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Effect of Assistance Timing in Knee Extensor Muscle Activation During Sit-to-Stand Using a Bilateral Robotic Knee Exoskeleton

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***Abstract*— The population of older adults experiences a significant degradation in musculoskeletal structure, which hinders daily physical activities. Standing up from a seated position is difficult for mobility-challenged individuals since a significant amount of knee extensor moment is required to lift the body's center of mass. One solution to reduce the required muscle work during sit-to-stand is to utilize a powered exoskeleton system that can provide relevant knee extension assistance. However, the optimal exoskeleton assistance strategy for maximal biomechanical benefit is unknown for sit-to-stand tasks. To answer this, we explored the effect of assistance timing using a bilateral robotic exoskeleton on the user's knee extensor muscle activation. Assistance was provided at both knee joints from 0% to 65% of the sit-to-stand movement, with a maximum torque occurring at four different timings (10%, 25%, 40%, and 55%). Our experiment with five able-bodied subjects showed that the maximal benefit in knee extensor activation, 19.3% reduction, occurred when the assistance timing was delayed relative to the user's biological joint moment. Among four assistance conditions, two conditions with each peak occurring at 25% and 40% significantly reduced the muscle activation relative to the no assistance condition ($p < 0.05$). Additionally, our study results showed a U-shaped trend (R^2= 0.93) in the user's muscle activation where the global optimum occurred between 25% and 40% peak timing conditions, indicating that there is an optimal level of assistance timing in maximizing the exoskeleton benefit.**

***Index Terms*— Robotic Knee Exoskeleton, Electromyography (EMG), Sit-to-Stand, Assistance Timing**

I. INTRODUCTION

Over the past century, the population of older adults in the United States has grown immensely (from 15 million to 55 million) [1]. Older adults tend to experience musculoskeletal weakness which can lead to limited mobility during daily activities [2]. Exoskeleton technology has shown its potential in augmenting humans for improved physical capabilities by providing assistance at lower-limb joints and alleviating muscle efforts [3], [4]. Most of these exoskeletons focus on assisting users during locomotion (e.g., level-ground walking) [5], [6], [7]. However, a major obstacle that mobility-impaired individuals encounter daily is a sit-to-stand transition. Since unstable sit-to-stand movement can potentially lead to injuries such as falling [8], exploring exoskeleton control strategies that can provide reliable sit-to-stand assistance is paramount.

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Several studies have investigated exoskeleton designs and control strategies for sit-to-stand assistance, and have shown the effectiveness in alleviating the user's biological demand for able-bodied adults. Vantilt *et al*. proposed a model-based control strategy for the exoskeleton to compensate for its own dynamics [9] and demonstrated a reduction in the user's muscle effort and joint moment by providing assistance using the controller. Rajasekaran *et al*. presented a mixed stiffness-damping control adaptation, evaluated it on healthy subjects performing sit-to-stand transfer, and presented the efficacy of the system [10]. Junius *et al*. utilized a misalignment-compensating hip exoskeleton to assist users during the sit-to-stand tasks and showcased the benefit of kinematically compatible joint structures by reducing metabolic consumption [11]. While these studies hold great promise in investigating control strategies and assisting able-bodied adults biomechanically, there are several limitations in the exoskeleton field for sit-to-stand applications. First, the field is limited in understanding the effect of exoskeleton assistance timing on the user's muscle activation. Second, there is limited information available for the optimal exoskeleton assistance strategy for the sit-to-stand task compared to cyclical locomotion such as walking overground and on inclined planes [12], [13], [14]. To bridge the gap and understand the optimal assistance strategy, we explored the effectiveness of peak assistance timing (ranging from early to very late compared to the burst of knee joint moment after a sit-off) in reducing the user's knee extensor muscle activity during sit-to-stand using a bilateral robotic exoskeleton.

The initiation of the sit-to-stand movement is commonly defined by the change in the horizontal acceleration (i.e., the user's trunk tilting forward) on the body's center of mass [15]. Using this representation, peak knee extensor moment occurs at 45% of the sit-to-stand phase. Instead, we defined the initiation of the sit-to-stand movement with a sit-off position to only focus on the region where the sit-to-stand movement was mainly contributed by knee extensors. Using our representation, the peak moment occurs at approximately 15% of the sit-to-stand phase. Our hypothesis is that assisting with a peak torque aligned in knee extensor moment timing will lead to a greater reduction in the user's knee extensor muscle activation than the delayed assistance strategy will. The underlying rationale is that the assistance that is aligned with the human biological moment will alleviate the relevant muscle activation required for sit-to-stand. To further understand the relationship, we swept through different assistance timings to explore the correlation between exoskeleton as-

