

Evaluating the Benefits of a Soft Inflatable Knee Exosuit During Squat Lifting

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Abstract—This work aims to investigate the effects of knee extension assistance during squat lifting. We hypothesize that adding an external torque to the knee joint using a soft inflatable exosuit can potentially induce a reduction in the muscular effort that extends to the posterior chain muscles. A total of 8 healthy test participants are recruited and instructed to lift a weight equivalent to 10% of their bodyweight. The muscle activities of the left and right Vastus Lateralis, Biceps Femoris, Gluteus Maximus, Erector Spinae (Iliocostalis and Longissimus) and Multifidus muscle groups were studied for baseline, non-assisted, and assisted conditions. The majority of participants (6 out of 8) demonstrated consistent reduction in the muscular effort of at least one muscle group of the posterior chain. A maximum reduction of 55% in the average muscle activity of the Multifidus muscle group is observed in one participant. Different neuromuscular adaptation mechanisms were observed among subjects that ultimately led to a reduction in lower-limb or back muscles activity. The results reveal that assisting knee extension during a lifting task has significant effects on muscle activity with benefits that extend to the posterior chain muscles. This work provides early evidence that the soft inflatable knee exosuit can be used in material handling tasks to reduce muscle effort and prevent work-related injuries.

I. INTRODUCTION

Manual material handling (MMH) involves lifting, carrying, and lowering heavy weights on a daily basis. These tasks put significant loads on the knees, hips, and lower backs of the workers, which may increase the risk of developing work-related musculoskeletal disorders (MSDs) [1]. In fact, more than 42% of lower-limb injuries in the physical work force are caused by over-straining and exertion, and prior work has found significant correlations between knee osteoarthritis and prolonged squatting and lifting weights [2]. As a result, a large number of self-reported sick leaves among these workers are due to MSDs [3]. Work-related injuries reduce the quality of life of workers and lead to increased costs of operation. It was reported that MSDs alone led to \$1.5 billion direct cost in 2007 in the United States [4].

In recent years, the use of wearable robotic systems to assist in physically strenuous tasks has been on the rise. Typically, these wearable devices can be divided into passive wearable devices [5]–[7] which utilize energy storage

mechanisms such as springs and elastic bands to store and release energy, and active systems [8]–[10] which generate force/torque to provide physical assistance. Passive systems have demonstrated efficacy of use in MMH tasks by demonstrating reduced muscle activities and fatigue levels over several trials, but they can only provide pre-defined assistance profiles [11]. To overcome the aforementioned issue, several groups have developed wearable robots that provide active assistance to the knee, hip and lumbar joints during lifting [8], [9]. Most wearable robots found in literature are rigid exoskeleton systems that provide variable and controlled assistance, but they can be bulky, heavy, and expensive [10].

The recent development in wearable soft robots provides a novel solution to mitigate the challenges in their rigid counterpart. These robots are typically composed of lightweight and compliant materials (e.g., textiles) to overcome the limitations of heavy and bulky exoskeletons [12]. Soft exosuits driven by cables (for the hip and lumbar joints) [13], [14] and pneumatic artificial muscles (for the knee joint) [15] have demonstrated reduced muscle efforts for the corresponding joints when assisting in a lifting task.

In our past work, a fabric-based soft-inflatable exosuit has been developed to provide knee extension assistance [16]. The benefits of this soft exosuit have been demonstrated in assisting healthy individuals [16] and stroke survivors [17] in walking experiments. However, these previous studies on healthy individuals focused only on walking tasks, restricted the analysis to muscles that interact directly with the knee joint, and did not include the muscles and kinematics of other joints involved in the task. The effect of adding an external torque to the knee joint during a closed-chain kinetic task on the adjacent joints is still unknown. During squat lifting, the knee, hip, and back muscles contract in order to raise the weight along with the center of mass of the human [18]. Since lifting of heavy objects from the ground requires coordination and synergy of the back, hip, knee, and ankle muscles [19], assistance to the knee joint during squat lifting may also alter activity of all the muscles involved in performing the task at hand. Therefore, it is important to understand how humans adapt to the assistive torque provided to a single joint during this complex movement and how this external torque impacts the muscle efforts of other joints. To the best of our knowledge, it is still unclear how knee joint assistance propagates to the posterior chain muscles in a closed kinematic task such as lifting.

This work aims to utilize the previously designed soft-inflatable exosuit to provide knee extension assistance during squat lifting and study the kinematics of the hip, knee, ankle,

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Fig. 1: The soft-inflatable exosuit system worn by a human subject. The system is composed of two soft-inflatable actuators for each leg, solenoid valves, Raspberry Pi and a push-button.

and lumbar joints as well as the surface electromyographic (EMG) activity of the muscles around these joints. This work will provide preliminary data to refine the design, control, and evaluation of wearable soft robots to maximize their benefits in repetitive and labor-intensive tasks.

