

Pneumatic Back Exoskeleton for Lifting Posture Detection and Correction

Yu Chen, Minda Wang, Yifan Wang*

Abstract—Low back pain is a widespread issue that affects people worldwide and can lead to serious conditions such as herniated discs, spinal stenosis, or lumbar radiculopathy. Improper posture while lifting heavy weights is a common cause of back pain, especially among laborers. However, current back exoskeletons are often bulky and require electric motors, making them challenging to use and consuming significant power. Some passive exoskeletons don't require power, but their fixed stiffness constrains normal motion. This paper presents a novel solution: a pneumatic back exoskeleton made of structured fabrics that can adjust stiffness under various air pressures. Additionally, it includes IMU sensors to detect lifting posture and correct it in real time. The exoskeleton's effectiveness was tested through lifting experiments, demonstrating that it significantly corrects lifting posture, reduces stress on the lumbar spine, and mitigates back muscle stress. This pneumatic back exoskeleton offers a promising solution to prevent low back pain during weight-lifting tasks and provides guidance for future back exoskeleton designs.

I. INTRODUCTION

Work-related musculoskeletal disorders (WMSDs) stand as a prominent concern, contributing significantly to employee absenteeism and imposing substantial burdens on healthcare systems. These disorders manifest in diverse anatomical regions and, on occasion, present as intermittent discomfort, serving as potential precursors to more severe pathological conditions. Consider, for instance, the case of low back pain (LBP), a prevalent affliction among manual laborers and novice athletes, often implicated in the etiology of debilitating conditions such as Herniated Disc, Spinal Stenosis, or Lumbar Radiculopathy. LBP, in fact, has ascended to the summit as the most pervasive form of back pain globally and constitutes a vital driver of disability. As of the year 2020, LBP exacted its toll on a staggering 619 million individuals across the globe, with projections portending an alarming escalation to 843 million cases by the year 2050 [1]. Lifting excessive weights with improper techniques can put human backs in a vulnerable position and lead to LBP. When the spine is flexed forward, the back muscles become less effective, and the ligaments become more supportive, leading to increased shear-loading forces on the intervertebral column. To prevent injury, it is essential to use proper posture and avoid overloading the back. Achieving a neutral spine

position can increase its strength by 25% to 40%, making it more resistant to compressive loads. This helps to reduce shearing forces on the lower back [2-7]. Therefore, assessing the lifting motion and supporting the human back during lifting tasks is important.

The physiological, biomechanical, and clinical evidence for two different lifting postures: stoop and squat, are well presented in [8-11]. The two techniques can be classified based on the value of knee angle and trunk flexion. The squat lift has a larger knee angle ($\sim 135^\circ$) and a smaller trunk flexion ($< 30^\circ$), while the stoop lift has a smaller knee angle ($< 45^\circ$) and a larger trunk flexion ($\sim 90^\circ$). Based on such quantitative differences in biomechanical parameters, researchers have created different systems to monitor the straightness of the user's back and offer guidance on how to correct lifting postures. R. Y. W. Lee et al. [12] explained a technique for measuring the real-time three-dimensional movements of the lumbar spine. W.Y. Wong et al. [13] developed a technique that utilizes a posture monitoring system to estimate changes in spinal curvature during movements in both the sagittal and coronal planes, allowing for monitoring of trunk posture during everyday activities as well. L. Jenkins et al. [14] created a wearable device with sensor nodes that gives users real-time posture feedback via a companion APP. These sensing techniques help to guide the future design of back exoskeletons that can assist during the lifting process.

Researchers have developed various types of exoskeletons to mitigate the load on spine or lumbar during lifting tasks. G. Ataei et al. [15] conducted a study on the impact of a self-designed wearable lift-assist vest (WLAV) in reducing erector spinae muscle forces during symmetric squat lifting tasks. U. Heo et al. [16] developed a portable pneumatic actuation system for a back support exoskeleton. X. Yang et al. [17] designed a spine-inspired exoskeleton that can assist both squat and stoop lifting while not impeding walking motion. However, most existing back exoskeletons are made up of rigid bodies and employ electric motors to produce torque at certain joints, thus leading to unwieldy weight and high power consumption, and may impede the natural movements of wearers.

In order to tackle these issues, a novel structured fabric - Chainmail [18]- is utilized for the development of a pneumatic soft and lightweight back exoskeleton that can detect and correct back posture in real-time during lifting tasks. The tunable property of fabrics allows the exoskeleton to function as soft wearable under inactive states and as assistive support under active states without impeding natural movement [19-21]. The contribution of this work includes

This research was supported by A*STAR Singapore through RIE2025 MTC IRG award (M21K2c0118) and RIE2020 AME YIRG award (A2084c0162), and the NAP award (020482) from Nanyang Technological University.