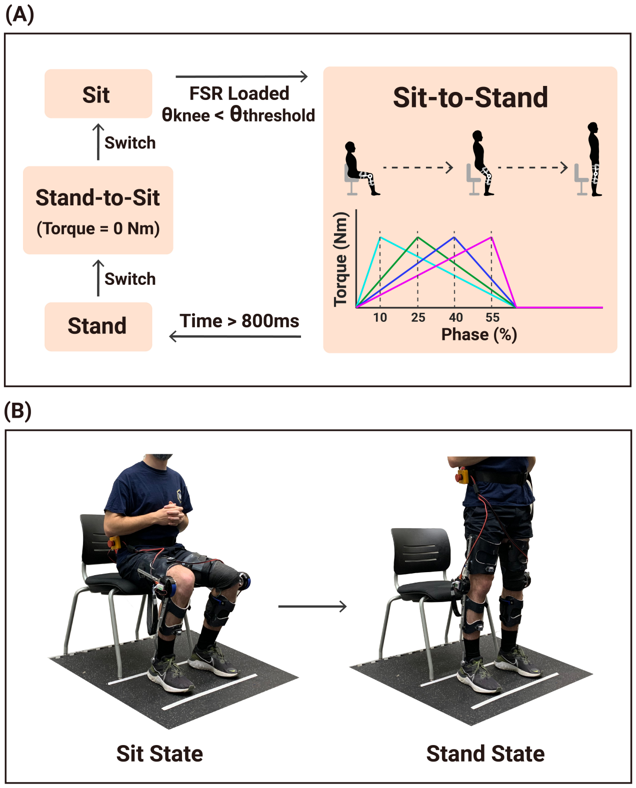

Fig. 1. (A) Finite state machine for sit-to-stand with torque assistance strategy varying in assistance timing. Maximum torque is provided at 10%, 25%, 40%, and 55% of the sit-to-stand phase. (B) Sit-to-stand task performed by a subject wearing a bilateral robotic knee exoskeleton. Knee joint encoders and unilateral EMG electrode measure the user's movement and biological demand, respectively.

sistance timing and muscle activation. Our study results will provide meaningful insights for exoskeleton researchers to develop an effective sit-to-stand controller.

II. METHODS

A. Exoskeleton Assistance Strategy

We developed a heuristic-based controller using a finite state machine (FSM) to determine the state of the user's movement in real-time (Fig. 1A). The FSM divides the user's movement into four main states: sit, sit-to-stand, stand, and stand-to-sit. First, the 'sit state' is defined as when the user sits still on the chair without any intention to lift the body. During this state, a force-sensitive resistor (FSR) attached at the user's heel is unloaded, and the knee angle is above the threshold sit angle as the user maintains an upright posture sitting on the chair. As the subject initiates an instant seat-off from the chair, the FSR becomes loaded and the knee angle goes below the threshold sit angle which initiates the 'sit-to-stand state'. The duration after detecting the start of the phase is 800 ms for the assistance, and this assistance duration was optimized with an initial pilot test. During this state, the controller assists at the knee joints from 0% to 65% of the sit-to-stand movement. Assistance torque linearly increases from the start of the sit-to-stand phase to the specified peak timing (10%, 25%, 40%, and 55%) with a peak magnitude and linearly decreases back to 0 Nm until 65% of the sit-to-stand movement. The magnitude of the peak torque is set to 25% of peak biological knee moment during able-bodied sit-to-stand [15]. The assistance is provided in a triangle shape to ensure that the controller provides the same amount of total torque over the duration across the different conditions. When the participant maintains the posture stability with the knees fully extended ('stand state'), a simple switch in the controller is used as the user passes 'stand-to-sit state' and returns to the 'sit state.'