II. DESIGN OF THE SOFT EXOSUIT

A. Functional Requirements

The biomechanics during lifting tasks were investigated to determine the functional requirements for actuator design. A study by Hwang et. al. [20] reported the human biomechanics when performing a squat down and lifting an object from the floor. Results showed that the knee extension peak torque for this task was 0.5 Nm/kg. As an assistive device, a partial support equivalent to 50% of this peak torque was selected as the target assistance. The required torque for each subject was computed using the results from this study and are presented in Table I. This study also defined the timing of knee joint peak torque as the instance when the human is on the lowest position of the squat, during maximum joint flexion with knee angles greater than 90° .

B. Design of the exosuit

To generate torque to assist the human knee joints, soft pneumatic inflatable actuators were designed to satisfy the requirement in Section II-A. The actuators are fabricated using heat-sealed thermoplastic polyurethane (TPU) films encased in an inelastic nylon fabric reinforcement, presented in Fig. 1. When deflated, the actuator is completely compliant and exerts no torque on the wearer. When the inflatable actuator is bent and pressurized, it generates a restoring torque that forces the actuator to the straight position. This mechanical principle was utilized to provide torque to the human joints. More details on the design and development of the soft-inflatable actuators can be seen in [16].

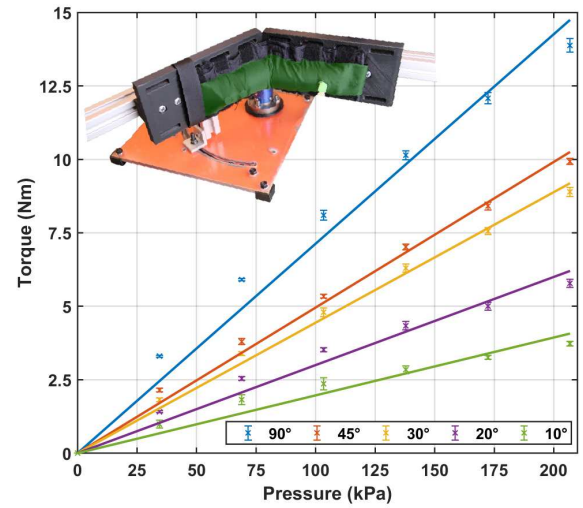


Fig. 2: Actuator torque characterization results for different operating angles and internal pressure. The characterization platform mounted with the actuator is presented on the top left. The soft-inflatable actuator is highlighted in green, and the torque sensor in blue.

An overview of the soft exosuit system is presented in Fig. 1. The exosuit consists of an elastic neoprene sleeve that conforms to the thigh and shank at the knee joint. Two pneumatic inflatable actuators are placed at the popliteal fossa to provide extension torque to the knee joint. Nylon fabric pockets were sewn into the sleeve to hold the actuators in place securely. We utilized hook and loop straps to ensure proper transmission of the assistive forces to the lower limbs. The exosuit garment worn by the user weighs 0.13 kg. The soft materials that comprise the exosuit make it lightweight, completely compliant, and transparent to the wearer.

A torque characterization experiment was performed to measure the torque generated by an inflatable actuator. The inflatable actuator was placed on a mechanism that simulates the human knee joint on the sagittal plane. This mechanism, presented in Fig. 2, was mounted on a static analog torque sensor (FTA-100NM, Forsentek Co., Limited, China) to measure the torque exerted by the actuator. For the data collection procedure, the analog joint mechanism was fixed at different angles within the knee joint's range of motion, and the actuator was pressurized from 0 to 207 kPa in increments of 34 kPa, and torque was measured at each step. The results of this characterization, presented in Fig. 2, exhibit a linear relationship between internal pressure and generated torque at a given angle. This demonstrates the capacity to modulate the assistive torque by controlling the actuator's internal pressure. To satisfy the biological torque requirements for all subjects in Table I, a maximum torque of 19.5 Nm is required. A single inflatable actuator has the capacity to generate 10 Nm torque inflated at 140 kPa, for joint flexion of at least 90° , which corresponds within the knee joint range of motion during squat lift [20] as indicated in Section II-A. To operate the exosuit within safe pressure magnitudes, two inflatable actuators are required for each respective knee joint. With this design, the operational pressure will not

exceed 140 kPa.

We integrated the electro-pneumatics of the system with a micro-controller (Raspberry Pi). The system consists of solenoid valves (MHE3-MS1H valves, Festo, Hauppauge, NY) to quickly switch between the pressurization and depressurization states of the actuators. A push-button was utilized to send the inflation and deflation commands to the micro-controller. We implemented pressure sensors (AS-DXAVX100PGAA5, Honeywell International Inc., Morris Plains, NJ) to monitor the internal pressure of the inflatable actuators.

