed in Table 1.

A total of 20 tasks were performed by 10 participants in two conditions. The first condition comprised a typical manual lifting of the load from the floor in a comfortable posture without the exoskeleton robot, whereas the second condition comprised the lifting of the load from the floor after wearing the exoskeleton robot. However, the effect of the exoskeleton robot on posture during load lifting was also analyzed in a presumed condition, in which we neglected the robot's weight and assistive force. Consequently, three analytical targets were considered: typical manual lifting, manual lifting with the robot (neglecting its weight and assistive force), and manual lifting with the robot (Figure 2).

There are various models that study the human movement based on weight, height, and joints; however, in this study, three-dimensional static-strength prediction program (3DSSPP): software developed by the University of Michigan, was used to analyze the low back compression during task performance. The weight, height and hand load of each participant was given as input to the software. The total hand load was assumed to be

Figure 1. Postures of a participant during typical manual lifting and lifting with exoskeleton robot

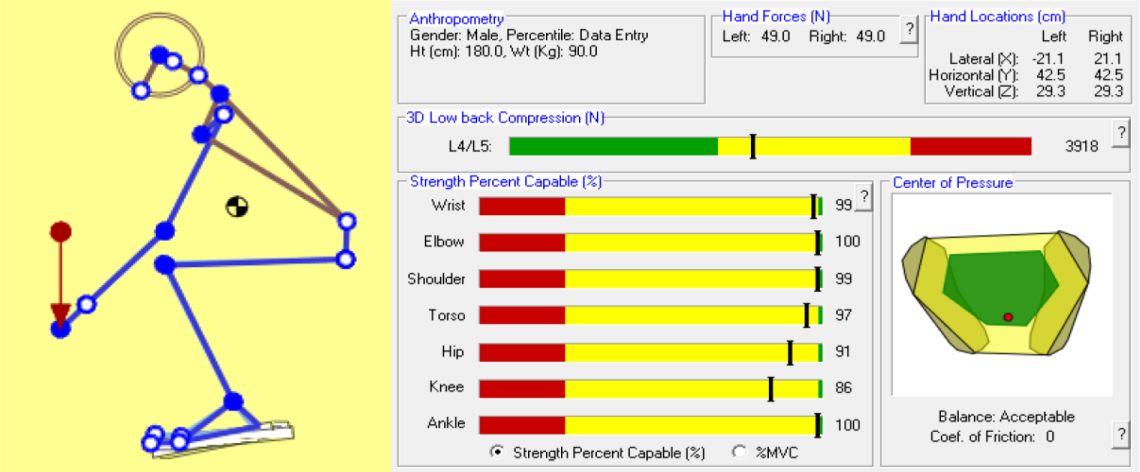
Table 1. Anthropometric data of participants

Subjects	Gender	Height (cm)	Weight (kg)	Hand load (kg)
1	M	180	90	10
2	F	163	58	5
3	F	157	51	5
4	F	165	70	5
5	M	180	95	10
6	M	187	87	15
7	M	173	70	15
8	M	165	60	15
9	M	176	65	15
10	M	184	76	15

equally distributed to both the hands, i.e., 5 kg on each hand, thereby resulting in a total of 10 kg. The dummy model was modified according to the actual postures of participants. This was done with the help of pictures that were captured during the task execution. It is difficult to reproduce the posture of the human body in the software; therefore, the created human models were reviewed by three human factor experts to obtain more precise models. We also noted the L4/L5 lower back compression that appeared for each task for each participant.

3. **Results.** The experimental results show that the use of the exoskeleton robot reduced the lumbar spine load of each participant. Table 2 lists the low back compression of each participant in all three conditions (typical manual lifting of load from the floor, lifting of load from the floor with exoskeleton robot (neglecting its weight and assistive force), and manual lifting of load with exoskeleton robot) analyzed by 3DSSPP.