B. Human Subject Experiment

The study was approved by the Georgia Institute of Technology Institutional Review Board and informed written consent was obtained for all subjects. Five able-bodied subjects with the age of 22.8 $\pm$ 3.9 years, the height of 171.0 $\pm$ 5.4 cm, and the body mass of 63.6 $\pm$ 8.1 kg were recruited for single-day experimentation. Our study utilized the autonomous bilateral robotic knee exoskeleton modified from our previous study (Fig. 1B) [16]. The exoskeleton has an overall mass of 2.4 kg while capable of providing a peak torque of 18 Nm. The exoskeleton torque was commanded using a tethered off-board controller unit (including a battery). The participants were asked to perform 10 sit-to-stand movements with 5 different exoskeleton assistance conditions: no assistance, assistance at 10%, 25%, 40%, and 55% of the phase for a total of 50 trials. Throughout the trials, the user's knee joint angle from the device and the electromyography (EMG) signal (bipolar snap electrode, Coapt LLC, US) from the user's Vastus Medialis (VM) were recorded. To ensure that the sit-to-stand was performed predominantly by the lower extremities, we utilized a chair without armrests, and participants were requested to fold their arms by their trunk while positioning the trunk upright to minimize the initial momentum. Before the data collection, the participants were asked to perform several sit-to-stand movements while wearing the exoskeleton to acclimate with the device. Foot placement and sitting position were adjusted to ensure the initial knee angle to be 105° of flexion [17]. Also, the position of the feet and chair were marked to ensure participants perform consistent motions throughout the entire trial.

Because the time-based controller provides assistance torque at the knee joint for a specific time duration, assistance peak timing can be significantly different if the time it takes to sit and stand varies across subjects and trials. To mitigate this error, it was crucial to maintain a rhythm throughout the entire trial. Therefore, an audible signal was provided using an electronic metronome at 75 beats per minute, and subjects switched between sitting and standing postures. The participants were asked to perform sit-to-stand movements 10 times, and the trials were performed in a randomized order. After the experiment, collected data including the knee joint angle, EMG signal, and device torque were analyzed.

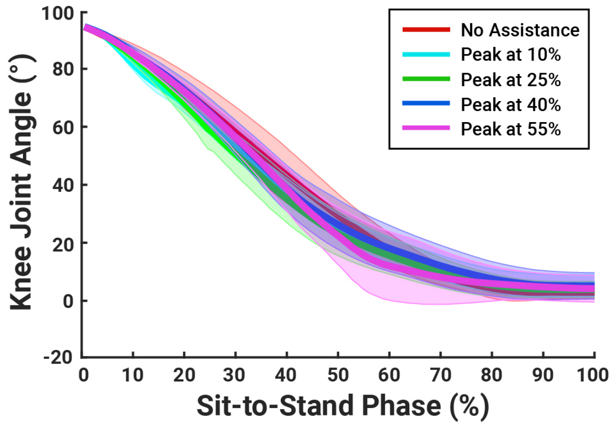

Fig. 2. Knee joint angle of five control conditions during sit-to-stand phase represented with different colored lines. The corresponding shaded region represents ± 1 standard deviation.

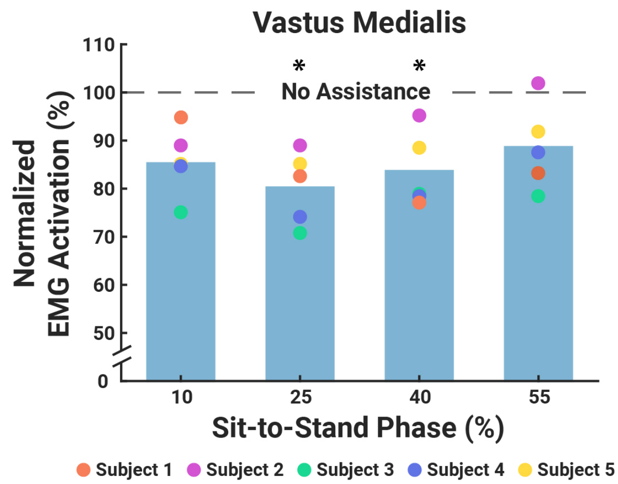

Fig. 3. Muscle activation levels of VM with different assistance peak timings (10%, 25%, 40%, and 55% of the sit-to-stand phase) averaged across 5 subjects. Colored dots represent normalized EMG activation values for each individual, and asterisks indicate statistical significance compared to no assistance ($p < 0.05$).

C. Analysis of the User's Kinematics and Electromyography

We utilized the knee joint angle to represent the experimental data into a defined sit-to-stand phase. The initiation of the sit-to-stand was defined as the knee angle passes the threshold sit angle, 95°, and the completion was defined as the knee angle converges to the standing angle for each subject. Within the region, the raw EMG signal was 20 to 400 Hz band-pass filtered, full-wave rectified, and 6 Hz low-pass filtered to generate a linear envelope of the user's muscle activity. The envelope was normalized to the maximum point of the average envelope during the no assistance condition. We averaged the maximum muscle activation across all trials within each condition for each subject.