III. EXPERIMENTAL PROTOCOL

A. Study Design

For this study, a total of 8 participants (5 male and 3 female) with no history of lower body and back pathologies were recruited. The experimental protocol was approved by the Arizona State University Institutional Review Board (IRB ID#: STUDY00011110). The anthropometric data of the subjects can be seen in Table I. The weight lifted was limited to 10% of their bodyweight to standardize the study across all participants. A plastic box of dimensions $0.40 \times 0.30 \times 0.17 \text{ m}^3$, contained evenly distributed weights that were adjusted according to each subject's bodyweight. Kinematics and EMG data were collected for three conditions: Baseline (exosuit not worn), Inactive (exosuit worn but not actuated), and Active (exosuit worn and actuated). An independent and identical exosuit was worn on each leg to provide symmetric assistance to the user.

The participants were instructed to start each trial standing upright. Upon a given signal, they would descend, grasp a box, and ascend to the upright position, as illustrated in Fig. 3. The ascent and descent for each trial were completed in one second, respectively, controlled using a metronome set at 60 beats per minute. A total of five trials for each condition were performed with each participant. For the active trials, the participants were given a button to inflate the exosuit. The participants were instructed to actuate the exosuit when they reached their lowest position during the squat. By relying on the cognitive skills of the human to choose the ideal timing, the control variables of the exosuit were simplified. The assistive torque from the exosuit was personalized by tuning the actuator pressure according to the torque requirement in Table I and the torque characterization results in Fig. 2.

TABLE I: Subject participants anthropometric data and joint torque requirement.

Subject	Gender	Age	Weight (kg)	Height (m)	Torque (Nm)
S1	F	23	65.7	1.57	16.43
S2	M	27	78	1.65	19.50
S3	F	27	55	1.54	13.75
S4	M	31	75.4	1.70	18.85
S5	M	25	78	1.72	19.50
S6	M	22	75.5	1.70	18.88
S7	F	27	55	1.58	13.75
S8	M	22	74.5	1.80	18.63
Mean		25.5	69.6	1.66	17.41
Standard deviation		3.12	9.82	0.09	2.46

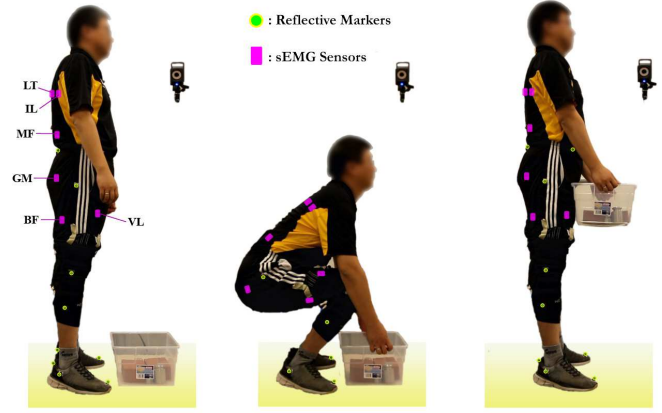


Fig. 3: Human subject wearing the soft-inflatable exosuit and performing the lifting task. The abbreviations of the muscles investigated are depicted in the left picture. The EMG locations are approximated in the figure as these were placed underneath the clothing. The exosuit is inflated when the participant has reached the lowest position during the squat (middle picture) and assists through the upward lift.

Between trials, each participant took a 15-min rest to prevent muscle fatigue.

B. Data Collection

Data collection of kinematics and EMG activity was performed using the experimental setup in Fig. 3. The kinematics were collected using a camera-based motion capture system (T40s, VICON Inc., Los Angeles, CA). Passive reflective markers were attached to the lower-body and the torso of each participant according to pre-defined marker sets (Vicon Plug-in Gait) as illustrated in Fig. 3. The kinematic data were collected at a sampling frequency of 100 Hz.

The EMG activity of the Vastus Lateralis (VL), Biceps Femoris (BF), Gluteus Maximus (GM), Multifidus (MF), and the erector spinae muscles (Iliocostalis (IL) and Longissimus (LG)) were selected for this study. The aforementioned muscles were investigated since they are highly active during a squat lifting. The MF, IL, and LG were investigated in order to study the effects of knee extension assistance on the posterior chain. The EMG data was recorded using a Delsys Trigno (Delsys, Natick, MA) system and sampled at 2000 Hz. The raw EMG data were first de-meaned and band-pass filtered (Butterworth, 4th order, 20 Hz and 450 Hz cutoff frequencies). The profile of the signal was obtained by computing the root-mean-square (RMS) envelope using a moving window of 250 ms. All EMG data were normalized using the maximum EMG values of all collected trials for each respective muscle. The EMG normalization method is valid since all the trials were performed in the same session without sensors being removed. The five lifting cycles for each condition were temporally normalized to percent lift completion and then averaged to determine a mean and standard deviation of muscle activity. This results in normalized EMG signal as a function of percent lift completion, where 0% corresponds to standing straight right before initiating the squat (Fig. 3 left), and 100% corresponds to finalized