The ANOVA results and descriptive statistics of this study shown in Table 3 and Figure 3 indicate that there is no statistically significant difference in the lumbar pressure ($p = 0.937$) for the three conditions (typical manual lifting, manual lifting of the load from the floor with exoskeleton robot (neglecting its weight and assistive force), and manual lifting of load with exoskeleton robot). The average value of lower back compression for all participants performing typical manual lifting task from the floor without exoskeleton robot is 3570.1 N, which is considerably high; therefore, it can cause lower back pain and injuries in a short period of time. However, after using the exoskeleton robot, the compression decreases as shown in Figure 3. The average value of lower back compression with exoskeleton robot (neglecting its weight and assistive force) is 3479.6 N, which is 90.5 N



Anthropometry
Gender: Male, Percentile: Data Entry
Ht (cm): 180.0, Wt (Kg): 90.0

Hand Forces (N)
Left: 49.0 Right: 49.0

Hand Locations (cm)

	Left	Right
Lateral (X):	-21.1	21.1
Horizontal (Y):	42.5	42.5
Vertical (Z):	29.3	29.3

3D Low back Compression (N)
L4/L5: 3918

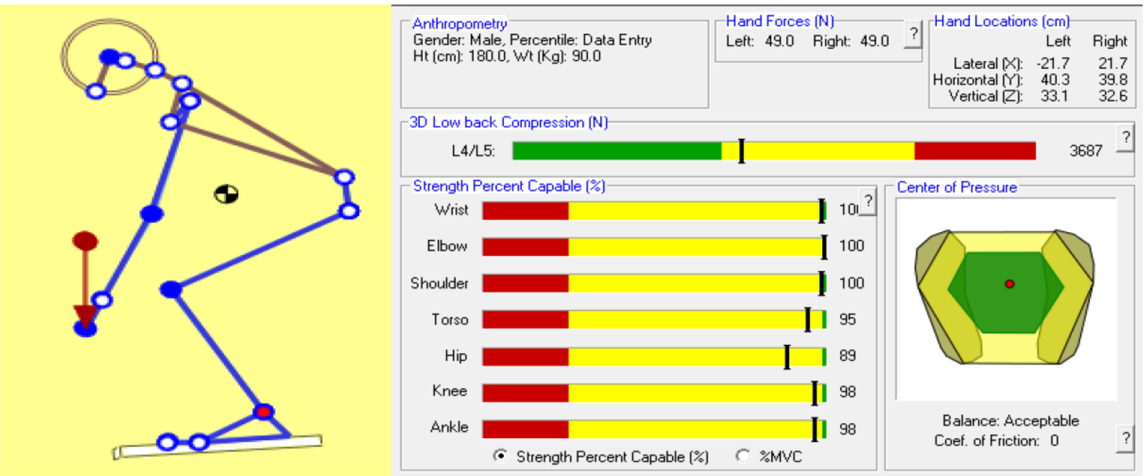
Strength Percent Capable (%)

Wrist	99
Elbow	100
Shoulder	99
Torso	97
Hip	91
Knee	86
Ankle	100

● Strength Percent Capable (%) ○ %MVC

Center of Pressure
Balance: Acceptable
Coef. of Friction: 0

(a) Typical manual lifting



Anthropometry
Gender: Male, Percentile: Data Entry
Ht (cm): 180.0, Wt (Kg): 90.0

Hand Forces (N)
Left: 49.0 Right: 49.0

Hand Locations (cm)

	Left	Right
Lateral (X):	-21.7	21.7
Horizontal (Y):	40.3	39.8
Vertical (Z):	33.1	32.6

