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Kinematic effects of a passive lift assistive exoskeleton

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ABSTRACT

The VT-Lowe's exoskeleton was designed to help support the back during repetitive lifting tasks. This study focused on the kinematic differences between lifting with and without the exoskeleton (With-Exo and Without-Exo) over three different lifting styles (Freestyle, Squat, and Stoop) and two different box weights (0% and 20% of bodyweight). Twelve young and healthy males (Age 23.5 +/− 4.42 years; Height 179.33 +/− 6.37 cm; Weight 80.4 +/− 5.59 kg) participated in this study. Variables analyzed include the ankle and knee angles and angle between the Shoulder-Hip-Knee (SHK); the shoulder, elbow, and wrist heights; and the lifting speed and acceleration. The relationships between the torso angle, SHK angle, center of mass of the torso, torso torque, box height, as well as electromyography (EMG) data from a related study were also analyzed. On average, wearing the exoskeleton resulted in a 1.5 degree increase in ankle dorsiflexion, a 2.6 degree decrease in knee flexion, and a decrease of 2.3 degrees in SHK angle. Subjects' shoulder, elbow, and wrist heights were slightly higher while wearing the exoskeleton, and they lifted slightly more slowly while wearing the exoskeleton. Subjects moved more quickly while bending down as compared to standing up, and with the 0% bodyweight box as compared to the 20% bodyweight box. The values for Freestyle lifts generally fell in between Squat and Stoop lift styles or were not significantly different from Squat. EMG data from the leg muscles had relationships with torso torque while the back and stomach muscles showed no significant relationships.

1. Introduction

The human body is capable of a wide variety of tasks, but the wear and tear from daily operations can take its toll. Work-related musculoskeletal disorders and specifically lower back pain are well-established problems in industry (Andersen et al., 2007; Andersson, 1981). The most commonly reported biomechanical risk factors for work-related musculoskeletal disorders include excessive repetition, awkward postures, and heavy lifting (Da Costa and Vieira, 2010).

Recently, exoskeletons have become more prevalent as a solution to these problems, and have been designed to increase strength or assist with uncomfortable postures. Review papers focusing on industrial exoskeletons (de Looze et al., 2016) and back support exoskeletons (Toxiri et al., 2019) provide a good overview of the designs and evaluations of these exoskeletons to date. In general, most exoskeleton studies are conducted in lab settings and primarily focus on the effect of the exoskeletons on muscle activity, through electromyography (EMG), instead of quantifying the kinematic changes due to exoskeleton use (Spada et al., 2017). While it is helpful to prove that the exoskeleton is beneficial in terms of muscle activity, it is also important to understand the kinematic changes caused by adding an additional device to the body.

Relatively few kinematic studies of passive back exoskeletons have been published (Baltrusch et al., 2018; Baltrusch et al., 2019; Baltrusch et al., 2019; Koopman et al., 2019; Koopman et al., 2020; Madinei et al., 2020; Näf et al., 2018). Baltrusch et al. tested the Laevo with twelve work-related tasks, and evaluated perceived comfort and objective performance (Baltrusch et al., 2018). They found that tasks involving hip flexion were perceived to be more difficult with the exoskeleton. Later research by the same group found that subjects had a nearly-significant decrease in the vertical range of motion of the center of mass (COM) while wearing the Laevo (Baltrusch et al., 2019). Another study on the Laevo found that peak lumbar flexion increased, but only during ankle-height lifts and not during knee-height lifts (Koopman et al., 2020). In a second study that examined both the Laevo and BackX (US Bionics, Inc., 2018), researchers did not find changes in the range of motion while wearing either exoskeleton

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(Madinei et al., 2020). A study of the SPEXOR exoskeleton examined the kinematics of lifting (Baltrusch et al., 2019). They did not observe a significant difference in the knee, hip, lumbar, or trunk joint angles or in the range of motion of the wearer's COM when the exoskeleton was worn. As compared to not wearing the exoskeleton, individuals wearing the Personal Lift Augmentation Device (PLAD) exoskeleton (Abdoli-E et al., 2006) were found to have increases in ankle flexion, significantly less lumbar and thoracic (mid back) flexion, and nearly identical hip flexion (Sadler et al., 2011).

The VT-Lowe's exoskeleton (Chang et al., 2020) tested in this study was designed to support the lower back during lifting tasks. Carbon fiber beams running along the user's back and legs provide a restorative force as the user bends down, as they attempt to straighten again. The beams are attached to the user through the use of soft goods including a waist belt, shoulder straps, and thigh pads. The number of carbon fiber pieces and straps of the soft goods are adjustable to accommodate users of different strengths and sizes. A previous study on the VT-Lowe's exoskeleton showed significant reductions in muscle activity (Alemi et al., 2019). The present study, which was conducted concurrently with the previous study, focused on whether or not wearing the VT-Lowe's exoskeleton has a significant impact on lifting kinematics during three symmetric lifting tasks (Freestyle, Stoop, and Squat) with two different box weights (0% and 20% of bodyweight). We hypothesized that wearing the exoskeleton would decrease the range of motion throughout the lifting cycle, as the exoskeleton creates a substantial torque around the hip and lower back. In this study, we also determined the relationships between torso angle and shoulder-hip-knee (SHK) angle, center of mass of a load versus the body's center of mass, torque to support the torso during lifting, and box height. We examined relationships between these variables and the EMG results reported in the previous study (Alemi et al., 2019). These data are useful for designing exoskeletons in the future and for modeling the kinematics of lifting.

2. Materials and methods

2.1. Participants

Twelve young and healthy males (Age 23.5 ± 4.42 years; Height 179.33 ± 6.37 cm; Weight 80.4 ± 5.59 kg) were recruited from the university and local community to participate in the study (IRB# 17-127). All subjects signed informed consent forms at the beginning of the study. None of subjects had a history of musculoskeletal disorders or had lower back pain in the past year, and all were capable of lifting at least 25% of their own body weight.

2.2. Preparation

The study was broken up into a training session and testing session, typically held on two separate days but occasionally held back-to-back due to participant availability. The exoskeleton straps at the chest, waist belt, and legs were adjusted for both size and comfort based on verbal feedback from each participant during the half-hour training session. All participants used the same number of carbon fibers (42 beams along the back and 14 along each leg) because of the time required to optimize the number of beams for each participant. During the training session each subject conducted several practice lifts, both with and without the exoskeleton, with each of the three lift styles (Freestyle, Squat, and Stoop) and two box weights (0% and 20% of bodyweight). Training continued until the participant felt comfortable with the exoskeleton. The participant then returned for the testing session, and were briefly re-familiarized with the lifting tasks and exoskeleton fit. 37 retro-reflective markers were placed on the specific landmarks shown in Fig. 1, and four markers were placed on the top corners of the box being lifted. Since the anterior superior iliac spine (ASIS) and posterior superior iliac spine (PSIS) markers were covered by the exoskeleton, we placed those markers on the exoskeleton waist belt during the With-Exo conditions.