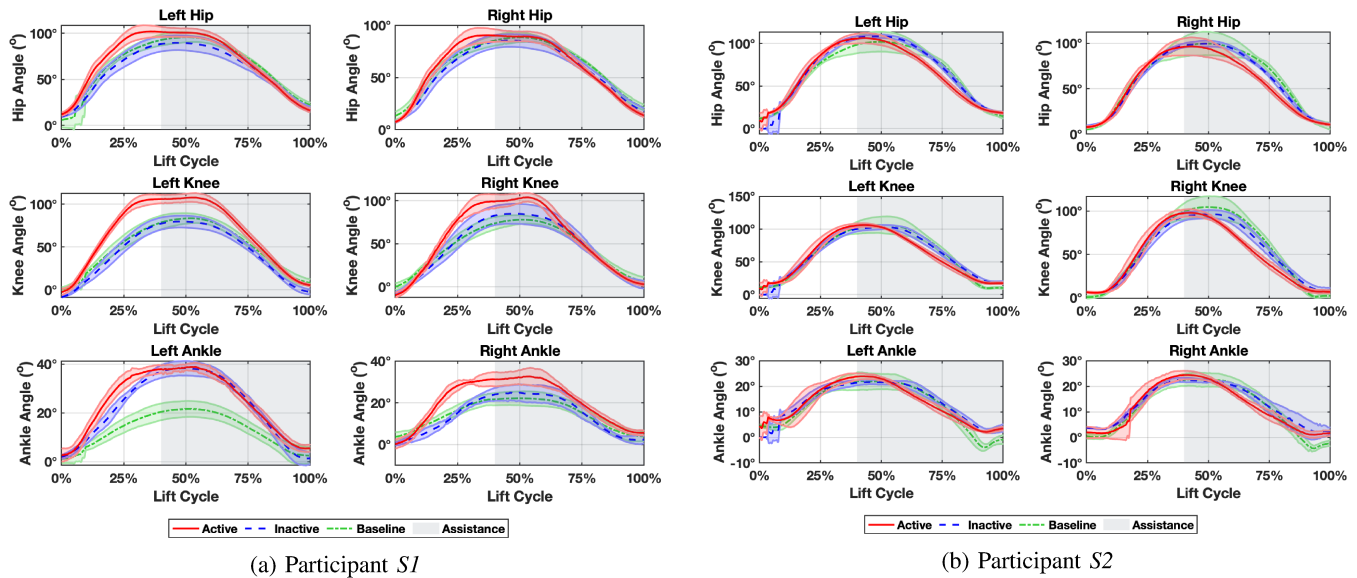


Fig. 4: Sagittal plane joint kinematics of participants *S1* (a) and *S2* (b) through the lifting cycle. The mean and standard deviation of five lifting cycles are plotted. The period that the exosuit assisted the knee joint is shaded in gray.

lifting of the box (Fig. 3 right). The mean and integral of the EMG envelope were computed for five lift cycles, and the statistical significance between each data set was calculated using an independent t-test ($p < 0.05$).

IV. RESULTS

A. Kinematic Results

The joint kinematics throughout the lift cycle of two representative subjects are presented in Fig. 4. For participant *S1*, the maximum flexion angles of the knee, left hip and right ankle joints increase, indicating an increase of the range of motion for these joints when the exosuit assisted knee extension. This participant squats to the lowest position i.e. the maximum knee flexion angle faster, and stays at this position for a longer duration, as shown in Fig. 4a. Participant *S2* shows a similar range of motion and the descending pattern between the two conditions. However, this participant spends less time in the lowest height and completes the lifting earlier when the exosuit is active, as shown in Fig. 4b. For both subjects, the maximum joint angles occur close to 40% of the lifting cycle, when the push button was pressed to start inflating the exosuit. This timing matches the initial period when statistically significant difference in EMG activity is first observed, as discussed in Section IV-B.

B. EMG Results

The processed EMG signals throughout the complete lift cycle of participants *S1* and *S2* are presented in Fig. 5. The results of the EMG activity for active conditions demonstrated a significant reduction for most muscle groups through the majority of the lift cycle compared to baseline conditions. Participant *S1* demonstrates this reduction in all the back and lower limb muscles through the mid to end of the lift cycle, initiating at approximately 40% of the lift cycle, which corresponds to the assistance onset timing. *S2* also demonstrates a similar reduction of EMG activity for most

of the muscles (7 out of 12 muscles). The period when the EMG shows a reduction matches the period when the exosuit assisted the user's knee joints. For both subjects, the greatest reduction was observed in the MF muscles, indicating that the lower back muscles exerted less effort during the lifting task. Furthermore, *S2* demonstrated a shift in the EMG envelope where the active case demonstrated earlier muscular activation levels in the lift cycle, especially from the middle until the end of the cycle. A similar shifted behavior is observed in the joint kinematics profile as discussed in Sec. IV-A.