3D Low back Compression (N)
L4/L5: 3687

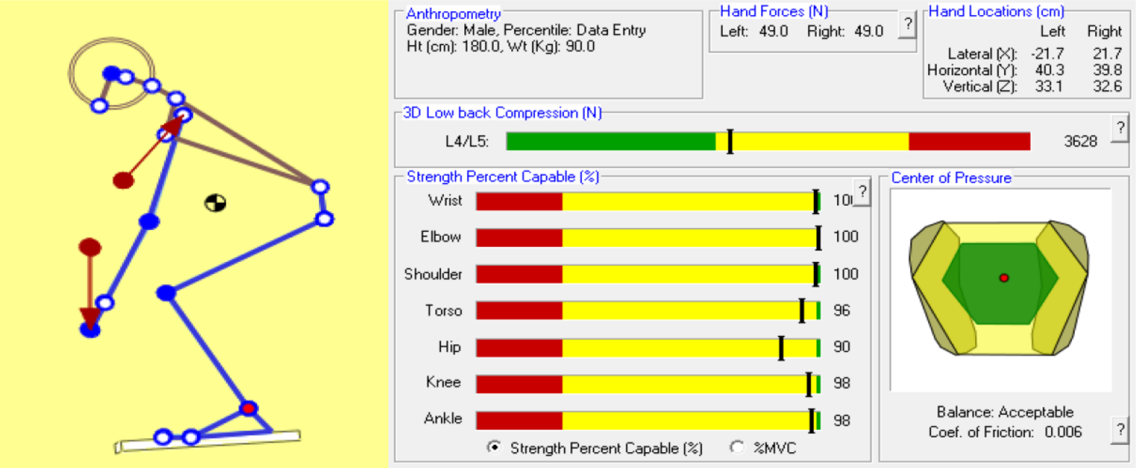
Strength Percent Capable (%)

Wrist	10
Elbow	100
Shoulder	100
Torso	95
Hip	89
Knee	98
Ankle	98

● Strength Percent Capable (%) ○ %MVC

Center of Pressure
Balance: Acceptable
Coef. of Friction: 0

(b) Lifting with exoskeleton robot (neglecting its weight and assistive force)



Anthropometry
Gender: Male, Percentile: Data Entry
Ht (cm): 180.0, Wt (Kg): 90.0

Hand Forces (N)
Left: 49.0 Right: 49.0

Hand Locations (cm)

	Left	Right
Lateral (X):	-21.7	21.7
Horizontal (Y):	40.3	39.8
Vertical (Z):	33.1	32.6

3D Low back Compression (N)
L4/L5: 3628

Strength Percent Capable (%)

Wrist	10
Elbow	100
Shoulder	100
Torso	96
Hip	90
Knee	98
Ankle	98

● Strength Percent Capable (%) ○ %MVC

Center of Pressure
Balance: Acceptable
Coef. of Friction: 0.006

(c) Manual lifting of load with exoskeleton robot

FIGURE 2. 3DSSPP models of a participant

less than the mean lower back compression of participants without the exoskeleton robot. This shows that the use of the exoskeleton robot can "correct" the posture according to the risk of a lower back injury. When an assistive force of 9.8 N was exerted vertically to the spine of a participant, then the value of lower back compression decreased further with a value of 65.2 N. The total decrease in the lumbar force amounted to 155.7 N.

Table 2. Lower back compression of participants in three different conditions

Subject number	Hand load (kg)	Low back compression (typical manual lifting)	Low back compression (manual lifting with robot neglecting its weight and force)	Low back compression (manual lifting with robot)
1	10	4425	4217	4150
2	5	2125	2155	2089
3	5	2125	1970	1905
4	5	2475	2480	2413
5	10	3918	3687	3628
6	15	4701	4695	4626
7	15	4211	4141	4077
8	15	3654	3563	3501
9	15	3604	3491	3427
10	15	4463	4397	4328

Table 3. Statistical results of object-liver effect test

Source	The 3 types of sum of squares	Degree of freedom	Mean squared	F	Probability of significance
Modified model	122279.267	2	61139.633	0.065	0.937
Intercept	364991296.033	1	364991296.033	386.772	0.000
Condition	122279.267	2	61139.633	0.065	0.937
Error	25479537.700	27	943686.581		
Modified total	25601816.967	29			