* Corresponding author: Yifan Wang: yifan.wang@ntu.edu.sg

Yu Chen, Minda Wang, and Yifan Wang are with the School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore 639798.

several aspects: a) A method of using IMU sensors to detect lifting posture and calculate the back angle in real-time was proposed. A commercially available optical motion capture system was utilized as a standard reference, to validate the difference in back angles during irregular and regular lifting process. b) A pneumatics back exoskeleton was created based on the IMU system, which was capable of changing mechanical properties and correcting the lifting posture of the wearer in real-time. c) The effectiveness of the proposed exoskeleton was tested based on the simulation results obtained from OpenSim software. A comprehensive analysis of biomechanical parameters, such as joint angles, moments, muscle activation, and metabolic costs, was conducted during a single lifting cycle. The structure of this article is as follows. Section II introduces the definition of back angles and the design of the back exoskeleton. Section III presents the experimental process of back angle acquisition and exoskeleton testification. Section IV discusses the experimental results and the effectiveness of the exoskeleton. Finally, Section V summarizes the work in this study.

II. METHODS

A. Acquisition of Back Angles

The two distinct lifting postures were defined as Regular and Irregular in this study. Regular lifting required the participant to maintain their back as straight as possible during the lifting process, while the irregular lifting posture involved stooping the back to reach the weight. A complete lifting cycle included lowering the torso to a lowest lifting point, grabbing the weight, and lifting it up to a stance position, as shown in Fig. 1(a).

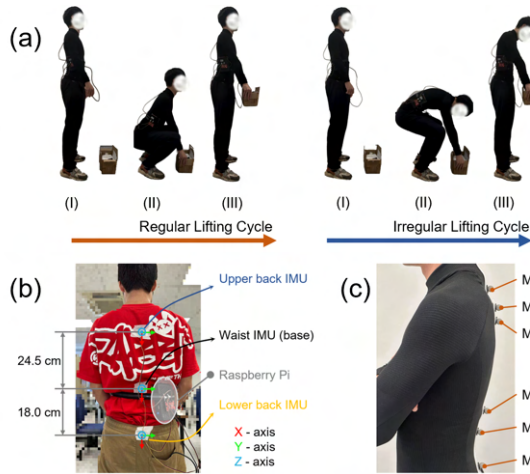


Fig. 1. (a) One lifting cycle using regular and irregular posture. (b) Location and orientation settings of low-cost IMU-based motion capture system. (c) Location settings of the reflective markers for OptiTrack system.

In order to quantify the difference between two lifting postures, the waist was chosen as a dividing line between the upper and lower back in this study. The upper and lower back were treated as two separate rigid bodies, and the angle between the two rigid bodies was evaluated for analysis.

TABLE I
COMPONENTS OF IMU-BASED MOTION CAPTURE SYSTEM

Component Name	Model	Unit Price (USD)	Quantity
Raspberry Pi	4B (4GB RAM) Basic Kit	296.00	1
IMU sensors	LSM6DSOX + LIS3MDL - Precision 9 DoF IMU	22.00	3
Qwiic Connector Cables	SparkFun - PRT - 14429	1.92	4
Qwiic Mux Breakout	SparkFun - BOB - 16784	13.55	1
Rechargeable Battery	/	15.00	1
Strap	/	1.50	1

In reference to [22], a low-cost IMU-based motion capture system was assembled for collecting motion data and calculating the back angle in real time. The capture system consisted of three 9-axis IMU sensors, a Raspberry Pi 4+, Qwiic connector cables, and a USB rechargeable battery. The cost of each component and unit price are listed in Table 1. In total, the IMU system costed around 400 USD. Fig. 1(b) depicts the location and orientation settings of the IMU sensors. The upper back, base, and lower back IMU sensors were attached separately to the scapula, waist, and pelvis. Each IMU sensor consisted of an accelerometer, a gyroscope, a magnetometer, and signal transmission modules, and the bending movement of the wearer's back was along the direction of Ω_y . Since gyroscope data was given in degrees per second, Eq. (1) is utilized to approximate continuous integral from discrete angular velocity [14].

$$\omega = \frac{\Delta\Phi}{\Delta t} = \frac{\Phi_n - \Phi_{n-1}}{t_n - t_{n-1}} \quad (1)$$

$$\Phi_n = \Phi_{n-1} + \omega * \Delta t$$

where Φ denotes the calculated angle value, ω denotes the angular velocity acquired by gyroscopes, Δt denotes the time interval between two sample points. Since the sample rate in this experiment could reach 240 Hz, which was high enough for approximation, the calculated angle value could be regarded as accurate.