D. Statistical Analysis

We conducted a one-way repeated measures analysis of variance (ANOVA) to compare the effect of different exoskeleton assistance conditions on the user's muscle activation (α = 0.05). A Bonferroni *post-hoc* correction for multivariate analysis was used to compute the statistical differences between each condition (MATLAB R2020b, US).

III. Results

The time-based torque assistance strategy was able to assist the sit-to-stand movement of users and lowered the user's muscle activation of the knee extensor muscle, VM. Figure 2 shows the knee joint angle profile of five different control conditions over the sit-to-stand phase. The threshold sit angle for the initiation of the sit-to-stand was defined as 95°, and the standing knee angle at the end of the sit-to-stand phase was 4.5 ± 1.0°. The 55% peak timing condition showed that assistance with a delayed peak potentially induced a kinematic deviation that may impede the user's intended movement. The assistance with a peak torque timed at 25% of the sit-to-stand phase was the most effective assistance condition in reducing the user's EMG (Fig. 2B). The muscle activation was reduced by 14.4 ± 7.7%, 19.3 ± 8.4%, 15.9 ± 7.7%, and 11.0 ± 9.4% for 10%, 25%, 40%, and 55% of the sit-to-stand phase compared to no assistance condition, respectively. Among the four assistance conditions, two conditions with each peak occurring at 25% and 40% significantly reduced the muscle activation relative to the no assistance condition ($p < 0.05$).

IV. Discussion and Conclusion

Our study explored the effect of exoskeleton assistance timing in reducing the user's knee extensor muscle activation during sit-to-stand. Overall, our exoskeleton assistance was able to reduce the user's VM EMG consistently across all conditions. Assistance conditions with a peak timing at 25% and 40% of the sit-to-stand phase significantly reduced the muscle activation relative to the no assistance condition. Across all assistance conditions, a general U-shaped trend (R^2= 0.93) was shown that the global optimum occurred within the region of 25% and 40% in maximizing the user's EMG reduction. However, while we did see a greater benefit in the user's EMG when providing a delayed assistance, we could not make a definitive statement about our initial hypothesis due to the low sample size (N=5). Relevant literature studies from other locomotor tasks explored optimal exoskeleton assistance levels and have resulted in similar trends as our findings. Kang *et al.* investigated the effect of exoskeleton assistance magnitude on the user's metabolic cost during walking and showed that the global optima for the lowest metabolic cost were in between the 13% and 26% conditions [12]. Zhang *et al.* utilized ankle exoskeleton and demonstrated the generality of optimized assistance with several types of walking conditions. The results of the study showed that the subject-varying assistance strategy is effective in reducing the energy cost of walking by 24.2% on average [18]. While sit-to-stand may not directly correlate to cyclical locomotor tasks, these literature studies indicate that similar paradigm of optimal assistance may exist to non-cyclical tasks. Thus, there is a need for further exploration in optimizing assistance strategies to maximize exoskeleton benefit during sit-to-stand.

Our study showed comparable results to other relevant sit-to-stand studies using exoskeletons on able-bodied subjects. Zheng *et al*. utilized a pneumatically driven exoskeleton to provide knee joint assistance during sit-to-stand and reduced knee extensor EMG ranging from 18% to 30% compared to no assistance condition [19]. The study was limited as the exoskeleton assistance level could not be modulated (e.g., different timing and magnitude). However, our study was able to show the reduction in knee extensor EMG by comparing different assistance timings with a modulated torque magnitude for each subject. Lee *et al*. evaluated passive knee wear for knee extension assistance during sit-to-stand [20], and the results showed a decrease in the user's metabolic cost by 3.2% compared to no assistance condition. The study had limitations as the EMG activation showed high variability among participants, and there were no statistically significant differences in muscle activity. Compared to their study findings, our study was able to successfully demonstrate a reduction in the user's muscle activation compared to no assistance condition using the autonomous exoskeleton.

In conclusion, we examined the effect of assistance timing in muscle reduction of knee extensor during the sit-to-stand task and showcased that the global optimum for the greatest EMG reduction occurs between 25% and 40% peak timing conditions. One limitation of our study is that the controller provided assistance based on time, which may not perfectly align with the user's complete sit-to-stand movement. Another limitation is that we set thresholds in the user's knee joint angle for sit-to-stand, which could hinder the user's natural behavior. For future works, we plan to develop a robust sit-to-stand phase-based control strategy and investigate the effect of optimal sit-to-stand assistance on other muscle groups.

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