2.3. Experimental procedures

For each lifting cycle in the tests, the subject bent down to grasp a 43 × 31 × 20 cm^3 plastic box (with the bottom of the handles 12.5 cm from the base of the box) from a 10 cm tall platform. They lifted the box as they returned to a standing posture, paused for a moment, bent down again to return the box to the platform, and finally returned back up to their original standing posture. This full lift cycle was repeated four times in a minute for each testing condition. A MATLAB (Release 2019a, MathWorks, Natick, Massachussetts) audio script gave prompts on when to start bending down (both at the start of the lifting cycle and after the pause in the middle), but the speed of each lift was up to the participant. All subjects performed twelve trials including three different types of lift (Freestyle, Squat, and Stoop) at two different weights (0% and 20% of bodyweight), both with and without the Exoskeleton. The trial order was randomized between subjects to minimize any postural changes due to fatigue or other unknown effects.

For Squat lifting, participants were instructed to bend their knees and keep their back straight while lifting. For Stoop lifting, participants were instructed to keep their legs straight (without locking their knees) and bend at the hip as they lifted the box. A little knee bending was allowed for those participants that were not flexible enough to complete a Stoop lift while keeping their legs straight. For Freestyle lifting, participants were told to ignore the directions for Squat and Stoop and instead choose their own

Fig. 1. Motion capture marker placement. The shoulder marker is placed on the acromion process. The elbow marker is placed on the lateral epicondyle of the humerous. ASIS and PSIS are the anterior and posterior superior iliac spine respectively. All markers are placed on both the left and right side of the subject.

preferred lifting style. This generally fell somewhere in between the Squat and Stoop styles. Foot positions were kept consistent within a lift style, but were allowed to vary between lift types. The subjects completed a few practice lifts while choosing their ideal foot position and then that position was marked on a piece of paper taped to the ground so they could return to that position later.

2.4. Instrumentation and data processing

Three dimensional kinematics data were collected at 120 Hz using an eight camera Qualysis motion capture system (Motion Analysis Corporations, Santa Rosa, CA). Visual3D software (C-Motion, Bethesda, Maryland) was used to filter the time-series data with a 4th order low-pass Butterworth filter with a 6 Hz cutoff frequency. Due to the exoskeleton waist belt obstructing the view of the participants' ASIS and PSIS, virtual markers were created in Visual3D, using an offset based on the thickness of the waist belt, to match the same anatomical locations without the waist belt. To ensure the virtual markers were located at the correct anatomical positions, the movement of the waist belt during the lift cycle was analyzed and adjusted in software. The distances between the iliac crest markers (placed directly on the person) and both the ASIS and PSIS markers (placed on the waist belt) and the hip marker (constructed through a model of the pelvis in Visual3D) were compared in MATLAB. The distances between these points were calculated while the subject was standing and at the peak of each lift. Due to natural skin motion, these distances changed slightly during the lifts in the Without-Exo conditions. For the With-Exo conditions, the marker positions at the peak of the lift were shifted in the sagittal plane so that they matched the shifts observed in the Without-Exo conditions. This assumes that the pelvis maintained the same orientation both With-Exo and Without-Exo. While the pelvis orientations in these two conditions are not exactly the same, they are very close. Since in this paper we are examining the effect of the exoskeleton on lifting, specifically at the lift peak, this procedure eliminated any unwarranted motion of the hip markers due to their being placed on the exoskeleton. The marker shift was calculated for each subject, lift style, and box weight, and was applied linearly throughout each lift from standing to the peak. The iliac crest marker was not used with our first few participants so for them we used an average offset based on the offsets from the remaining participants for that specific lift style and box weight. Additionally, during the experiment, trials with movement of the waist belt noticeable to the researchers were repeated to minimize the movement as much as possible. Visual3D was also used to calculate the ankle angle in the sagittal plane. Ankle angle is the angle between the foot and the shank with dorsiflexion movement considered the positive direction.

Additional heights and angles were calculated in MATLAB using marker position data. These included shoulder height, elbow height, wrist height, knee angle, shoulder - hip - knee angle (referred to as "SHK"), and the torso angle. The ankle, knee, and hip markers were used to calculate the knee angle in the sagittal plane, with extension considered the positive direction. The shoulder, hip, and knee markers were used to calculate the SHK angle in the sagittal plane. These markers roughly correspond to the locations on the body on which a back exoskeleton contacts a person, as compared to the hip angle, for example, which does not take into account the back. The SHK angle is computed by 180° minus the angle between the shoulder, hip, and knee in the sagittal plane, so that a person standing straight has an SHK angle close to zero. The torso angle is calculated in the sagittal plane as the angle between a vector from the shoulder to the hip and a vertical unit vector at the origin. During the experiment, the C7 marker was often hindered from the view of the cameras by the exoskeleton. Therefore to calculate the torso and SHK angles, the average of the shoulder markers was used instead of the C7. The valleys, corresponding to the deepest part of the bend as determined by the height (z-coordinate) of the shoulder marker (i.e., the peak of the lift), were used to align the data. All values presented are based on the portion of the lift from when the subject picks up the box to when they place it back down. Force plate data were unavailable, therefore full body and torso center of mass were calculated using the markers at joint positions and anthropometric data of the percent body weight for individual segments of a human (Huston, 2013; Winter, 2009).

The current kinematics study was conducted concurrently with an EMG study (Alemi et al., 2019) with corresponding data for 11 out of 12 subjects. For the overlapping subjects, the peak (i.e., the maximum value, not necessarily at the deepest portion of the lift) and mean EMG results were compared to the joint angles and torso torques at the deepest portion of the bends.

2.5. Statistical analysis

The main independent variables in this study are: exoskeleton use (With-Exo and Without-Exo), lift style (Freestyle, Squat, and Stoop) and box weight (0% and 20% of bodyweight, referred to as "0P" and "20P" respectively in the rest of the paper). A three factor repeated measures ANOVA was carried out through JMP Pro 15 (SAS, Cary, NC) to analyze joint angles and joint heights at the deepest portion of the bend. Subject ID number was treated as a random effect. A fourth independent variable, direction (whether the subject was bending down or standing up), was included while carrying out the analysis for speed and acceleration. The values that were found to be significant were followed up with a post hoc Tukey HSD analysis. A significance level of 0.05 was used to analyze all the dependent variables. Both fixed and interaction effects are reported below. Several graphs were made showing relationships between variables, and these used best fit lines with R^2 values to quantify the relationships. When calculating the best fit lines for the relative torques and angles, a best fit line for an individual subject's data was first calculated and then averaged together to get the overall best fit line. R^2 values were calculated by comparing the best fit line to all the relevant data. The dependent variables examined include the torso and shoulder-hip-knee (SHK) angles, the center of mass of a load and the body's center of mass, the torque to support the torso during lifting (including the total contribution from both the body and the exoskeleton for the With-Exo condition), the box height, and the muscle activations from the EMG study.

A line of best fit was also used when examining the relationships between the peak torso torque and the EMG values. R^2 and p-values were calculated to determine the significance of the relationship. For these graphs, the average value per person for each of the 12 trials (exo condition, lift style, and lift weight) was computed before comparing across all of the subjects.

3. Results

3.1. Joint angles

Each lift style has unique joint angles and postures. For a clear picture of the changes in kinematics, joint positions averaged over all 12 subjects at the deepest portion of the bend (Fig. 2), the trajectory of the ankle, knee, and SHK angles over the course of the lift cycle (Fig. 3), and values for the range of motion for each of these joint angles (Fig. 4 and Appendix Tables 4–6) are presented for each lift style and box weight. Our statistical analyses (Table 1) focused on the values at the deepest portion of the bend.