To validate the correctness of the self-designed IMU system, a commercialized optical motion capture system (OptiTrack, NaturalPoint Inc.) was employed as a standard reference, which comprised 4 optical cameras and operates at 240 Hz. The system utilized 6 reflective markers (M1-M6) for back posture tracking, as shown in Fig. 1(c). M1 was attached to the end of cervical spine (C7), and M2, M5, M6 was located at scapula, waist, and pelvis, respectively. M3 was placed 5 cm below M2, and M4 was placed 10 cm above M5, which is tested to be the best place for back angle calculation. Three markers located at the upper side (M1-M3) formed the Upper-Back rigid body, and three markers located at the lower side (M4-M6) formed the Lower-Back rigid body. Additionally, the angle between the two rigid bodies was defined as Upper-Lower Back (UpLoBa) Angle, and Eq. (2) was introduced to calculate the UpLoBa Angle using the location data of markers in space.

$$\begin{aligned}
k_1 &= \frac{y_3 - y_1}{z_3 - z_1} \\
k_2 &= \frac{y_6 - y_4}{z_6 - z_4} \\
\text{UpLoBa Angle} &= \cot \left(\frac{k_1 - k_2}{1 - k_1 * k_2} \right)
\end{aligned} \tag{2}$$

where k_1 and k_2 denotes the slope factors of the Upper-Back and Lower-Back rigid bodies, respectively.

B. Design of the Pneumatic Back Exoskeleton

Based on the aforementioned methods of using IMU sensors to calculate the back angles and distinguish the regular and irregular lifting posture, a pneumatic back exoskeleton was developed to detect and correct the wearer's lifting posture in real-time. The IMU-based motion capture system was integrated into the exoskeleton for sensing and actuation. The entire system weighs less than 3 kg, excluding the external pressure source. The basic structure of the exoskeleton system is illustrated in Fig. 2(a).

The core material of the exoskeleton was chainmail fabrics [18], which were a unique type of material that can interlock and become stiff when negative pressure was applied to their boundaries. A three-point bending test was conducted to investigate the mechanical properties of chainmail fabrics at different confining pressure, as shown in Fig 2(b). These fabrics were strategically enveloped in rectangular heat seal bags, and then placed to cover the human back and attach to various anchor points on the body. When not under negative pressure, the exoskeleton remained inactive, and the fabric was soft and flexible. However, once activated, the fabric became rigid, preventing the wearer's back from bending forward into an irregular posture. An air pump and a DC solenoid valve were required to enable negative pressure, with the microcontroller connected to DC relays. When an activation signal was received, the pump and valve would turn on through the relay. Emergency switches were also in place in case of any issues, and gas pipes were necessary to connect the entire system.

Fig. 2(c) depicts the control strategy utilized for the back exoskeleton system. The system incorporated three distinct angles (Up-Mid angle, Mid-Low angle, and Mid-Low angle) as inputs. The angles were calculated and compared to predetermined threshold angle values in the microcontroller, as explained in Section II-A. There was a predetermined threshold for each input angle to determine whether the exoskeleton should be activated. Should the angles exceed the established threshold, the motion will be deemed as improper lifting, triggering a signal transmission from the microcontroller to the relay. The chainmail fabrics will then interlock and stiffen through negative pressure release, halting the wearer's back from further bending forward into a hazardous posture. As soon as the wearer returned to their natural posture and the back angles descend below the set limit, a signal will be transmitted from the microcontroller to the relay for deactivation. This will restore the chainmail

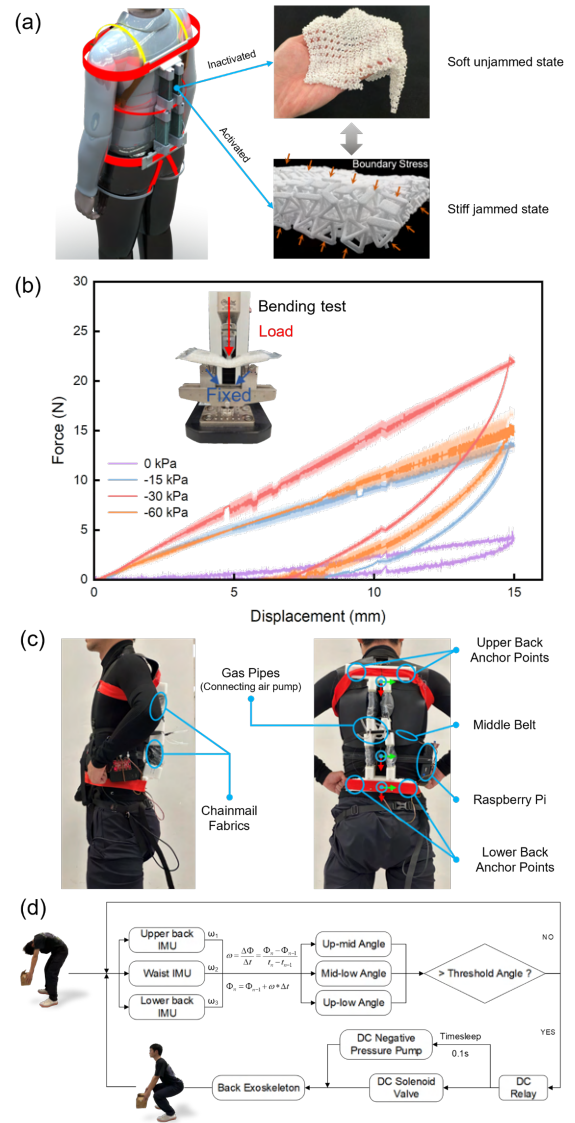


Fig. 2. System description of the back exoskeleton. (a) CAD design and stiffening mechanism. (b) Force-displacement curves for chainmail fabrics. (c) The hardware components. (d) The close-loop control strategy.

fabric to its original pliability, allowing the wearer to move smoothly and unrestrictedly.

