The Oxeous Back-Support Exoskeleton: Soft, Active Suit to Reduce Spinal Loading

ME 59900 - Advanced Mechatronics Course Project
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I. INTRODUCTION

According to the Bureau of Labor Statistics (BLS), back injury is the nation's number one safety problem at the workplace. One in every five workplace injuries is a musculoskeletal back injury. On an average, these injuries cost the industry $16 billion dollars (USD) per year. From the statistics, 80% of the back injuries are caused by improper lifting (BLS, 2017). These injuries create sprains and strains causing overstretching and tearing in ligaments or muscle. With the back exoskeleton we propose in this paper, we aim to decrease the amount of stress in the lower back, which may help prevent the back injuries.

The lumbar region of the spine is the main load-bearing region of the spine and consists of five vertebrae, labeled L1-L5. Between each spinal link are intervertebral discs that act as cushions to absorb the stresses incurred by the body from movement. The two most common sites for spinal injury are the L5-S1 and L4-L5 junctions/joints (Asher 2018), especially the discs at those particular junctions. Compressive forces are increased with the muscle/ligament forces acting along the spine because the muscles act on a moment arm smaller than the upper-body and therefore need to generate a larger force. Large muscle forces and large compression forces are grounds for injury in the lumbosacral joint (L5-S1) but high shear forces are a concern as well. Shear forces cause vertebra to slide out of place, which can introduce lower back pain as well.

The free-body diagram shown in Figure 1 was used as a model for our back exoskeleton.

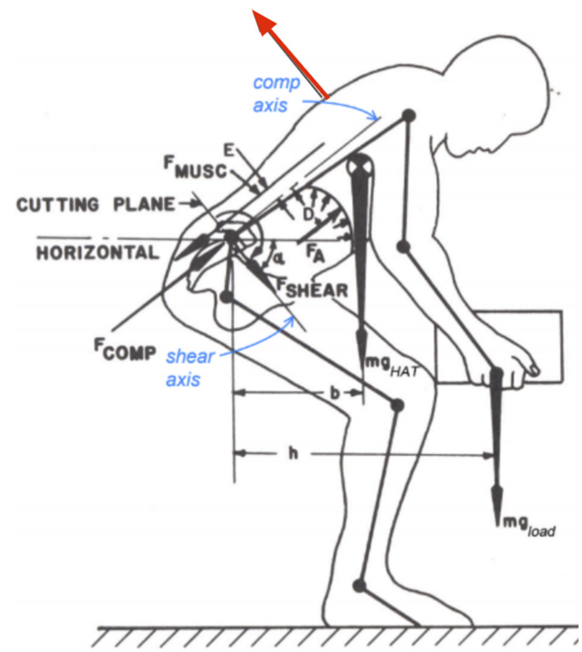

Figure 1. Adapted Free Body Diagram of Low-Back Biomechanical Model from "Occupational Biomechanics" from Chaffin et al., 1999.

The relationships between the force exerted by the exoskeleton (Fexo), erector spinae muscle force (Fe), compression force (Fc) and shear force (Fs) are shown below.

$F_{exo} \uparrow, then\ F_e \downarrow$ [1]

$M_{L5-S1} = m_{load} D_{load} + m_{body} D_{body}$ [2]

$M_{L5-S1} = F_{exo} D_{exo} + F_e D_e + F_a D_a$ [3]

$F_e \downarrow, then\ F_c \downarrow$ [4]

$F_c = m_{load} g cos\theta + m_{body}\, g cos\theta + F_e - F_a$ [5]

$F_{exo} \uparrow, then\ F_s \downarrow$ [6]

$F_s = m_{load}\ g\ sin\theta + m_{body}\ g\ sin\theta - F_{exo}$ [7]

Torque at the L5/S1 disc while lifting a 40 lb weight was calculated as shown below.

$\tau_{s5} = -M_{body}\, g\ (L_{body} sin(\theta_b))$ [8]

The highest torque value, 175 N.m for an average user, was shown to be at 90 degrees' trunk flexion or the stooped position.

Angle α (∘)	Calculated Torque (Nm)
0	0
15	45.293
30	87.5
45	123.74
60	151.55
75	169.04
90	175

Table 1. Corresponding torque values at changing trunk angles.