The integral (area under the curve) of the EMG envelope was computed and is presented in Fig. 6. The EMG integral quantifies the total muscular effort through the complete lift cycle. Two types of EMG response patterns were observed in several subjects, shown in Fig. 6a-b. The EMG integral of *S1* reveals that all the muscles, except BF, demonstrate a reduced muscular effort when the exosuit supports knee extension compared to the baseline. On the other hand, *S4* demonstrates a reduction in the posterior chain muscles, but an increase in the lower-limbs muscles. It should be noted that the lower-limbs muscles of *S4* also demonstrated an increase when the exosuit was worn but not inactive compared to the baseline, indicating that wearing the exosuit is a possible source of increased muscular activity observed when the exosuit provides extension torque. On average, the subjects demonstrated a significant reduction in the overall effort of the MF muscle when the exosuit provided extension torque (baseline vs. active) as observed in Fig. 6c. In addition, an increase over total muscular effort was observed in a few lower-limb muscles, specifically the VL, left BF and right GM, when the exosuit was worn but inactive (baseline vs. inactive) and when the exosuit provided extension torque (baseline vs. active).

The difference in the average EMG signal between different conditions is presented in Fig. 7. This figure illustrates

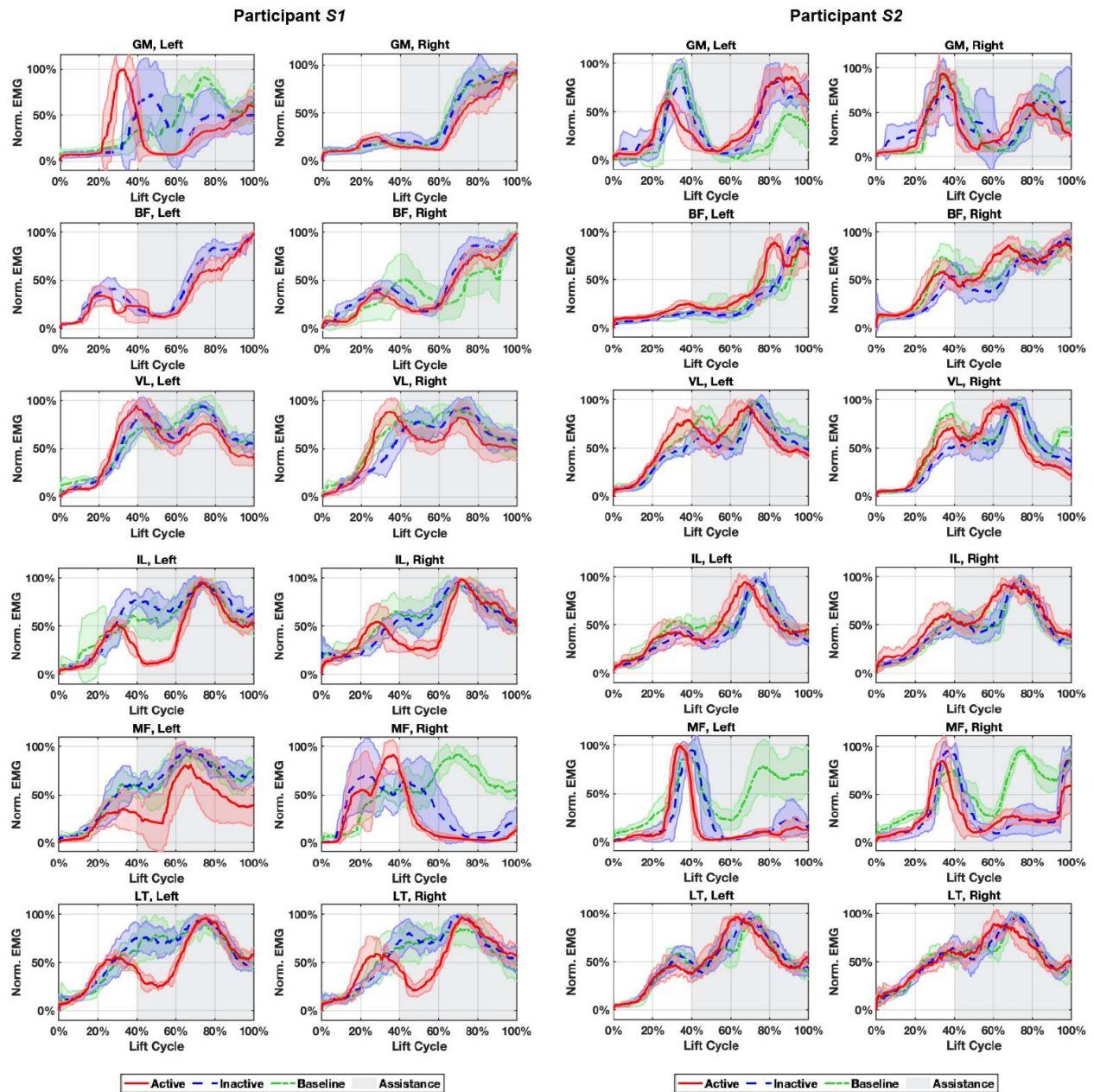


Fig. 5: EMG activity through the lifting cycle of participant *S1* (left) and participant *S2* (right). The mean and standard deviation for the active case is presented in solid red line, the inactive case in blue dashed line and the baseline case in green dash-dotted line. The period in which the exosuit assisted the knee joints is shaded in gray, approximately from 40% to 100% lift cycle. The baseline data for the left BF of participant *S1* was corrupted and therefore not included.