III. EXPERIMENTAL PROTOCOL

A. Back Angle Acquisition

Three healthy male participants (P1: 173cm, 62 kg; P2: 180 cm, 73 kg; P3: 175 cm, 65 kg) were recruited for this study. The individuals gave their consent to take part in the study after being fully informed. The experiments performed in Nanyang Technological University were approved by the ethics committee. The experimental procedures adhered to the Helsinki Declaration.

Throughout the experiment, the participants were tasked with lifting a 5 kg box from the ground in both regular and irregular postures. To ensure accuracy, each trial consisted of 10 continuous lifting cycles which were repeated three times,

resulting in 30 regular and irregular lifts for each participant. In order to recreate the work conditions of laborers, the participants were given the freedom to choose the distance between their feet and the box, as well as the distance between their two feet. This allowed for a comfortable posture that was maintained throughout the experiment. Participants stood with their feet shoulder-width apart, facing forward, and held the calibrated position for 5 seconds during each condition. The experiment was conducted using both optical and IMU-based motion capture systems to ensure precision.

B. Back Exoskeleton Analysis

In order to assess the efficacy of a back exoskeleton, a comprehensive full-body simulation was conducted utilizing OpenSim 4.4 software [23], based on the motion data acquired by an IMU-based motion capture system. The simulation process was described in detail in [22]. The primary objective of this simulation was to meticulously analyze joint angles, joint moments, muscle activation, and metabolic states of an individual both before and after the activation of the exoskeleton, while performing both regular and irregular lifting tasks. A full-body musculoskeletal model [24] was employed, which contained 92 musculotendon actuators representing 76 muscles of the lower extremities and torso. The IMU sensors mappings, data collection process, and the data analyze methods were described in detail in [25]. One healthy male participant (173 cm, 62 kg) was recruited for the experiment, and was instructed to repeat the same lifting trials described in Section III-A.

IV. RESULTS AND DISCUSSION

A. Back Angle in Motion Capture Systems

The back angle data included the Up-Mid angle, Mid-Low angle, and Up-Low angle acquired from IMU-based motion capture system, and the UpLoBa angle acquired from optical system. All angle values were computed using MATLAB R2023a from raw motion capture data and filtered with a 4 Hz lowpass filter to eliminate high frequency noise.

Fig. 3 presents the calculation results from two systems. It is apparent that irregular lifting caused an increase in the back angles. With regards to the optical system, it was observed that all three participants had an UpLoBa Angle of approximately 50 degrees during irregular lifting, while the angle remained below 25 degrees during regular lifting. Moreover, the findings from the IMU system were consistent with those of the optical system, as all three angles were higher during irregular lifting. There was a slight variation between the angular value recorded by the IMU system and the optical system. The reason for this difference was the misalignment between the location of IMU sensors and reflective markers. Considering the placement of markers, it was expected that the UpLoBa Angle would be higher than the Up-Mid angle and lower than the Up-Low angle. This aligns with the final result.

To establish a precise threshold for activating the exoskeleton, the maximum absolute value of back angles obtained by the IMU system were examined. During regular

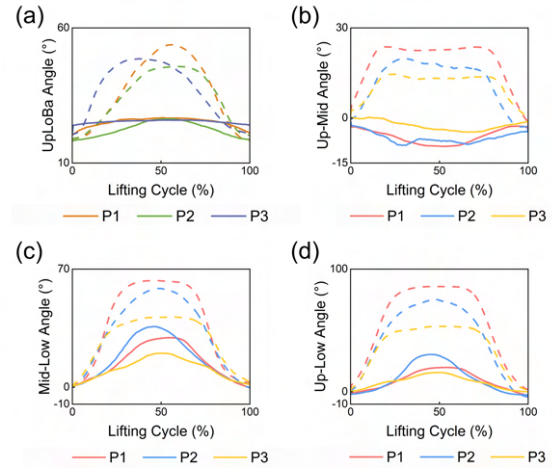


Fig. 3. The back angles obtained from optical and IMU-based motion capture system. The regular and irregular lifting are represented by solid lines and dashed lines respectively. (a) UpLoBa Angles of three participants (P1-P3) from optical system. (b-d) Up-Mid, Mid-Low, and Up-Low angles of three participants (P1-P3) from IMU-based system.

