Evaluation of Trunk-Supporting Exoskeleton

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Trunk Supporting Exoskeletons are increasingly being evaluated in workplaces as viable ergonomic interventions for reducing the risk of back injuries. A series of trunk-supporting exoskeletons have been designed and built at the University of California at Berkeley and suitX. These exoskeletons decrease the forces on the wearer's back at L5/S1 location. This article describes one of these exoskeletons, referred to as backX, and its evaluation method. backX is designed not only to reduce the forces and torques on the wearer's back at L5/S1 location, but also to allow the wearer to perform all kinds of maneuvers such as walking, squatting, ascending and descending stairs, slopes and ladders, riding bicycles and driving trucks. This study finds that average muscle activities of the thoracic and lumbar erector spinae muscles among equal populations of male and female subjects, wearing backX while maintaining forward bending postures, are reduced by 75% and 56% respectively. The results of this study and extended field evaluations indicate that wearing backX minimizes the risk of back injuries among workers who repeatedly go through stooping, squatting, and bending postures for various tasks, such as lifting objects.

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I. INTRODUCTION

The overall objective of our research is to develop accessible, highly effective, comfortable, transparent exoskeletons that can be worn all day long and reduce the risk of back injuries among workers. Figure 1 shows one version of backX built at suitX. It consists of two leg straps and a vest coupled to each other by two torque generators at both hip joints. Consider the situation where a person has bent his/her torso from vertical posture by α as shown in Figure 2. In a static case and in the absence of any load, the torque imposed at L5/S1 can be represented $[M_B \;\, g \; l_B \sin(\alpha)]$ where M_B represents the mass of the person's upper body (including the human trunk, head and arms), g represents the gravity acceleration, and l_B is the distance between the upper body center of mass and L5/S1 point. A simple calculation shows that the bending moment at L5/S1 can reach up to 200 Nm even when the person has not picked up a load. Obviously, this range of bending moment increases during load handling and dynamic maneuvers. When the worker wears the proposed backX, the torque generators create a torque between the device vest and the device thigh straps. This torque produces a force F onto the person opposing the torque due to the torso weight. This means the torque imposed at L5/S1 is reduced to a new value: $[M_B \;\, g \; l_B \, sin(\alpha) - FL]$ where L is the distance from force F to point L5/S1 (Figure 2.) This shows the basic concept proposed here, where backX decreases the bending moment at L5/S1 and consequently decreases the likelihood of injuries during repetitive maneuvers. Muscle force F_M decreases as force F increases. Muscle force F_M, in quasi-static operations when a part with mass of M_P is lifted is, can be expressed as:

$$F_M = \;(M_B l_B + M_P l_P)\;\frac{g}{d}\sin(\alpha) - \frac{FL}{d} \qquad (1)$$

Spine compression force F_{CS} similarly decreases as force F is increased and can be expressed as:

$$F_{CS} = \;(M_B l_B + M_P l_P)\frac{g}{d}\sin(\alpha) + (M_B + M_P)\; g\cos(\alpha) - \frac{FL}{d} \qquad (2)$$

This analysis assumes F_{CS} and F_M to act perpendicularly to force F, and bending acceleration to be negligible. As these equations demonstrate, when force F is increased, both the forces in the erector spinae muscle and the Spine Compression force (shown by F_{CS} and F_M above) are decreased. Further static analysis shows the spine shear force F_{SS} decreases as represented by equation (3)

$$F_{SS} = \;(M_B + M_P)g\sin(\alpha) - F \qquad (3)$$

The above analysis shows that to reduce muscle force F_M, and spine compression force F_{CS}, there needs to be an imposing force F on the wearer trunk (chest or shoulder) as shown in Figure 2. However, in practice we have found that this force should be present only when the wearer is bending and should automatically disappear during all other wearer's postures. If force F is present during other maneuvers, such as climbing stairs or walking (even for a short amount of time), the wearer's motion will be impeded, and the wearer may even fall. In this paper, we provide an architecture for passive backX (*Figure 1*) that faithfully provides force F only during bending and stooping.