the transparency of the exosuit (baseline vs. inactive) and the mean reduction in EMG activity when the exosuit assists the human's knee extension motion (baseline vs. active). The results reveal that six participants demonstrate a statistically significant reduction in the average muscle activity of both the left and right side of at least one muscle group of the posterior chain when the exosuit provides extension torque to the knee joint (e.g. left and right MF of *S2*). The results of participants *S1*, *S3* and *S4* in Fig. 7, show that at least 8 muscles demonstrated a consistent reduction of the average EMG activity when the exosuit provides extension torque.

Furthermore, all of the back muscles (IL, MF, and LT) demonstrated a significant reduction in mean EMG activity, with a maximum reduction of 55% for the MF muscle of *S1*. Participants *S2* and *S4* demonstrate an average increase in the EMG of a few of the lower limb muscles for both cases in Fig. 7, which indicates the possibility that source of increased EMG activity is the exosuit interface.

V. DISCUSSION

Knee extension assistance during squat lifting demonstrated minimal alterations to the participants' kinematics. The kinematic profile throughout the lift cycle followed a

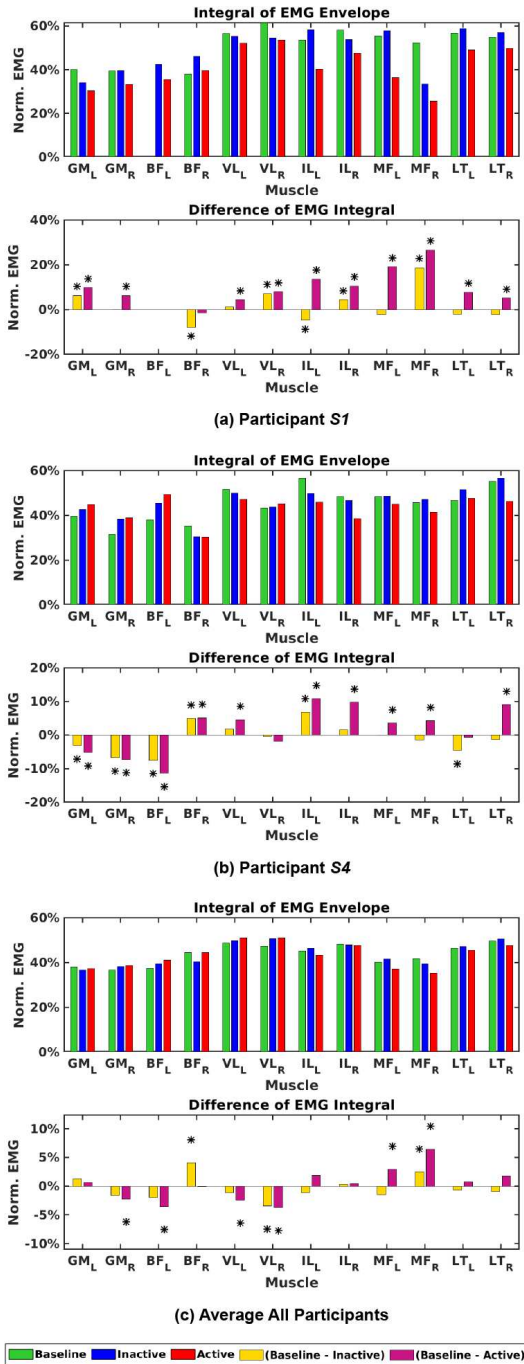


Fig. 6: Integral of EMG envelope for different conditions (top), and the difference of the EMG integral among conditions (bottom). * indicates statistically significant difference ($p < 0.05$).

similar path when the exosuit was active, indicating that the human coordinated with the exosuit assistance to maintain a similar trajectory. This also demonstrates the exosuit's capacity to assist knee extension without significantly altering the natural motion during squat lifting.

The EMG results of all four representative subjects demonstrated the potential for reducing muscular activity during squat lifting tasks when using a soft robotic exosuit that assists the knee extension motion. The results show that

the subjects tend to present significant reduction in EMG activity for both the back and lower-limb muscles ($S1$, $S2$) or at least in one of two muscle groups ($S3$, $S4$). Moreover, the majority of participants (6 out of 8) demonstrated a consistent reduction in the EMG activity of at least one muscle group of the posterior chain. This indicates that when the exosuit provides knee extension torque, the back muscles require less effort to perform the lifting task. Among all muscle groups, the MF shows the greatest reduction in muscular effort, which plays a primary role in lifting tasks as it stabilizes the lower back. A reduction in the effort of the MF muscle group indicates the feasibility of reducing the risk of injury during a lifting task. While some subjects demonstrate an increase in the EMG activity of a few lower-limb muscles, the increase is present in both the active and inactive cases, indicating that the increase in muscular effort most likely comes from the interaction of the exosuit interface and the human. In fact, the contact of the exosuit with the EMG sensors (e.g. contact area) which could ultimately affect the quality of the measurements. The results from this study show a favorable human interaction to single-joint assistance and the benefit of reducing muscular activity with a soft exosuit, motivating the further development and testing of such soft wearable robots.