lifting process, the Up-Mid angles of three participants were 9.44 ± 2.04 degrees, 8.96 ± 1.86 degrees, and 4.69 ± 1.92 degrees; the Mid-Low angles were 29.41 ± 2.86 degrees, 35.98 ± 5.71 degrees, and 20.18 ± 2.82 degrees; the Up-Low angles were 19.89 ± 2.81 degrees, 30.49 ± 12.44 degrees, and 15.75 ± 3.67 degrees. The exoskeleton's activation mechanism is intended to initiate when the back angle surpasses the established range for regular lifting, so that the harmful posture could be prevented. Therefore, to ensure proper activation, the threshold should be set below the maximum back angle, accounting for the time required for the response. Based on the angle value acquired in the experiment, the threshold values were established at 5 degrees, 25 degrees, and 20 degrees for Up-Mid angle, Mid-Low angle, and Up-Low angle respectively.

B. Hip and Knee Joint Angles

After importing the motion data into OpenSim, a comprehensive simulation including inverse kinematics, inverse dynamics, residual reduction control, and computed muscle control was conducted. During the simulation, the hip flexion, hip adduction, hip rotation, and knee angle of each lower extremity throughout a lifting cycle was examined, as presented in Fig. 4.

The results showed no significant difference in hip adduction and hip rotation pre and post the activation of the exoskeleton in both regular lifting and irregular lifting tasks. However, upon activation of the exoskeleton, a discernible improvement in hip flexion was observed. In standard lifting scenarios, the right hip flexion raised by 42.46% while the left hip flexion increased by 32.50%. In cases of irregular lifting, the right hip flexion increased by 59.70% and the left hip flexion by 60.29%, which indicates that the wearer was guided by the exoskeleton to squat lower, leading to increased rotation of thighs around hip joint.

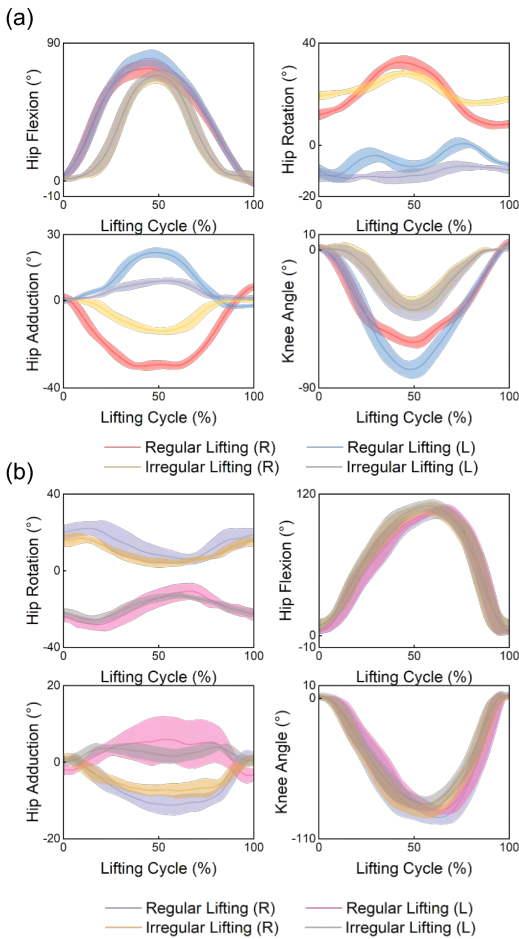


Fig. 4. The hip and knee joint angles during regular and irregular lifting wearing (a) inactivated exoskeleton; (b) activated exoskeleton.

A more noticeable difference in knee angle was observed during regular and irregular lifting, with an absolute increase of 55.00% (R) and 12.99% (L) in the former, and 151.43% (R) and 110.26% (L) in the latter. These findings indicate that the exoskeleton not only aided in irregular lifting but also converted the semi-squat lift to a fully-squat lift, rendering it advantageous for regular lifting as well. The knee angle presented in Fig. 4(B) was comparable with that of squat lift described in [9].

In summary, the activation of the exoskeleton led to an improvement in the angles of the hip and knee joints. This suggests that the exoskeleton assisted the user in maintaining a proper squatting position when lifting, rather than bending over, thereby rectifying their lifting posture.

C. Lumbar Extension and Moments

In reference to the previous research of LBP and back exoskeletons [6, 17, 22], the joint angles and joint moments of lumbar spine were examined in this study.

Figure 5 illustrates lumbar extension during both regular and irregular lifting, with and without the assistance of the exoskeleton. It was observed that integrating exoskeletons for irregular lifting tasks resulted in a significant reduction

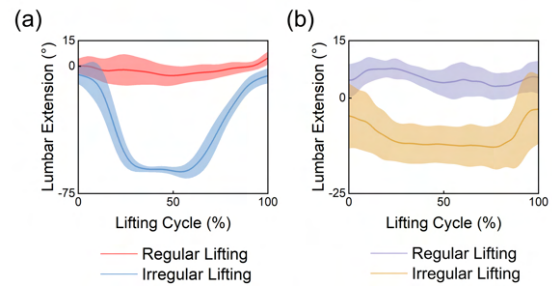


Fig. 5. The lumbar extension during regular and irregular lifting wearing (a) inactivated exoskeleton; (b) activated exoskeleton.

in lumbar extension. However, no significant effects were noted during regular lifting.