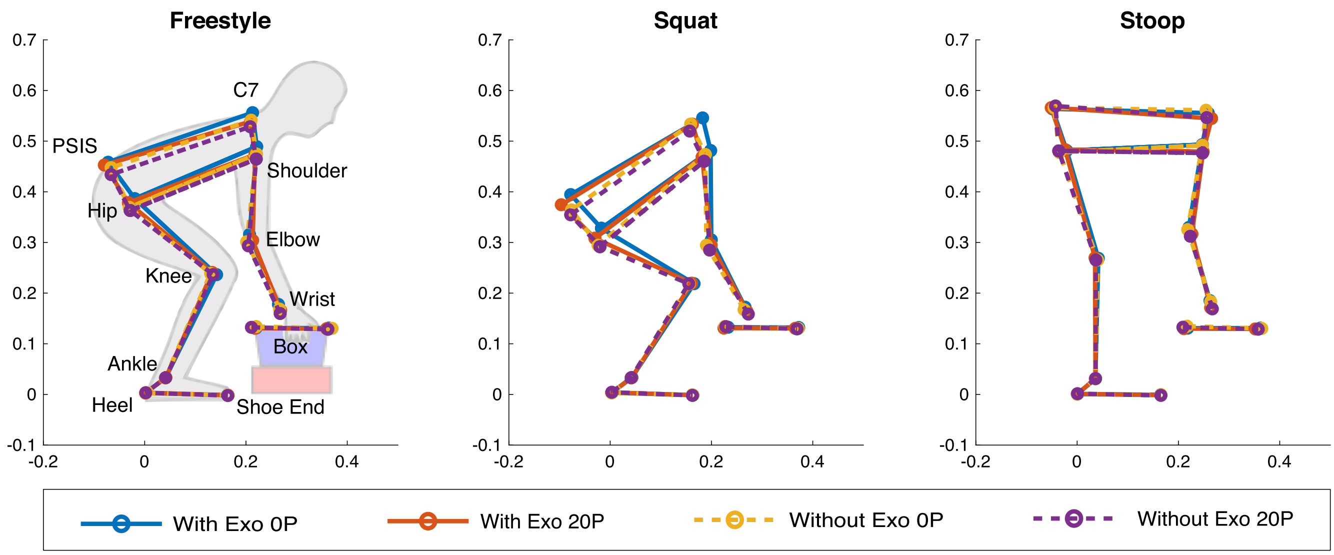

Fig. 2. Average joint positions at the lowest point of the bend during Freestyle, Squat, and Stoop lifting. Each lift is carried out both with and without the exoskeleton, and with both an empty box and a box weighing 20% of the subject's body weight (0P and 20P respectively). All positions have been normalized to subject height.

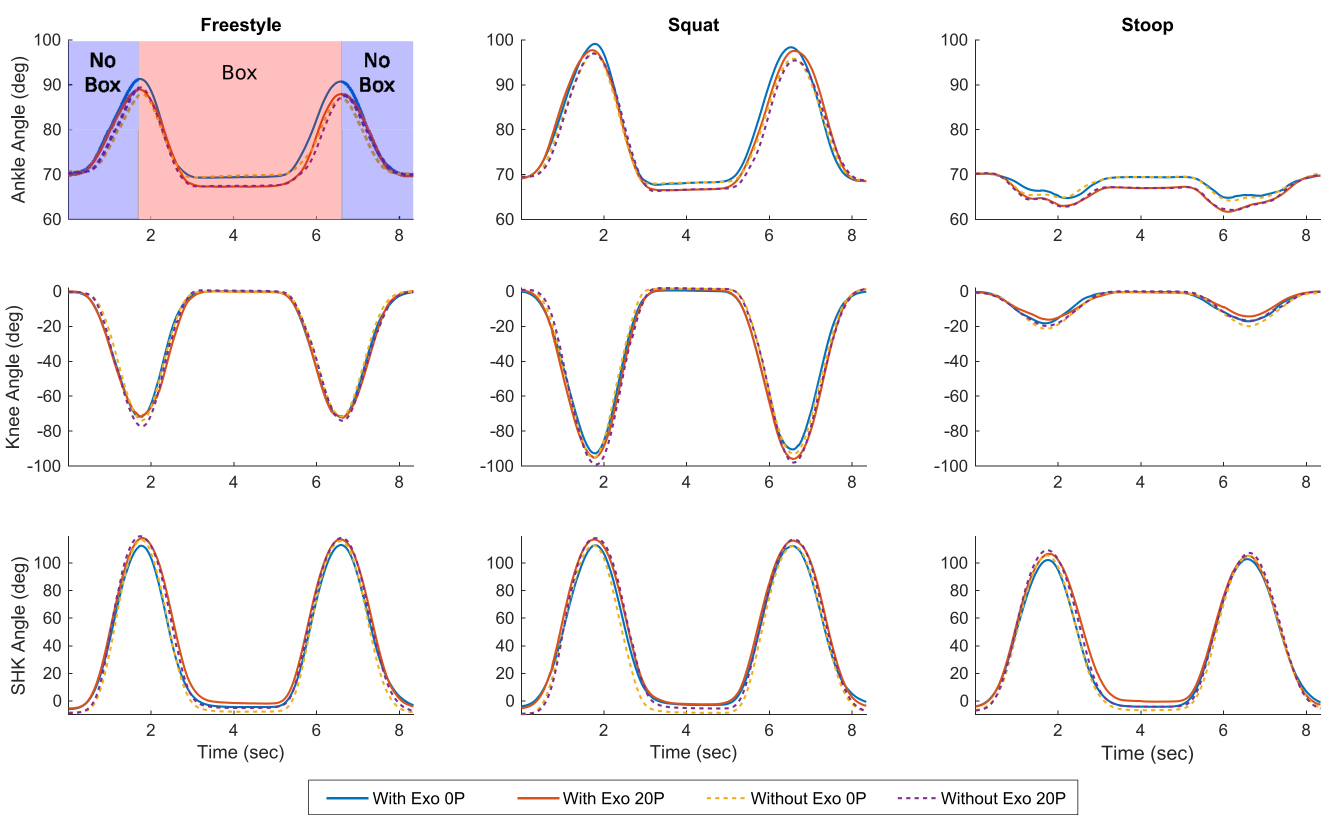

Fig. 3. Ankle, Knee, and SHK angles throughout the lift.

The ankle angle was significantly different between the With-Exo and Without-Exo conditions as well as between all three lifting styles. On average, subjects dorsiflexed their ankle 1.5° more while wearing the exoskeleton.

Similar to the ankle, the knee angle also was significantly different between the With-Exo and Without-Exo conditions as well as between all three lifting styles. However, unlike the ankle, subjects had on average 2.6° less knee flexion while wearing the exoskeleton. An interaction effect between lift style and box weights shows that while freestyle and squat have greater knee flexion for the 20P condition, stoop has greater knee flexion during the 0P case.

For the SHK angle there was a significant difference between the With-Exo and Without-Exo as well as between the 0P and 20P conditions. Freestyle was not significantly different from Squat lifting, but both were significantly different from Stoop lifting. Across all lifting styles and box weights, the SHK angle decreased (i.e., there was less hip flexion) by an average of 2.3° while wearing the exoskeleton as compared to not wearing the exoskeleton.