In a closed kinetic task, such as object lifting, the required energy will be constant regardless of whether the exosuit is active or inactive. When the exosuit is active, the additional energy supplied by the exosuit contributes to the total energy required for the task and thus the energy required by the human to finish the task is reduced. This study shows that humans can develop diverse but effective strategies to cooperate with the exosuit assistance, resulting in an overall reduction of their muscular activities.

Despite the overall reduction in EMG activity with the soft robotic knee exosuit, the magnitude of this benefit varies across subjects. This could be attributed to the high compliance of the exosuit system and its interfacing with soft tissues of the thigh. Also, another factor could be the high degree of freedom of the human musculoskeletal system that leaves the whole body's muscular response to each individual's different motor adaptation strategy. Moreover, the subjects were asked to determine the timing of inflation of the soft actuators, and this could contribute to inconsistent reductions in muscular activities. Modeling the contact forces between the exosuit and the human body could provide further insight into the transmission of assistive torques to the human body to accurately quantify the exosuit behavior.

VI. CONCLUSIONS

In this paper, we studied the neuromuscular response to knee extension assistance during a lifting task with a novel soft-inflatable exosuit and eight healthy participants. The effects of knee assistance on the joint kinematics and muscle activity of the lower limbs and posterior chain muscles were investigated during squat lifting of weights equivalent

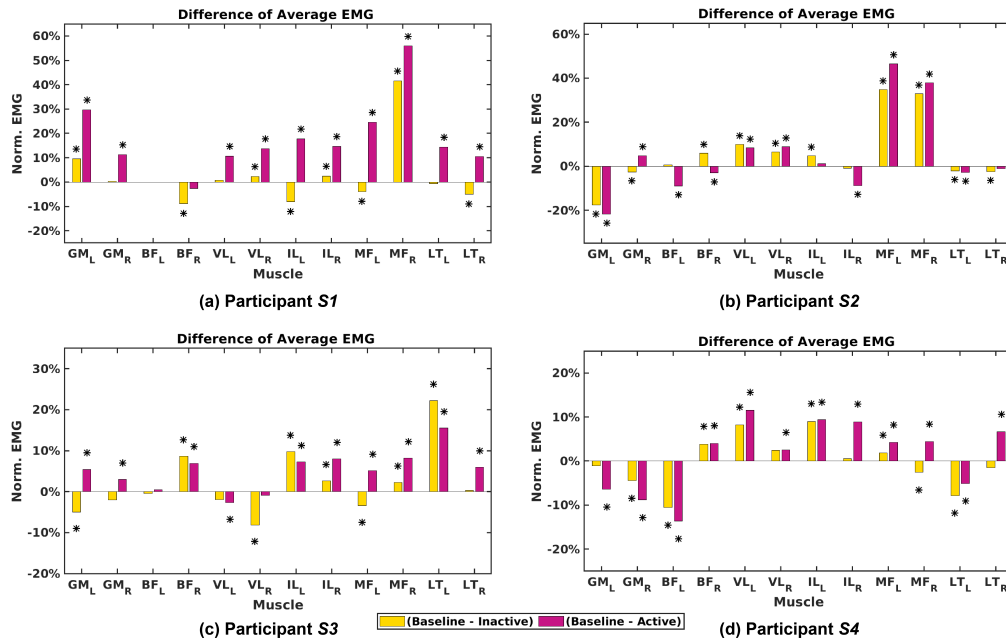


Fig. 7: Difference of average EMG activity between conditions. * indicates statistically significant difference ($p < 0.05$).

to 10% of their bodyweight. Results demonstrated a statistically significant EMG reduction for the great majority of the lower-limb and back muscles, with the Multifidus (MF) showing the maximum average EMG reduction of 55%. Different neuromuscular adaptation mechanisms were observed among subjects that ultimately led to a favorable reduction in lower-limb or posterior chain muscle activity. This work provided early evidence that the soft inflatable exosuit could potentially reduce muscle effort by assisting knee extension during a squat lifting task.

Future work includes the development of a robust controller that detects the optimal timing for autonomous inflation and deflation of the exosuit using real-time wearable sensor data. A more comprehensive human study will be conducted, with a larger number of participants, different tasks to execute, and different control strategies for the exosuit. The exosuit will be expanded to other joints to provide more versatile assistance during different material handling tasks.

