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A Semi-Wearable Robotic Device for Sit-to-Stand Assistance

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Abstract— **With the aging of the population in the United States, an increasing number of individuals suffer from mobility challenges. For such individuals, the difficulty of standing up from a seated position is a major barrier for their daily physical activities. In the paper, a novel assistive device, namely Semi-Wearable Sit-to-Stand Assist (SW-SiStA), is presented, which provides effective lower-limb assistance to overcome such difficulty for the mobility-challenged individuals. Unlike traditional exoskeletons, the SW-SiStA can be easily detached after the completion of the sit-to-stand process, and thus will not cause additional burden to the user during the subsequent ambulation. The SW-SiStA is powered with a pneumatic actuator, leverage its advantages of low cost and high power/force density. The complexity of the device is reduced by the use of a simple solenoid valve in combination with two adjustable needle valves, providing the desired individualized adjustability without the expensive proportional valves. Human testing of the device indicated that the SW-SiStA was able to provide effective sit-to-stand assistance in a natural way, and the users were able to expend significantly less muscle efforts in the process.**

I. INTRODUCTION

The population in the United States is experiencing a rapid aging process: by the year of 2030, there will be 71 million older adults, accounting for 20% of the U.S. population by 2030. In general, aging is associated with profound changes in body composition and muscle strength, often resulting in reduced functional capacity.[1] For example, the maximum physical work capacity declines by 25% to 30% between the ages of 30 and 70 [2], and loss of strength in healthy elderly individuals has been estimated at 1.5% per year, and loss of power at approximately 3.5% per year [3]. As a result, a large number of elderly individuals suffer from impaired mobility due to the strength and endurance weakness in the lower extremity, resulting from the gradual degeneration of the musculoskeletal structure, or the related musculoskeletal or neural pathologies (e.g. stroke). With the impaired mobility, such individuals are more likely to live in a sedentary lifestyle, and suffer from the various problems associated with the sedentary lifestyle, e.g. high blood pressure, depression, obesity, etc..

For an individual with mobility impairment, the first major obstacle in his/her daily physical activities is the challenge of standing up from a seated position. Sit-to-stand (SiSt) is a highly demanding process that requires significant joint torque to lift the body center of mass. Related studies (such as[4]) show that knee torque as high as 2.2 N-m/kg (body mass normalized) is needed for unassisted SiSt motion, far exceeding that for walking (~0.6 N-m/kg peak torque [5]). With reduced muscle strength, a mobility-challenged individual is likely to need substantial physical assistance from caregivers to complete the SiSt process.

To address this issue, a type of equipment, known as sit-to-stand lifts, are widely used to help frail individuals in the transition from a seated position to a standing position. Most of these lift devices have a mobile base for easy positioning. The assistance is provided by lifting the upper body through a belt routed around the user's trunk (under the arm pits) or lifting the user's bottom through a moving supporting plate situated underneath. Despite their usefulness, these devices have a few common problems: they are usually heavy and bulky, difficult to maneuver (especially in tight spaces), and the users tend to rely on the lifting assistance instead of using their own muscle strength to complete the SiSt process. In recent years, with the advances in robotic technologies, assistive robots have also been developed for the SiSt assistance. Some of them take the form of powered walkers, e.g., the smart mobile walker incorporates a motor-powered support plate that lifts the user's upper body through a lifting force applied under the elbow [6]. As the lifting mechanism is similar to that used by SiSt lifts, this smart walker needs to expand its area of support for stability enhancement, which increases the complexity of the mechanism. Alternatively, researchers have also explored the possibility of using wearable robots (i.e. exoskeletons) to provide joint assistance (primarily for the knee joint) in the SiSt process. Typical examples include the AlterG Bionic Leg [7] and the torque-controlled knee exoskeleton by Shepherd and Rouse [8]. These wearable devices are much more compact and lighter than SiSt lifts. Furthermore, these devices are able to encourage the users' active participation in the process, with their capability of regulating the torque outputs in real time.