The decrease in lumbar extension played a pivotal role in diminishing muscular exertion, subsequently leading to a notable reduction in the likelihood of experiencing muscular fatigue within the lumbar spine. This effect, in turn, exerted a positive influence on mitigating the risk factors associated with the development of chronic lower back pain. By moderating lumbar extension during activities, laborers could potentially minimize the strain placed on the muscles and supporting structures of the lower back. This, in combination with appropriate biomechanics and ergonomic practices, could collectively contribute to a more favorable environment for spinal health, decreasing the chances of chronic lower back pain emergence over time.

Same result can be generated from the joint moments on the lumbar spine, as shown in Fig. 6.

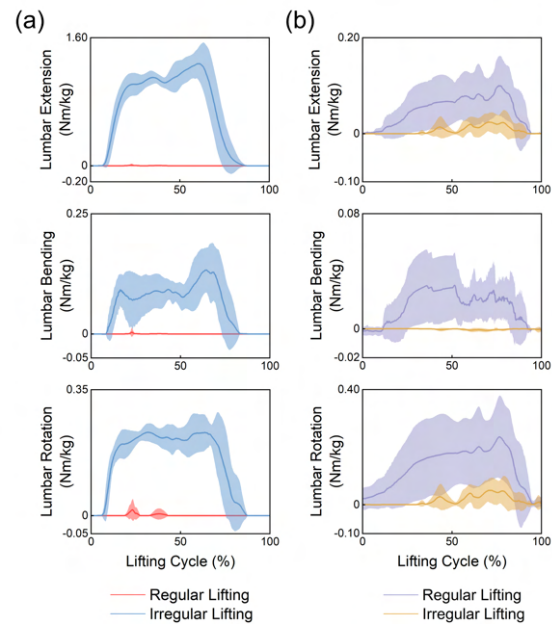


Fig. 6. The joint moments on lumbar spine during regular and irregular lifting wearing (a) inactivated exoskeleton; (b) activated exoskeleton.

To normalize the result, the joint moments were divided by the participant's body weight. The results indicates that while the moments of lumbar rotation were similar during

irregular lifting, the moments of lumbar extension exhibited a significant decrease, dropping from 1.27 Nm/kg to a mere 0.014 Nm/kg. Furthermore, the lumbar bending data showed a decrease to 0.0011 Nm/kg from the initial value of 0.13 Nm/kg. These findings prove that our pneumatic exoskeleton was excellent in relieving the burden on lower back, especially on lumbar spine during irregular lifting process.

D. Muscle Activation and Metabolic Cost

As one of the most important muscles on human back, the erector spinae play a crucial role in supporting human body during listing tasks. Therefore, the muscle activation level of erector spinae during one lifting cycle was also investigated in this study, as shown in Fig. 7.

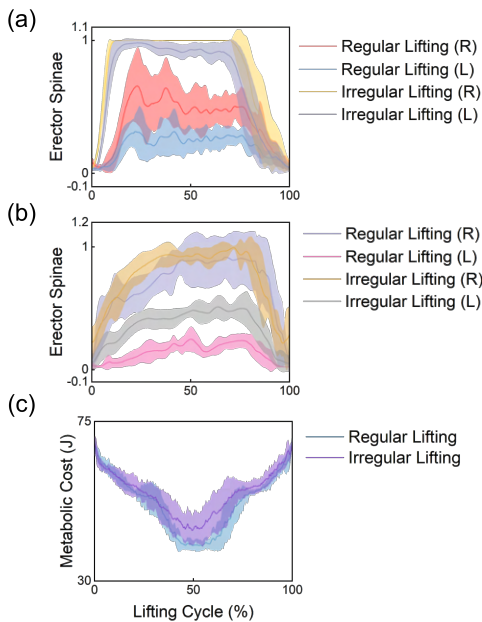


Fig. 7. (a) The muscle activation level of erector spinae wearing inactivated exoskeleton; (b) The muscle activation level of erector spinae wearing activated exoskeleton; (c) The metabolic cost of the participant wearing activated exoskeleton.

It is evident that lifting irregularly without the assistance of the exoskeleton resulted in a greater activation level in comparison to regular lifting. Nonetheless, incorporating the exoskeleton resulted in a reduction of the erector spinae muscle activation level by 6.29% on the right side and 48.08% on the left side during irregular lifting. This decline rendered the activation level similar to that of regular lifting.