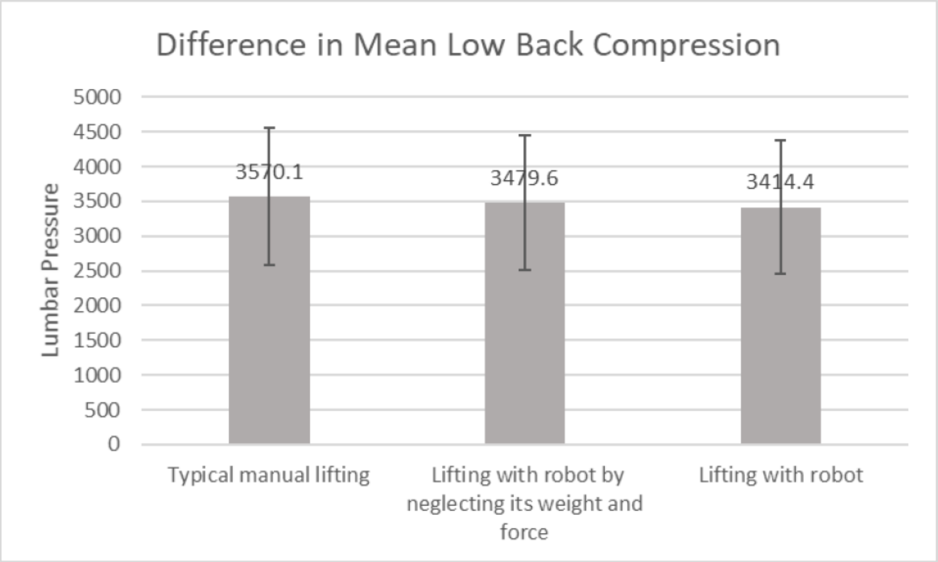


Figure 3. Mean difference of lower back compression during typical manual lifting and the lifting with exoskeleton robot

4. **Discussion and Conclusion.** This study highlighted the application of the exoskeleton robot in a real-world environment. The results of this study show that lifting loads with awkward posture can cause musculoskeletal disorder in workers owing to the high value of lower back compression. The use of the exoskeleton robot results in posture

correction that drastically decreases the lower back compression in workers performing manual load lifting; this indicates that the robot is effective for lifting tasks. The 9.8 N shoulder force further decreases the lumbar pressure according to the results. This shows that by increasing the assistive force, we can additionally decrease the lumbar pressure.

The statistical results of this study show that the use of the exoskeleton robot reduces both the L4/L5 lumbar compression force and the human effort during weight lifting tasks. Workers mostly lift loads directly from the floor; therefore, it is highly recommended to design workplaces according to human effort and instruct workers not to store or lift heavy loads from the floor or ground. This is also indicated by past studies. Mechanical lifting aid must be used to raise heavy objects to a certain height during manual handling [6]. This can decrease the effort to lift the load. The spinal compression force is considered an important factor in preventing lower back injuries [21]. According to the NIOSH, 3400 N lower back compression is assigned as the lower limit to protect workers from injuries [7]; however, in this study, lower back compression of all participants is above that limit. Using exoskeleton robot with assistive force reduces the mean lumbar pressure (3414.4 N) that almost reaches the NIOSH limit. This shows that applying more assistive force can further decrease the lumbar pressure.

This study concludes that the mean value of lumbar pressure on L4/L5 is 3570.1 N, 3479.6 N, and 3414.4 N for typical load lifting, manual load lifting with exoskeleton robot (neglecting its weight and assistive force), and manual load lifting by considering the weight and force of exoskeleton robot, respectively. The use of the exoskeleton robot corrects the posture during load lifting, which decreased the lumbar pressure by a value of 90.5 N in this study. An assistive force that is vertically perpendicular to the spine, when applied to the shoulder, decreased the lumbar pressure further by 65.2 N, thereby causing a total decrease of 155.7 N in the lumbar pressure. The results show that the use of the exoskeleton robot can decrease the lumbar spine load and correct the posture during manual load lifting.

The limitation of this study is that the model developed by the 3DSSPP program may not indicate the real results because the model body is divided into the limited number of joints, whereas the actual human body has many more joints. Therefore, the model does not reflect the effects of every joint and muscle in the actual human body. In future, a variety of experiments need to be carried out to increase the effectiveness of exoskeleton and to analyze the comfort level due to exoskeleton robot. More research using technical devices i.e., EMG, ECG may help to make this exoskeleton more effective.

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