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On the other hand, due to their wearable nature, the exoskeletons are usually worn by the users in the activities following the SiSt process (primarily walking), despite the much lower joint torque requirements in such activities. As such, the high torque capacities of these exoskeletons are largely underutilized, and the devices become extra burdens for their users.

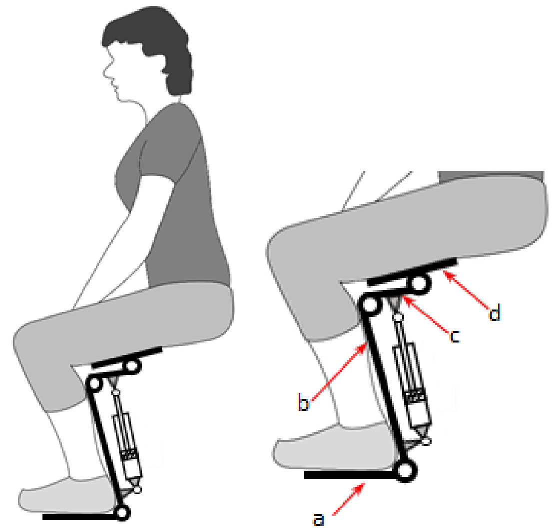
In this paper, the authors present a novel semi-wearable robotic device for SiSt assistance, which can be detached from the user easily after functioning as an exoskeleton during the SiSt process. This unique design provides the same advantages associated with the SiSt exoskeletons as described above, while avoiding the aforementioned extra burden problem in the subsequent movement. The semi-wearable design also comes with the additional benefit of alleviating the strict weight/volume requirements associated with a fully wearable exoskeleton. As a result, less expensive technologies and components can be utilized to make the system more affordable for the future real-world application. In the subsequent sections, the design, control, and experimental testing of the robotic device, which is named as Semi-Wearable Sit-to-Stand Assist (SW-SiStA) for the conciseness of presentation.

II. Design of the SW-SiStA

As the name indicates, the SW-SiStA is a semi-wearable device that is attached to the user's lower limb in the SiSt process. It provides multiple advantages common to wearable robots, such as compact profile, direct joint assistance, and coordinated action with human movement. Furthermore, with its unique semi-wearable design, the SW-SiStA allows easy detachment after use, and thus the weight of the device itself does not constitute additional load for the user in his/her free movement. As such, portability is no longer a strict requirement, which enables the use of less complex and less expensive components for cost reduction. The current SW-SiStA prototype is powered with an off-the-shelf pneumatic cylinder, leveraging the two major advantages associated with pneumatics: low cost and high force/power density. Pneumatic actuation has been successfully utilized in the authors' prior lower-limb exoskeleton research, and its effectiveness was demonstrated in the corresponding human testing [9].

The structure of the SW-SiStA consists of four rigid segments connected with three joints, as shown in Fig. 1. The foot plate ("a"), placed under the user's foot, is connected with the shank bar ("b") with the "ankle" joint, and the shank bar ("b") is connected with the thigh bar ("c") with the "knee" joint. Note that the thigh bar is not in direct contact with the user's biological thigh to avoid concentration of the contact force. Instead, a dedicated thigh plate ("d") is incorporated to provide even distribution of the pushing force over a large contact area underneath the thigh segment. As the thigh plate is pivoted to the edge of the thigh bar ("c"), it is always in full contact with the thigh regardless of the position of the "knee" joint. For the actuation of the "knee" joint, a double-acting pneumatic cylinder is mounted between the shank bar and the thigh bar to form an inverted crank-slider mechanism, with the details shown in Fig. 2.

Providing sufficient assistive torque is an important design objective of the SW-SiStA. As the knee torque in the SiSt process changes significantly with the joint position, a single value is not sufficient to characterize the torque requirement. On the other hand, the actuation torque also varies with the joint position, as determined by the crank-slider mechanism.



(a) (b)

Fig. 1. The SW-SiStA assisting a user in the sit-to-stand process: (a) the complete view of the human-robot system; and (b) the major components of the SiStA.