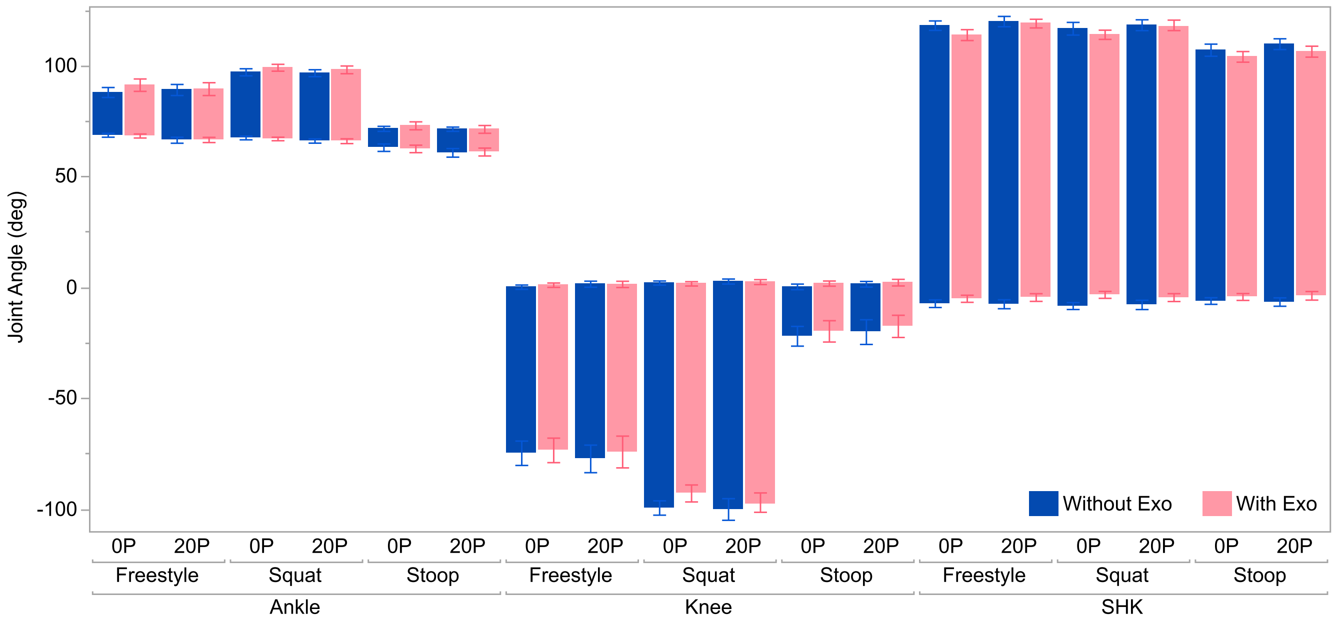

Fig. 4. Range of motion of the Ankle, Knee, and SHK joint angles for each liftsyle, box weight, and exo condition. Each error bar is one standard deviation from the mean.

Table 1
Aggregation of Ankle, Knee, and SHK Angles in [degrees] at the deepest portion of the bend for each Exo condition, Lift style, and Box weight.

		Ankle	Knee	SHK
Exo	Without	82.9 (15.8)	−64.1 (36.7)	114.9 (7.7)
	With	84.4 (16.5)	−61.5 (37.0)	112.6 (8.9)
	p-value	0.0400 ⁎	0.0444 ⁎	0.0059 ⁎
Lift Style	Freestyle	89.5 (8.1)	−74.8 (17.8)	117.8 (5.7)
	Squat	97.9 (5.4)	−97.4 (12.4)	116.8 (7.4)
	Stoop	63.6 (6.8)	−18.6 (15.7)	106.9 (7.2)
	p-value	<0.0001 ⁎	<0.0001 ⁎	<0.0001 ⁎SqF vs St
Box Weight	0P	84.3 (15.7)	−62.8 (35.9)	112.4 (8.6)
	20P	83.0 (16.6)	−62.8 (37.8)	115.1 (7.9)
	p-value	0.1188	0.5085	0.0021 ⁎

⁎ denotes a statistically significant difference between conditions with $p < .05$.
⁎SqF vs St denotes that Squat and Freestyle are not significantly different from each other, but both are significantly different ($p < .05$) from Stoop.

Table 2
Aggregation of Shoulder, Elbow, and Wrist Heights normalized to subject height, at the deepest part of the bend for each Exo condition, Lift style, and Box weight.

		Shoulder	Elbow	Wrist
Exo	Without	0.474 (0.020)	0.302 (0.020)	0.168 (0.012)
	With	0.481 (0.020)	0.311 (0.019)	0.172 (0.012)
	p-value	0.0020 ⁎	<0.0001 ⁎	0.0004 ⁎
Lift Style	Freestyle	0.475 (0.020)	0.304 (0.018)	0.168 (0.014)
	Squat	0.471 (0.022)	0.295 (0.019)	0.165 (0.010)
	Stoop	0.485 (0.016)	0.321 (0.012)	0.177 (0.010)
	p-value	0.0092 ⁎Sq vs St	<0.0001 ⁎SqF vs St	0.0001 ⁎SqF vs St
Box Weight	0P	0.484 (0.022)	0.312 (0.021)	0.175 (0.014)
	20P	0.470 (0.016)	0.301 (0.017)	0.165 (0.008)
	p-value	0.0001 ⁎	0.0002 ⁎	0.0002 ⁎

⁎ denotes a statistically significant difference between conditions with $p < .05$.
⁎Sq vs St denotes that Squat and Stoop are significantly different from each other ($p < .05$), but neither is significantly different from Freestyle.
⁎SqF vs St denotes that Squat and Freestyle are not significantly different from eachother, but both are significantly different ($p < .05$) from Stoop.

Across all lifts with the 20P box, the SHK angle was larger (i.e., there was more hip flexion) by an average of 2.7° as compared to all lifts with the 0P box.

3.2. Shoulder, elbow, and wrist heights

The statistical analyses for height values (Table 2), taken at the deepest portion of the bend (Table 2), provide insight into how the arm changed its kinematics due to the exoskeleton. The range of motion for the wrist, elbow, and shoulder heights (Fig. 5 and Appendix Tables 8–10) are also provided.

The shoulder height shows a significant difference between With-Exo and Without-Exo and between both Box weight conditions. On average, subjects lowered their shoulders 1.3 cm less while wearing the exoskeleton. Stoop and Squat lifting were significantly different from each other while Freestyle overlapped with