Such reduction of muscle activation level could improve endurance and prevent muscle fatigue during activities that involve the lower back. This helps decrease the likelihood of sudden strain and the development of chronic discomfort while also easing the burden on spinal structures. By reducing compression forces on intervertebral discs and facet joints, the spine's structural integrity can be maintained, and good posture can be promoted. These combined effects can reduce the risk of microtrauma that can lead to chronic lower back pain over time.

Nonetheless, a noticeable disparity in activation levels was consistently observed between the participant's right and left sides. It is hypothesized that this could be attributed to the participant's asymmetric movements and a potential orientation error in the musculoskeletal model utilized during simulation.

Furthermore, by integrating a metabolism probe into the musculoskeletal model during simulation within OpenSim, the total metabolic cost of the participant during a lifting cycle is obtained, as illustrated in Fig. 8.

The minimum and maximum metabolic cost during regular lifting was 39.95 ± 1.30 J and 69.75 ± 1.72 J, while that for irregular lifting was 44.70 ± 4.40 J and 69.20 ± 1.79 J. Both minimum and maximum values were within error ranges, indicating that the correction process will not impose extra metabolic burden on wearers.

E. Limitations and Future Work

The proposed back exoskeleton design has some limitations that require attention. One is the need for a large air pump capable of generating enough negative pressure to maintain the rigidity of the chainmail fabrics and provide adequate support for the wearer's back. Additionally, while the IMU-based system is wearable, gas pipes are still necessary to connect the exoskeleton with the immovable pump.

Another limitation is that the current sensing and actuating mechanism only focuses on the back angle during the lifting cycle and cannot distinguish other activities such as walking or running. Consequently, the exoskeleton can only aid the wearer during weightlifting tasks.

Future efforts will concentrate on enhancing the pump system and rendering the entire back exoskeleton system completely wearable. Furthermore, more sophisticated control strategies will be introduced to study the wearer's motion patterns, anticipate their movements, and create a versatile exoskeleton that can aid in a variety of tasks.

V. CONCLUSION

Our research presents a novel pneumatic back exoskeleton that is capable of detecting and correcting improper lifting posture. To differentiate between regular and irregular lifting posture, we utilized back angles and incorporated a low-cost IMU-based motion system for calculating these angles. The difference in back angles during lifting tasks was then validated using an optical motion capture system. Our back exoskeleton was made of chainmail fabrics that can modify mechanical properties under negative pressure, and it effectively guided the wearer to maintain proper lifting posture. Through experiments and musculoskeletal simulations, we tested the exoskeleton and analyzed biomechanical parameters during a single lifting cycle. Our goal is to provide valuable insights into the design and evaluation of back exoskeletons.