REFERENCES

- [1] M. Antwi-Afari *et al.*, "Biomechanical analysis of risk factors for work-related musculoskeletal disorders during repetitive lifting task in construction workers," *Autom. Constr.*, vol. 83, pp. 41–47, 2017.
- [2] S. Amin *et al.*, "Occupation-related squatting, kneeling, and heavy lifting and the knee joint: a magnetic resonance imaging-based study in men," *J. Rheumatol.*, vol. 35, no. 8, pp. 1645–1649, 2008.
- [3] J. Hubertsson *et al.*, "Sick leave patterns in common musculoskeletal disorders—a study of doctor prescribed sick leave," *BMC Musculoskelet. Disord.*, vol. 15, no. 1, pp. 1–9, 2014.
- [4] A. Bhattacharya, "Costs of occupational musculoskeletal disorders (msds) in the united states," *Int. J. Ind. Ergon.*, vol. 44, no. 3, pp. 448–454, 2014.
- [5] P. Maurice *et al.*, "Evaluation of paexo, a novel passive exoskeleton for overhead work," *Comput. Methods Biomech. Biomed. Engin.*, vol. 22, no. suppl, pp. S448–S450, 2019.
- [6] M. M. Alemi, J. Geissinger, A. A. Simon, S. E. Chang, and A. T. Asbeck, "A passive exoskeleton reduces peak and mean emg during symmetric and asymmetric lifting," *J. Electromyogr. Kinesiol.*, vol. 47, pp. 25–34, 2019.
- [7] E. P. Lamers, A. J. Yang, and K. E. Zelik, "Feasibility of a biomechanically-assistive garment to reduce low back loading during leaning and lifting," *IEEE Trans. Biomed. Eng.*, vol. 65, no. 8, pp. 1674–1680, 2017.
- [8] M. Jeong, H. Woo, and K. Kong, "A study on weight support and balance control method for assisting squat movement with a wearable robot, angel-suit," *Int. J. Control. Autom. Syst.*, vol. 18, no. 1, pp. 114–123, 2020.
- [9] F. Sado, H. J. Yap, R. A. R. Ghazilla, and N. Ahmad, "Design and control of a wearable lower-body exoskeleton for squatting and walking assistance in manual handling works," *Mechatronics*, vol. 63, p. 102272, 2019.
- [10] S. Toxiri *et al.*, "Back-support exoskeletons for occupational use: an overview of technological advances and trends," *IIEE Trans. Occup. Ergon. Hum. Factors*, vol. 7, no. 3-4, pp. 237–249, 2019.
- [11] S. Baltrusch, J. Van Dieën, C. Van Bennekom, and H. Houdijk, "The effect of a passive trunk exoskeleton on functional performance in healthy individuals," *Appl. Ergon.*, vol. 72, pp. 94–106, 2018.
- [12] E. Q. Yumbla, Z. Qiao, W. Tao, and W. Zhang, "Human assistance and augmentation with wearable soft robotics: a literature review and perspectives," *Curr. Robot. Rep.*, vol. 2, pp. 399–413, 12 2021.
- [13] Z. Yao, C. Linnenberg, R. Weidner, and J. Wulfsberg, "Development of a soft power suit for lower back assistance*," in *2019 IEEE Int. Conf. Robot. Autom. (ICRA)*, 2019, pp. 5103–5109.
- [14] S. Yu *et al.*, "Design and control of a high-torque and highly backdrivable hybrid soft exoskeleton for knee injury prevention during squatting," *IEEE Robot. Autom. Lett.*, vol. 4, no. 4, pp. 4579–4586, 2019.
- [15] S. Mohri *et al.*, "Development of endoskeleton type knee auxiliary power assist suit using pneumatic artificial muscles," in *2016 IEEE Int. Conf. Adv. Intell. Mechatron. (AIM)*. IEEE, 2016, pp. 107–112.
- [16] S. Sridar, Z. Qiao, N. Muthukrishnan, W. Zhang, and P. Polygerinos, "A soft-inflatable exosuit for knee rehabilitation: Assisting swing phase during walking," *Front. Robot. AI*, vol. 5, p. 44, 2018.
- [17] S. Sridar *et al.*, "Evaluating immediate benefits of assisting knee extension with a soft inflatable exosuit," *IEEE Trans. Med. Robot. Bionics*, vol. 2, no. 2, pp. 216–225, 2020.
- [18] J. Vakos, A. Nitz, A. Threlkeld, R. Shapiro, and T. Horn, "Electromyographic activity of selected trunk and hip muscles during a squat lift. effect of varying the lumbar posture," *Spine*, vol. 19, no. 6, pp. 687–695, 1994.
- [19] A. Roozbazar, "Biomechanics of lifting," in *Biomechanics IV*. Springer, 1974, pp. 37–43.
- [20] S. Hwang, Y. Kim, and Y. Kim, "Lower extremity joint kinetics and lumbar curvature during squat and stoop lifting," *BMC Musculoskelet. Disord.*, vol. 10, no. 1, p. 15, dec 2009.