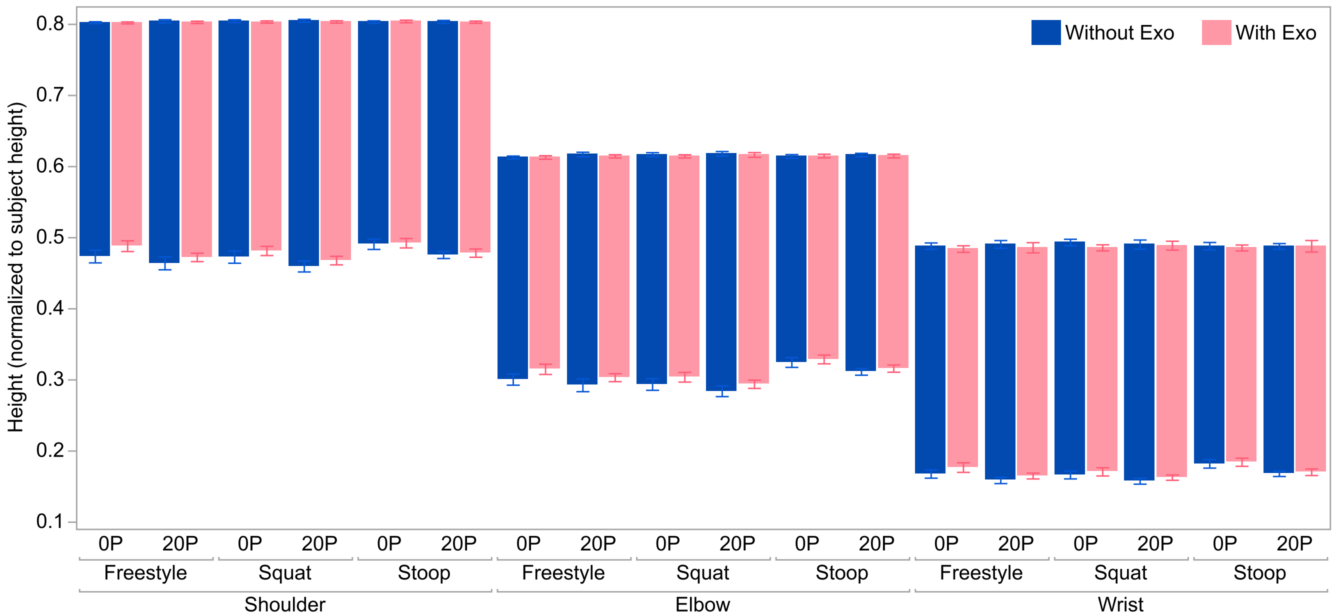

Fig. 5. Range of motion of the Shoulder, Elbow, and Wrist heights (normalized to subject height) for each Lift style, Box weight, and Exo condition. Each error bar is one standard deviation from the mean.

both of the other lifting styles. There was also a significant interaction effect between Exo and Lift style. Subjects bent lower without the exoskeleton for Squat and Freestyle lifting, but there was no significant difference between With-Exo and Without-Exo shoulder height for Stoop lifting.

The minimum elbow height was significantly different between the With-Exo and Without-Exo conditions and between the two box weight conditions. On average, subjects lowered their elbows 1.6 cm less while wearing the exoskeleton. Freestyle and Squat lift styles were not significantly from each other, but were both significantly different from Stoop lifting. There was also an interaction effect between Exo and Lift style where a greater difference between With-Exo and Without-Exo occurred for Squat and Freestyle lifting than Stoop lifting.

When looking at the wrist height, there were significant differences between the With-Exo and Without-Exo conditions and between the two box weight conditions. On average, subjects lowered their wrists 0.7 cm less while wearing the exoskeleton. Freestyle and Squat lifts were not significantly different from each other, but both were significantly different from Stoop lifts.

3.3. Speed and acceleration

The speed and acceleration of movement were analyzed by observing both the shoulder markers and the box markers (Fig. 6) to further determine how each variable affects subject movement. Lifting direction (bending down or standing up) was also considered in the statistical analyses (Table 3). For both aver-

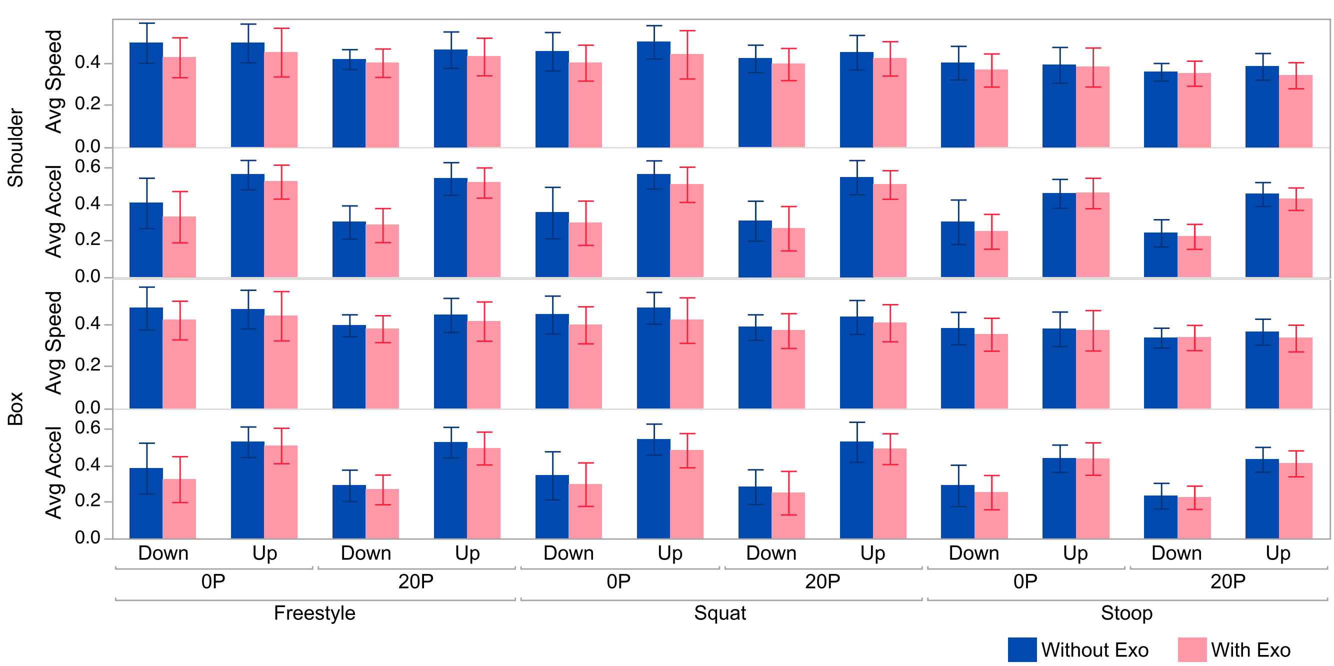

Fig. 6. Average speed and acceleration of lifting calculated from the box and shoulder markers. Both speed and acceleration have been normalized to subject height so speed has units of $1/s$ and acceleration has units of $1/s^2$. Each error bar is one standard deviation from the mean.

Table 3
Aggregation of average speed and acceleration of lifting calculated from the shoulder and box markers. Distance has been normalized to subject height giving units of $1/s$ for speed and $1/s^2$ for acceleration.