Figure 1: An experimental backX for workers. The torque generators at the hip compensate for the torque due to the upper body weight and therefore minimize the erector spinae muscle forces at L5/S1 location

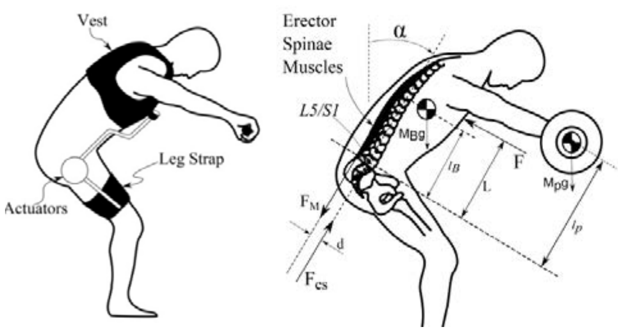


Figure 2: A schematics of the trunk-supporting exoskeleton proposed here consists of two leg straps and a vest coupled to each other by two torque generators. The torque generators create a torque between the torso and the thigh links. This torque produces a force F onto the person, compensating the torque due to the user's torso weight. In this simple model, the erector spinae muscle force, F_M, acts in parallel with the spine with the distance d from the spine center. This muscle force creates a compression spine force by F_{CS}.

II. PROPOSED EXOSKELETON ARCHITECTURE

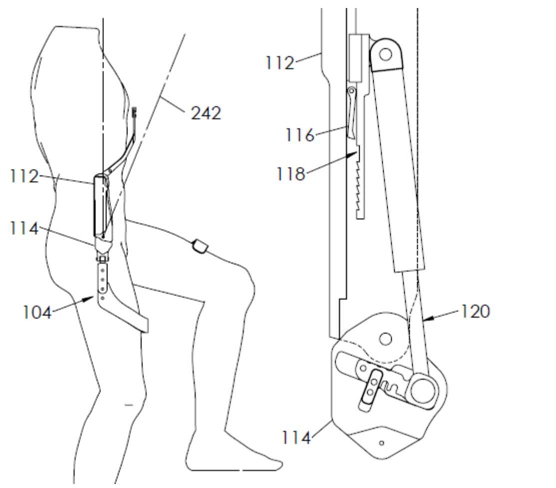
The torque generators of backX are passive and use gas springs for generating force, however this is only done when the wearer bends. The gas springs are not in effect when the operator is walking or climbing stairs. *Figure 4* shows a version of backX with passive torque generators in two postures: (A) when the operator is not bent; (B) when the operator is bent. The drawings in *Figure 4* show the close-up view of our passive torque generator with the covers removed. As shown, the passive torque generator in *Figure 4* is a novel device that provides a torque in reaction to the trunk gravity only when the user's upper body bends forward. This torque generator comprises of:

1) an upper bracket, 112, coupled to vest which is worn by the person;
2) a lower bracket, 114, which is coupled to thigh strap 104. The lower bracket 114 rotates relative to upper bracket 112 in the sagittal plane. This allows for flexion and extension of the legs relative to the trunk (hip rotation).
3) a pendulum, 116, which is mounted on upper bracket 112. The pendulum is free to rotate along its upper end depending on the direction of gravity and the orientation of the upper bracket.
4) an engagement bracket, 118, which is slidingly coupled to the upper bracket.
5) a compression spring, 120, which is rotatably coupled to the lower bracket from its first end and rotatably coupled to the engagement bracket from its second end.

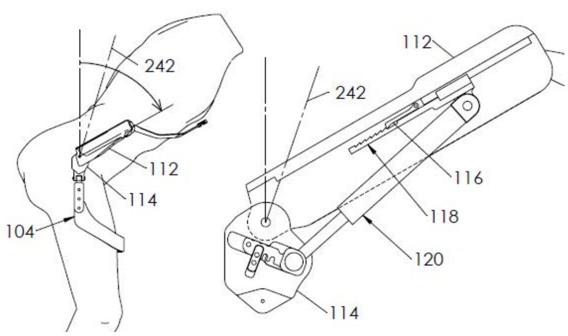
In operation, when the operator bends his/her trunk forward past an engagement axis 242, as depicted in *Figure 4*B, pendulum 116 comes into contact with the engagement bracket 118 and prevents from sliding, causing compression spring 120 to provide a resisting torque between upper bracket 112 and lower bracket 114. With this construction, as the wearer bends further in the sagittal plane such that the supporting trunk axis 216 deviates beyond engagement axis 242, gas spring 120 will create a higher compression force and the torque generator will impose a resisting torque between upper bracket 112 and lower bracket 114 (i.e. between the supporting trunk and its corresponding thigh link). As a result, during forward lumbar flexion, the bending moment at L5/S1 is greatly reduced.