REFERENCES

- [1] "Global, regional, and national burden of low back pain, 1990-2020, its attributable risk factors, and projections to 2050: a systematic analysis of the Global Burden of Disease Study 2021," (in eng), *Lancet Rheumatol*, vol. 5, no. 6, pp. e316-e329, Jun 2023, doi: 10.1016/s2665-9913(23)00098-x.
- [2] A. Luttmann, M. Jager, B. Griefahn, G. Caffier, F. Liebers, and W. H. Organization, "Preventing musculoskeletal disorders in the workplace," 2003.
- [3] S. McGill, *Ultimate Back Fitness and Performance*. Backfitpro Incorporated, 2004.
- [4] S. M. Hsiang, G. E. Brogmus, and T. K. Courtney, "Low back pain (LBP) and lifting technique — A review," *International Journal of Industrial Ergonomics*, vol. 19, no. 1, pp. 59-74, 1997/01/01/ 1997, doi: [https://doi.org/10.1016/0169-8141\(95\)00086-0](https://doi.org/10.1016/0169-8141(95)00086-0).
- [5] Ç. Tüzün, İ. Yorulmaz, A. Cindaş, and S. Vatan, "Low Back Pain and Posture," *Clinical Rheumatology*, vol. 18, no. 4, pp. 308-312, 1999/06/01 1999, doi: 10.1007/s100670050107.
- [6] Roy SH, De Luca CJ, Casavant DA. Lumbar muscle fatigue and chronic lower back pain. *Spine (Phila Pa 1976)*. 1989 Sep;14(9):992-1001. doi: 10.1097/00007632-198909000-00014. PMID: 2528828.
- [7] M. Fares, J. Fares, H. Salhab, H. Khachfe, A. Bdeir, and Y. Fares, "Low Back Pain Among Weightlifting Adolescents and Young Adults," *Cureus*, vol. 12, p. e9127, 07/11 2020, doi: 10.7759/cureus.9127.
- [8] M. Abdoli-Eramaki, M. Agababova, J. Janabi, E. Pasko, and C. Damecour, "Evaluation and comparison of lift styles for an ideal lift among individuals with different levels of training," *Applied Ergonomics*, vol. 78, pp. 120-126, 2019/07/01/ 2019, doi: <https://doi.org/10.1016/j.apergo.2019.02.007>.
- [9] N. B. Washmuth, A. D. McAfee, and C. S. Bickel, "Lifting Techniques: Why Are We Not Using Evidence To Optimize Movement?," (in eng), *Int J Sports Phys Ther*, vol. 17, no. 1, pp. 104-110, 2022, doi: 10.26603/001c.30023.
- [10] L. M. Straker, "A review of research on techniques for lifting low-lying objects: 1. Criteria for evaluation," *Work*, vol. 19, pp. 9-18, 2002.
- [11] L. M. Straker, "A review of research on techniques for lifting low-lying objects: 2. Evidence for a correct technique," *Work*, vol. 20, pp. 83-96, 2003.
- [12] R. Y. W. Lee, J. Laprade, and E. H. K. Fung, "A real-time gyroscopic system for three-dimensional measurement of lumbar spine motion," *Medical Engineering & Physics*, vol. 25, no. 10, pp. 817-824, 2003/12/01/ 2003, doi: [https://doi.org/10.1016/S1350-4533\(03\)00115-2](https://doi.org/10.1016/S1350-4533(03)00115-2).
- [13] W. Y. Wong and M. S. Wong, "Trunk posture monitoring with inertial sensors," *European Spine Journal*, vol. 17, no. 5, pp. 743-753, 2008/05/01 2008, doi: 10.1007/s00586-008-0586-0.
- [14] L. Jenkins and R. Weerasekera, "Sport-related back injury prevention with a wearable device," *Biosensors and Bioelectronics: X*, vol. 11, p. 100202, 2022/09/01/ 2022, doi: <https://doi.org/10.1016/j.biosx.2022.100202>.
- [15] G. Ataei, R. Abedi, Y. Mohammadi, and N. Fatouraee, "Analysing the effect of wearable lift-assist vest in squat lifting task using back muscle EMG data and musculoskeletal model," *Physical and Engineering Sciences in Medicine*, vol. 43, no. 2, pp. 651-658, 2020/06/01 2020, doi: 10.1007/s13246-020-00872-5.
- [16] U. Heo, S. J. Kim, and J. Kim, "Backdrivable and Fully-Portable Pneumatic Back Support Exoskeleton for Lifting Assistance," *IEEE Robotics and Automation Letters*, vol. 5, no. 2, pp. 2047-2053, 2020, doi: 10.1109/LRA.2020.2969169.
- [17] X. Yang et al., "Spine-Inspired Continuum Soft Exoskeleton for Stoop Lifting Assistance," *IEEE Robotics and Automation Letters*, vol. 4, no. 4, pp. 4547-4554, 2019, doi: 10.1109/LRA.2019.2935351.
- [18] Y. Wang, L. Li, D. Hofmann, J. E. Andrade, and C. Daraio, "Structured fabrics with tunable mechanical properties," *Nature*, vol. 596, no. 7871, pp. 238-243, Aug 2021, doi: 10.1038/s41586-021-03698-7.
- [19] X. Yang, M. Liu, T. Chen, Y. Chen, and Y. Wang, "Tunable mechanics of architected composites from particle assemblies," *Extreme Mechanics Letters*, vol. 67, p. 102121, 2024/03/01/ 2024, doi: <https://doi.org/remotex.ntu.edu.sg/10.1016/j.eml.2024.102121>.
- [20] X. Yang et al., "Hierarchical tessellation enables programmable morphing matter," *Matter*, doi: 10.1016/j.matt.2023.11.002.
- [21] X. Yang et al., "Self-Sensing Robotic Structures from Architected Particle Assemblies," *Advanced Intelligent Systems*, vol. 5, no. 1, p. 2200250, 2023, doi: <https://doi.org/10.1002/aisy.202200250>.
- [22] G. Wang, Y. Chen, M. Wang, and Y. Wang, "Musculoskeletal Model Construction of Deep Squat Using Low-Cost Inertial Measurement Units," in *2023 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)*, 28-30 June 2023 2023, pp. 896-901, doi: 10.1109/AIM46323.2023.10196164.
- [23] S. L. Delp et al., "OpenSim: open-source software to create and analyze dynamic simulations of movement," (in eng), *IEEE Trans Biomed Eng*, vol. 54, no. 11, pp. 1940-50, Nov 2007, doi: 10.1109/tbme.2007.901024.
- [24] S. R. Hamner, A. Seth, and S. L. Delp, "Muscle contributions to propulsion and support during running," *Journal of Biomechanics*, vol. 43, no. 14, pp. 2709-2716, 2010/10/19/ 2010, doi: <https://doi.org/10.1016/j.jbiomech.2010.06.025>.
- [25] S. Toxiri et al., "Rationale, Implementation and Evaluation of Assistive Strategies for an Active Back-Support Exoskeleton," (in English), *Frontiers in Robotics and AI, Original Research* vol. 5, 2018-May-25 2018, doi: 10.3389/frobt.2018.00053.