		Box		Shoulder	
		Avg. Speed	Avg. Accel	Avg. Speed	Avg. Accel
Exo	Without	0.416 (0.083)	0.400 (0.138)	0.437 (0.084)	0.418 (0.142)
	With	0.387 (0.088)	0.368 (0.137)	0.401 (0.087)	0.381 (0.142)
	p-value	0.0013 *	0.0002 *	0.0002 *	0.0002 *
Lift style	Freestyle	0.430 (0.089)	0.413 (0.138)	0.448 (0.088)	0.432 (0.142)
	Squat	0.417 (0.085)	0.400 (0.147)	0.436 (0.085)	0.416 (0.151)
	Stoop	0.357 (0.068)	0.339 (0.117)	0.372 (0.068)	0.352 (0.124)
	p-value	<0.0001 *SqF vs St	<0.0001 *SqF vs St	<0.0001 *SqF vs St	<0.0001 *SqF vs St
Box Weight	0P	0.419 (0.096)	0.401 (0.136)	0.434 (0.097)	0.416 (0.143)
	20P	0.383 (0.073)	0.367 (0.139)	0.403 (0.073)	0.383 (0.142)
	p-value	0.0032 *	0.0091 *	0.0147 *	0.0256 *
Direction	Down	0.390 (0.080)	0.285 (0.102)	0.408 (0.079)	0.296 (0.109)
	Up	0.413 (0.092)	0.484 (0.089)	0.429 (0.094)	0.504 (0.087)
	p-value	0.0984	<0.0001 *	0.1546	<0.0001 *

* denotes statistically significant difference between conditions with $p < 0.05$.
*SqF vs St denotes that Squat and Freestyle are not significantly different from each other, but both are significantly different from Stoop ($p < .05$).

age speed and acceleration the Freestyle and Squat lifts were not significantly different from each other, but both were significantly different from Stoop. Box weight was significant for both the speed and acceleration of the box and shoulder. Direction was significant for box and shoulder acceleration and also frequently showed up as an interaction effect. For box speed, box acceleration, and shoulder acceleration, subjects bent down faster while carrying the 0P box. For shoulder speed the greatest difference in speed between moving up and down was seen for squat. Subjects had a lower average speed and acceleration while wearing the exoskeleton. Their average speed at the shoulder was 0.78 m/s in the Without-Exo condition versus 0.72 m/s in the With-Exo condition. Subjects also lowered the box more quickly than they raised it.

3.4. Relative torques and angles

To facilitate using the data in exoskeleton design and analysis, best-fit lines (either linear or quadratic) were applied to the torso angle as a function of SHK angle, the torque to support the torso as a function of the SHK angle, the torso angle relative to the height of the box, and the subject's center of mass (COM) relative to the height of the box. The equations (Appendix Tables 11–14) and the graphs for lifting the 0P box both With-Exo (Fig. 7) and Without-Exo (Appendix Fig. 9) are presented. While not included here, the results for the 20P box were similar. The Without-Exo torso torque was also compared to the change in the SHK values between With-Exo and Without-Exo (Appendix Fig. 10), and we did not find a significant relation between the two variables.

3.5. Relationships between kinematics and EMG

While comparing With-Exo to Without-Exo conditions, we did not find statistically significant relationships between the EMG reductions in Alemi et al. (2019) and the changes in peak joint angles or torso torque measured in this paper. Considering just the Without-Exo condition, we also did not find a relationship between the peak torso torque and the peak or mean back and stomach muscle EMG values (p-values between 0.18 and 0.96). However, we did find relationships between the peak torso torque and the peak leg muscle EMG values. Graphs of the peak torso torque versus leg EMG values for lifting the 0P box (Fig. 8) as well as the equations (Appendix Table 15) are presented. There was a positive relationship between the muscle activity of the biceps femoris and the torso torque, while the vastus lateralis had a negative relationship. These trends were similar for the 0P and 20P boxes.

4. Discussion

Overall, subjects dorsiflexed their ankles more and had less knee and hip flexion at the lowest portion of the lift while wearing the exoskeleton. The exoskeleton creates a torque of around 70 Nm around the hips and lower back in the direction of extension. It appears that this large torque caused the subjects to decrease hip flexion and slightly increase knee extension. Given the smaller flexion angles at the hip and knee, the ankle angle necessarily increased in dorsiflexion so that the subjects could still reach and grasp the box.

It is interesting to compare our results to those of a few earlier studies that explored the effects of back-support exoskeletons on lifting kinematics. One study examined both the Laevo and BackX, and did not find changes in the peak flexion angle while wearing either exoskeleton (Madinei et al., 2020), while another study on just the Laevo found that the lumbar flexion angle increased (i.e., subjects bent further) during ankle-height lifts with the box close by Koopman et al. (2020). While researchers studying the SPEXOR did not find significant changes in knee, hip, lumbar, or trunk joint angles (Baltrusch et al., 2019), it appears that the knee and hip angles did decrease in flexion, similar to our results. Researchers testing the PLAD exoskeleton found greater dorsiflexion ankle angles while wearing the exoskeleton, similar to our results, and found decreased lumbar and thoracic flexion, so that subjects kept their backs straighter (Sadler et al., 2011). The decreased lumbar and thoracic flexion broadly corresponds to a smaller SHK angle, as we observed with the exoskeleton. Finally, one study on an active back support exoskeleton found reductions in the lumbar flexion angle (Koopman et al., 2019). Thus, while some previous works found similar results to our study, there is not consistency in the literature about the effects of a back-support exoskeleton on lifting kinematics.

While the dynamics of lifting are different than those during walking, a number of studies have examined the effects of lower body exoskeletons on the joint angles during walking and may provide insight into our results. In those studies, torques pushing a joint in a given direction cause the joint to have a smaller angular change in that direction. Torques pushing the ankle toward plantarflexion during pushoff have caused it to be less plantarflexed by as much as 10° (Jackson and Collins, 2019; Koller et al., 2015), and torques extending the hip have caused it to be less extended by around 4° (Young et al., 2017). Thus, it is plausible that for large torques extending the hip during lifting, a similar biomechanical response is observed that corresponds to less hip extension. It