The Biomechatronics and Intelligent Robotics (BIRO) lab has provided the team with a motor of 16 Nm torque and about 10% of torque assistance.

II. DESIGN SOLUTION

The device's components consist of one top fixture, one bottom fixture, eight disc-ball-disc joints, cables, motor, motor housing, and a pulley. For comfort and convenience, the exoskeleton is attached to an off-the-shelf harness vest as shown in Figure 3.

Figure 3. Full assembly of exoskeleton

Our exoskeleton is inspired by semi-rigid structures found in nature such as elephant trunks, snake skeletons, and human spines. The artificial spine, shown in yellow in Figure 4, is connected with cables and is fixed both at the top and the bottom.

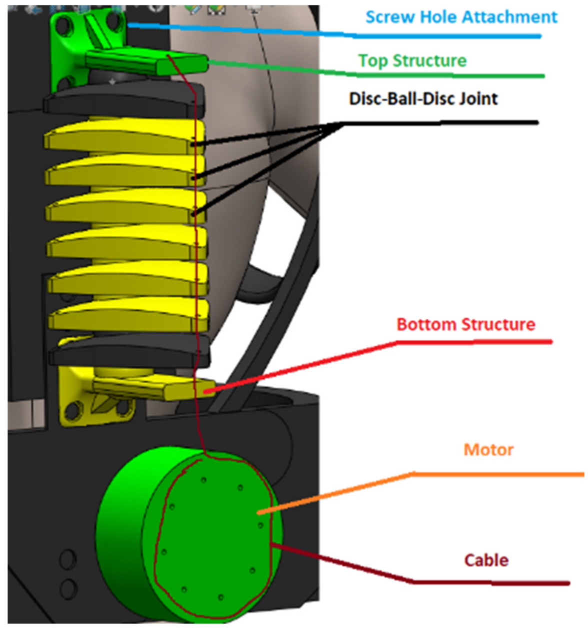

Figure 4. CAD assembly of exoskeleton suit

The exoskeleton system is controlled by an Arduino Due microcontroller. The microcontroller Due would connect to a CAN bus shield designed specifically by the BIRO lab, in order to communicate with the Inertial measure units (IMU) and the controller of the motor. The IMU sensor is used to determine the dynamic torque. The dynamic torque is used to estimate where the person is in the gait cycle, and when to activate. Using IMU sensors remove the need for muscle sensors and the like that could provide the error in measurement. Only a single IMU sensor located at the trunk of the individual was needed, optimally cutting down the processing time.

III. TESTING AND CONCLUSION

The motor was tested with and without the user. Without the user, the back harness did extend when the motor was activated. The motor was moved an eighth of a turn, to ensure proper extension. The motor successfully pulled the artificial spine upwards and normal to the user's back.

Figure 5. Exoskeleton in neutral state

Figure 6. Exoskeleton with motor engaged.

With the user, a box weighing approximately 40 pounds was lifted.

We reached our goal for a lightweight exoskeleton suit, although it is powered and controlled externally. Additionally, the Arduino DUE is a potential controller that would not affect the weight of the suit much. The product is completely plausible as shown in the prototype.

More iterations need to be done to redesign the structure and transmission. The motor was not securely placed on the person, causing the motor to occasionally ride up when testing. A more rigid belt structure around the user's waist would be ideal in making sure the motor and lower back portion of the suit does not move with respect to the wearer. The cable transmission at the top structure should be improved. A redesigned cable transmission can help the motor translate the force normal to the user's back. The motor pulley was not exactly aligned with the cable, causing the cable to slip when the motor was turned on. This slippage can be solved by increasing the pulley width and height to match the path of the cable. Designing for a wearable harness is difficult as it is softer and more flexible than plastics or metals. Additionally, thoroughly testing the device and acquiring dynamic biomechanical analysis is necessary to have more accurate data on muscle activation, compression forces and shear forces acting on the spine. A future suggestion would be to use a top-down approach with IMU sensors to record kinematic data, map it on a biomechanical modeling software such as OpenSim or AnyBody and do a reverse kinematic analysis to determine the joint reactive forces and muscle forces at the L5-S1 disc.

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