III. METHOD AND EXPERIMENTS

Subjects. The decrease in erector spinae muscle activity data when backX is used in comparison to when it is not used demonstrates backX effectiveness on lower back musculature. To evaluate the backX performance, an experimental procedure was created with 8 subjects of varying heights and even gender distribution performed a series of repeated tasks. Subjects provided informed consent and the protocol was approved by the University of California, Berkeley Investigational Review Board. The evaluation method was an experimental study of the subjects in two equal stooping operations which differed in only one aspect: one operation used the backX and the other did not. Each stooping task was repeated six times: three times with the backX, and three times without backX (order randomized). The subjects became familiar with the backX through observation and practice. For training purposes, each subject wore the backX a few days prior to the measurement day. This allowed the subjects to become familiar with the details of the backX and the experiments. The activities of Left Thorax Lumbar Erector Spinae (LTLES), Right Thorax Lumbar Erector Spinae (RTLES), Left Thorax Thoracic Erector Spinae (LTTES), and Right Thorax Thoracic Erector Spinae (RTTES) were identified as a measure of backX effect. Surface EMG (Electromyography) electrodes were attached superficially over the four erector spinae muscles as shown in *Figure 5*. The evaluation consisted of two phases: without the backX and with the backX. In the first phase, the subjects were instructed to perform forward torso flexion at an angle of 60 to 65 degrees from the vertical while their hands are touching a stack of papers without imposing forces on it as shown in Figure 6. The knees were straight. The torso angle of the subjects was measured by placing a Mitutoyo digital protractor at the subjects' spinal vertebrae T7 section.

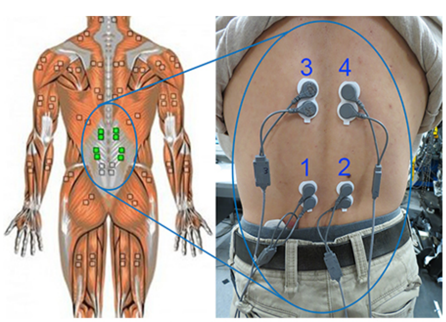


A



B

Figure 3: The schematics of backX in two configurations. A: The wearer is not bent, and the torque generator is not engaged. B: The wearer is bent, and the gas spring is compressed and generated an appropriate amount of supporting torque.



1- LT Lumbar Erector Spinae
2- RT Lumbar Erector Spinae
3- LT Thoracic Erector Spinae
4- RT Thoracic Erector Spinae

Figure 4: Photograph and drawing showing the location of the surface EMG electrodes on the subject's lower

Once this position was found by adjusting the height of stacked paper, the Noraxon MR2.5 EMG processing software started recording the EMG activities and the subject held this static stoop position for 5 seconds. Three trials were taken for data accuracy. The second phase with the backX repeated the steps from the first phase. Each subject was instructed to wear the backX and adjust it to their comfort level, then performed static stooping of the torso at the angle range of 60 to 65 degrees from the vertical. A two-minute rest was given to each subject between each experiment.

IV. RESULTS

For all subjects, erector spinae muscle activation was reduced, which is consistent with equation 1 and the expected result. *Figure 7* shows the averaged median data for the entire population. *Figure 7* shows that the lowest muscle reduction was in the LTLES muscle group with 51% reduction, and the highest reduction was seen in the RTTES group with 76% reduction. As seen the evaluation of the subjects resulted in greater reduction for the LTTES/RTTES muscle groups, ranging from 75-76%, than the LTLES/RTLES muscles groups, ranging from 51-62%. These results demonstrate the exoskeleton's effectiveness on lower back muscles; there was at least a 51% reduction in muscle activity. The data in *Figure 7* indicates an average of 75% reduction in averaged median EMG activities in thoracic erector spinae and average of 56% reduction in averaged median EMG activities in lumbar erector spinae muscle group. Overall, the results clearly show that backX is useful for reducing lower back muscle activity in a static stoop position for all populations represented in the experiment. For workers who spend part of their worktime in a forward bent posture, our results indicate that wearing a backX will reduce muscular back activity and consequently will reduce the risk in developing back complaints or even disorders.

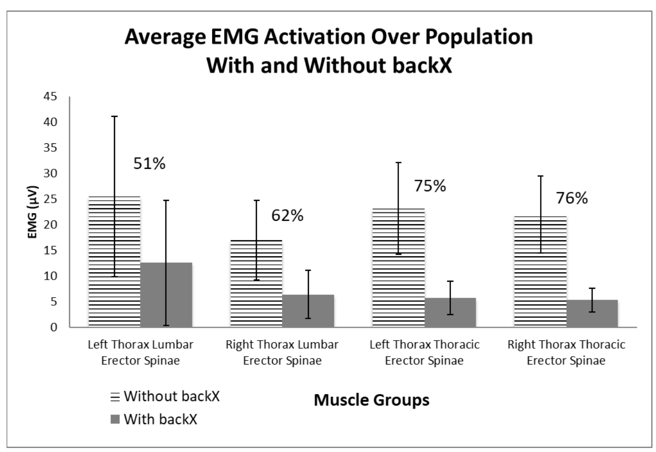


Figure 5: The averaged median EMG activities of four muscle groups for total population sampled.