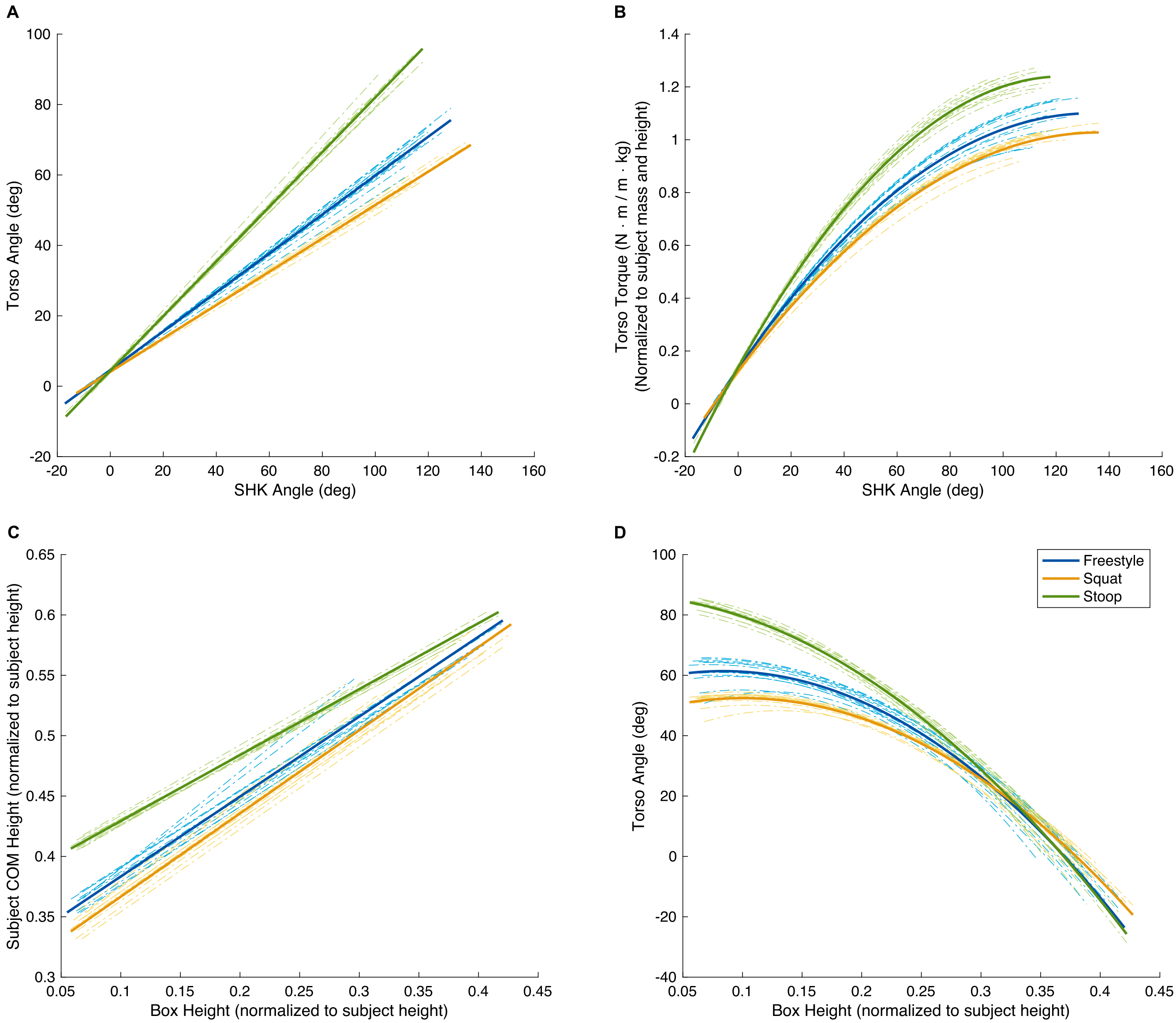

Fig. 7. Freestyle, Squat, and Stoop lifts while lifting the 0P box with the exoskeleton. A, Torso Angle versus SHK Angle. B, Torso Torque versus SHK Angle. C, Subject COM Height versus Box Height. D, Torso Angle versus Box Height. In each plot, the lighter shaded dashed lines are the best fit lines for each individual participants' data. The solid thick line is the average of the best-fit lines for each participant. A and C have linear fits while B and D have parabolic fits. The equations of the best fit lines are given in Tables 11–14 for subplots A-D, respectively. The torso angle is calculated as the angle between a vector from the shoulder to the hip and a vertical unit vector at the origin. SHK angle is calculated as 180° minus the angle between the shoulder, hip, and knee in the sagittal plane. Subject COM is calculated using markers at the joint positions and anthropometric data. Box height is calculated with an offset from the box markers to get the COM of the box. The torso torque includes the contributions from both the human and the exoskeleton.

may be that these changes were observed with our exoskeleton while they were not observed in previous works since our exoskeleton applied a somewhat larger torque than prior exoskeletons: ours provided around 70 Nm, while other works (including the PLAD (Abdoli-Eramaki et al., 2007), Laevo (Koopman et al., 2019), Biomechanically-Assistive Garment (Lamers et al., 2017), and SPEXOR (Baltrusch et al., 2019) provided between 23 and 50 Nm. Indeed, our exoskeleton's torque might have been too strong, based on reasons described in our limitations section, for one female subject who volunteered for the study and who was excluded on that basis. The most appropriate torque for a given height and mass of person is currently unknown. While we investigated the relationship between the change in SHK angle and the torso torque, we did not find a significant relationship (Appendix Fig. 10). It may be that the changes in the SHK angle were small because the box was always at the same height, so the maximum change in SHK angle was limited.

The kinematics changes resulting from wearing the exoskeleton may also be due in part to participants not being fully adapted to the exoskeleton. Exoskeletons assisting walking can require more than two days to enable the wearers to be fully adapted, and during this time the wearer's kinematics slowly become closer to what they were without an exoskeleton (Gordon and Ferris, 2007). In our experiment, no participants had worn the exoskeleton extensively, and some participants wore the exoskeleton for the first time on the day of the tests. Further studies would be useful to explore the effects of adaptation on back exoskeletons.

In comparing our kinematics results to our EMG results, we had expected that the further a person bent their torso forward, the larger the back muscle activity would be since the muscles are used to raise the torso back to a vertical posture. This was possible to examine within each subject since each person flexed their torso different amounts while doing Stoop, Squat, and Freestyle lifts. Surprisingly, we did not observe this with the back muscles. It

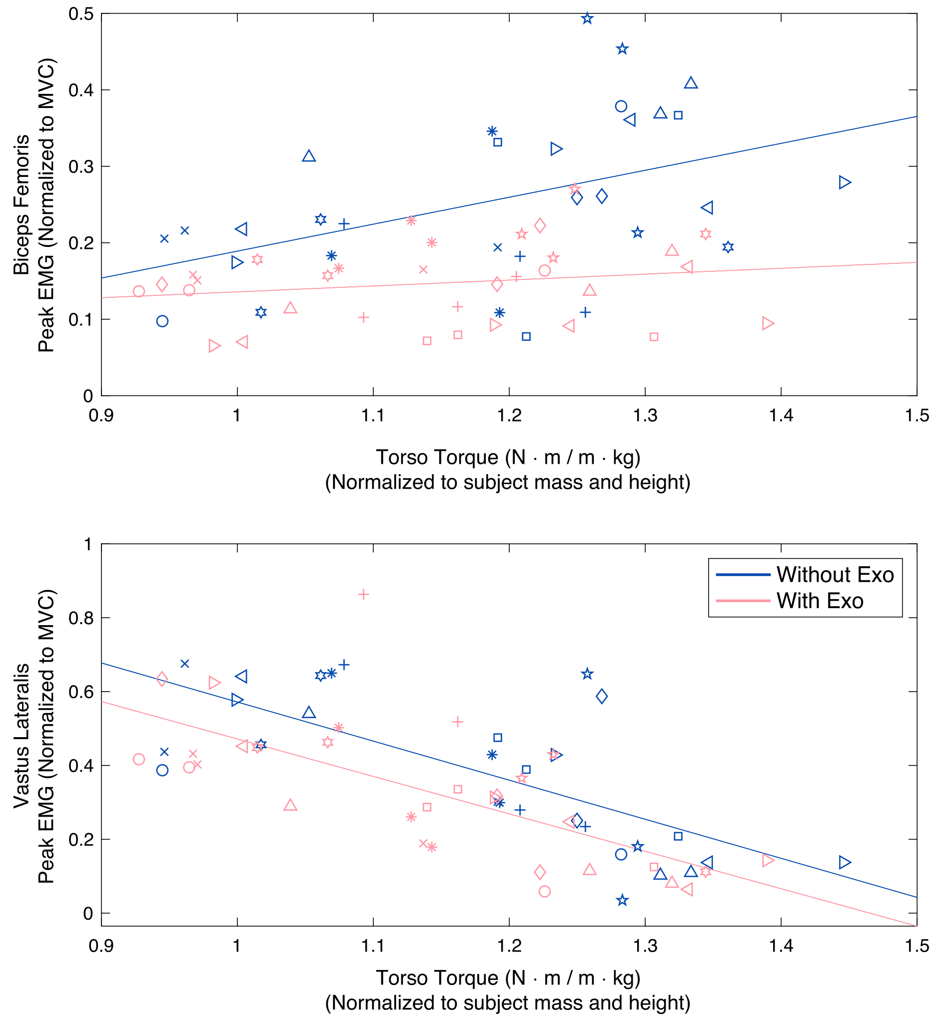

Fig. 8. Peak EMG muscle activity for the leg muscles versus torso torque at the peak of the lift. Peak EMG was normalized to MVC and torso torque was normalized to subject mass and height giving units of $N \cdot m/m \cdot kg$. Lines of best-fit are shown for both the With Exo and Without Exo conditions.

may be that looking at the overall back muscle activity (peak or mean EMG) versus the peak torso angle or peak torso torque is not enough to see a relationship, and comparing the muscle activity with the torso angle at each point in time would be more informative. Alternatively, it may be that passive structures in the back were responsible for a high percentage of the torques created by the back at high torso flexion angles, and thus the muscle activity did not change very much after a certain point (Bazrgari et al., 2007; Dolan et al., 1994; Koopman et al., 2019; Olson et al., 2009).

Interestingly, we did see a relationship between the torso torque and peak leg muscle activity. Although there is a change in the torso torque with lift style, it appears that the back contributes similar amounts of muscle activity while the legs compensate for the change. Wearing the exoskeleton results in a shallower slope in the relationship between the torso torque and vastus lateralis activity, so by supporting the back it also appears to relieve some of the effort required by the legs.

The shoulder, elbow, and wrist heights were always further from the ground at the lowest portion of the lift while wearing the exoskeleton. This also appears to be an effect of the decrease in the SHK and knee angles. Since the arms were higher above the box, presumably the box handles were held closer to the distal ends of the fingers, although this was not measured directly. It would be informative to measure if this resulted in a decrease in the security of their grip on the box. However, subjects bent further so their arms were closer to the ground when picking up the 20P box as compared to the 0P box, possibly to gain a better grip on the box. It may be that subjects were not fully adapted to the exoskeleton when they were evaluated, and further experience would lead to their being better able to relax and allow the exoskeleton to support them. This may lead to kinematics more similar to lifting without an exoskeleton. Anecdotally, subjects that lifted the 0P box after lifting the 20P box especially noticed the extra support from the exoskeleton and took extra practice lifts while switching between box weights so they could properly adjust to the exoskeleton while lifting a substantially lighter weight.

Our examination into lifting speed and acceleration found slightly slower movements while wearing the exoskeleton. This is similar to an effect seen with the Laevo in two studies, which found an 18% reduction (Koopman et al., 2020) and a 7.1% reduction (Madinei et al., 2020) in speed. Given the support from the exoskeleton, subjects may have preferred to move more slowly to maintain better control, or possibly the slower motion was beneficial to the muscle-tendon dynamics: a muscle moving more slowly has a greater capacity for force generation (Fenn and Marsh, 1935; Farris et al., 2014). While Madinei et al. (2020) suggests that possibly a slower speed is due to an inadequate torque generated by the Laevo, that is clearly not the case for our exoskeleton. Thus, reductions in speed with an exoskeleton are likely due to other effects such as increased stability or energy efficiency.

The decrease in muscle activation while wearing the exoskeleton (Alemi et al., 2019) could be partially due to the slower movement. However, the decrease in shoulder speed (7.1% or 0.0538 m/s) and acceleration (8.8% or 0.120 m/s^2) was small. As such, most of the reduction in back muscle activity (31.5% peak reduction and 29.3% mean reduction) is due to the exoskeleton's torque and not speed of movement. It may be that the support from the exoskeleton unintentionally further reduces muscle activity beyond that offset by the exoskeleton's torque, due to the reduced lifting speed.

Overall, the box markers showed that subjects bent down faster than they stood back up. The slower speed could be due to additional exertion required while returning to a vertical posture. As expected, subjects lifted the 0P box faster than the 20P box.

Data presented in Fig. 7 are useful for the future design of exoskeletons, as a lift-assistance exoskeleton will need to support the weight of the torso while applying a torque around the hip. The torso angle and torque versus SHK angle are important since a passive exoskeleton should create a torque to support the torso, but it is worn around the hip and thus bends to an angle related to the SHK angle. Characterizing these relationships allows exoskeleton designers to choose mechanisms that appropriately support the torso during a range of motions. Additionally, characterizing the COM height versus the Box height is useful for understanding the energetic requirements for moving a box from one height to another.

While other studies have looked into the difference between Stoop, Squat, and Freestyle lifting (Van Dieën et al., 1999; Vecchio, 2017), and specifically the joint angle difference between Stoop and Squat (Hwang et al., 2009), this study also presents the joint angles for Freestyle and allows for comparison with Stoop and Squat. As expected, Freestyle falls in between Stoop and Squat, but it is interesting to see where it falls. Although Stoop lifting is more metabolically efficient (Garg and Herrin, 1979), our participants chose their Freestyle lifts to more resemble Squat lifting. This resemblance may be due to the fact that many of the participants were trained in weight lifting and had been previously taught to use Squat style lifting.

Our study had several limitations. Our shifting of the hip markers may have resulted in small errors in the true hip position, especially for the individuals who did not have an iliac crest marker; any errors would affect the SHK and knee angles. Our shifting assumed that the pelvis maintained the same orientation both With and Without Exo, which is not perfectly true. However, even if the hip markers were incorrectly moved by 1 cm, the SHK angle would change at most by 1.3° and the knee angle by 0.9°, so the effect would be small (we observed differences of 2.3° and 2.6° due to the exoskeleton for the SHK angle and knee, respectively).

Also, only men and only one exoskeleton strength were tested. The exoskeleton strength depends on the number of carbon fiber pieces, and it was not feasible to customize the fit to each participant due to the time required. The exoskeleton appeared to be too strong for the one female (approximately 170 cm tall, average weight) that was interested in participating in our study and was therefore excluded. When they first visited the lab, subjects bent at their waist to find their "free hang" position, where they could stay bent over and have their torso entirely supported by the exoskeleton. Ideally participants would reach a torso angle of at least 60°, but this was not formally measured. The one female who was excluded only reached around 45°. This free hang position depends on the wearer's body size and mass, but also depends on the individual trusting the exoskeleton's support and fully relaxing. It is possible that not enough time was given to build that trust for the one female. In addition to this, the waist belt did not stay in place and would slide up her hips while bending forward. A second female was also not included due to scheduling constraints. Finally, the adaptation time to the exoskeleton was limited, as previously discussed.

5. Conclusion

The VT-Lowe's exoskeleton has already been proven to show a significant EMG reduction for the back and upper leg muscles in various lifting types (Alemi et al., 2019); this study evaluated the kinematics of the VT-Lowe's exoskeleton. The results demonstrated an increase in the ankle dorsiflexion angle and decreases in the knee and waist flexion angles while wearing the exoskeleton. Future studies should investigate if this difference is maintained if individuals are fully adapted to the exoskeleton. We also presented equations relating a person's torso angle, SHK angle, torso torque, COM height, and box height. Together, these provide a basis for analyzing the work and energy used during human motion, and provide specifications for future exoskeletons assisting lifting.

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Declaration of Competing Interest

A. Asbeck is a co-inventor of a patent on the exoskeleton.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jbiomech.2021.110317.

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