V. DISCUSSION

The aim of this study was to develop a trunk supporting exoskeleton to reduce the muscle activities in the wearer's back during forward bending postures. The exoskeleton developed here, backX, show substantial reduction in muscle activities during forward bending posture. Other studies on passive back support exoskeletons also show reduced muscle activities when resistive torque is applied at the hip. For example, Baltrusch et al. in (Baltrusch et al. 2018) report a significant decrease in task difficulty in forward bending wearing Laevo, while significant difficulties were observed in several other tasks, like walking, squatting and wide standing. Bosch et al. (Bosch et al., 2016) also evaluated Laevo and reported reduction of muscle activities of the erector spinae by 35-38%, although they emphasized discomfort is a challenge in the design of exoskeletons. Näf et al. in (Näf et al. , 2018) reports a back-support device using flexible beams where an increase of 25% range of motion of the trunk in the sagittal plane was observed. On active exoskeletons, decrease of discomfort during forward bending have been reported (Huysamen et al., 2017) and (Miura et al., 2017.) These studies demonstrate that, in general, resistive torques at the hip do reduce muscle activities in the back during forward bending postures. The amount of reduction in muscle activities depends on the strength of torque generators in the device, fitness of the device on the person, the person physical strength and many other practical factors. However, the workers will not use trunk-supporting exoskeletons if the exoskeletons do not allow for comfortable walking. In general, regardless of the magnitude of force reduction in the back, if the user cannot do other required maneuvers comfortably, they will not use the device. Walking is an important daily maneuver in many work settings. Climbing and descending stairs and slopes are also common maneuvers in various work settings. We even observed that riding a bicycle is a common maneuver in shipbuilding industries. We further observed that driving a truck is essential for those workers who load delivery trucks. In general, workers who bend frequently in their work, also do other tasks. An exoskeleton that reduces the lower back muscle activities must not impede other workers' motions. All devices referenced here do reduce the forces in the lower back because they produce torque at the hip during forward bending posture. However isolated forward bending posture is an extremely limited maneuver. Engineers, ergonomic experts and other professionals in the field, should focus on what capabilities are lost when an exoskeleton is added to the person. We believe adding a capability to a human or augmenting a human, through robotics, is relatively easy, but ensuring no function is lost during this augmentation can be quite difficult if not impossible. Figure 8 shows some of the field evaluations of backX to ensure that the workers can perform all kinds of maneuvers easily. A casual glance over these photos or other work settings concludes that, for widespread use of any exoskeleton, the exoskeleton must seriously remain transparent to the wearer.

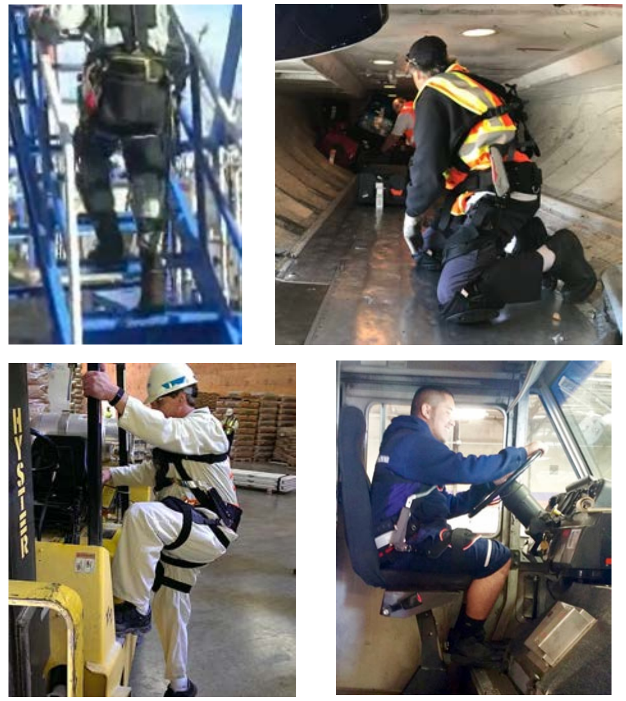


Figure 8: Some examples of peripheral tasks performed by workers wearing backX.

VI. REFERENCES

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