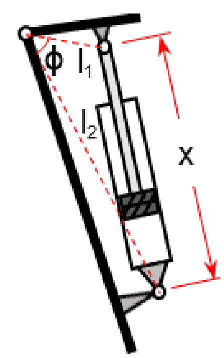


Fig. 2. The inverted crank-slider mechanism that drives the knee motion.

As such, the torque capacity of the actuated joint is modeled as a function of the joint position, which is then compared with the desired assistive torque profile on the position-torque plane. Based on the mechanism in Fig. 2, the joint torque is the product of the actuator force F and the moment arm r:

$$\tau = Fr \tag{1}$$

The moment arm r can be calculated as the derivative of the length x with respect to the angle φ:

$$r = \frac{dx}{d\phi} \tag{2}$$

where ϕ can be calculated from the current joint position θ:

$$\phi = \Omega - \theta \quad (3)$$

where Ω is the value of ϕ when the knee position is at 0° (i.e., totally straight). From the law of cosines, the length x is a function of ϕ:

$$x = \sqrt{l_1^2 + l_2^2 - 2 l_1 l_2 \cos\phi} \quad (4)$$

Substituting into (2), the moment arm becomes

$$r = \frac{l_1 l_2 \sin\phi}{\sqrt{l_1^2 + l_2^2 - 2 l_1 l_2 \cos\phi}} \quad (5)$$

which can be substituted into (1) to obtain the joint torque equation:

$$\tau = F\left(\frac{l_1 l_2 \sin\phi}{\sqrt{l_1^2 + l_2^2 - 2 l_1 l_2 \cos\phi}}\right) \quad (6)$$

To construct the SW-SiStA prototype, an off-the-shelf pneumatic cylinder (173.5-DPY, Bimba Manufacturing, University Park, IL) was selected as the actuator. It has a pressure rating of 1724 kPa (250 PSI) and a bore size of 38 mm (1.5 inches), producing an actuating force up to 1965 N. The mounting positions of the actuator were carefully determined to keep it close to the shank bar, with the purpose of minimizing the possibility of interfering with the user's chair in use. Based on the design values of l_1=257 mm and l_2=64 mm, the torque capacity of the actuated joint is plotted against the joint position, as shown in Fig. 3. Also plotted in this figure is the knee torque trajectory in the SiSt process for a 47 kg person, with the data from [4]. As can be observed in Fig. 3, the peak of the knee torque trajectory matches the curve representing the torque capacity of the SW-SiStA, indicating that the robot is able to provide all the torque required to complete the SiSt process. Note that the original torque data in [4] is body weight-scaled. For individuals with greater body weight (>47kg), although the SW-SiStA could not provide 100% of the SiSt torque at the peak, the high torque capacity of the device still enables it to relieve a significant percentage of the knee torque in the SiSt process. Therefore, we expect that such individuals may still benefit from the device and be able to stand up with much less effort under the SW-SiStA's assistance, making it possible for frail older adults to stand up by themselves or with minimal assistance from caregivers.

III. Instrumentation and Control of the SW-SiStA

As the SiSt is a transitional process that connects the sitting and standing postures, it has a clearly defined initial and final states, which make its control less challenging than cyclical movement such as walking. Such reduced difficulty makes it possible to simplify the instrumentation to reduce cost and improve reliability. As the basis of controller development, the position and torque trajectories (Fig. 4) were carefully studied. Based on the distinct biomechanical characteristics, the SiSt can be divided into two phases: (1) Loading and (2) Rising, separated by the instant of seat-off (approximately 33% of the motion progress, as shown in Fig. 4).

In the loading phase, the body weight is shifted from the seat to the individual's lower limbs. As such, the knee joint provides an increasing amount of torque to support the body weight and initiate the upward motion. When the individual's bottom is lifted from the seat, the motion enters the rising phase, in which the knee torque decreases with the joint extension. When the SiSt process is completed, the joint is nearly fully extended and the joint torque settles at a close-to-zero steady-state value.

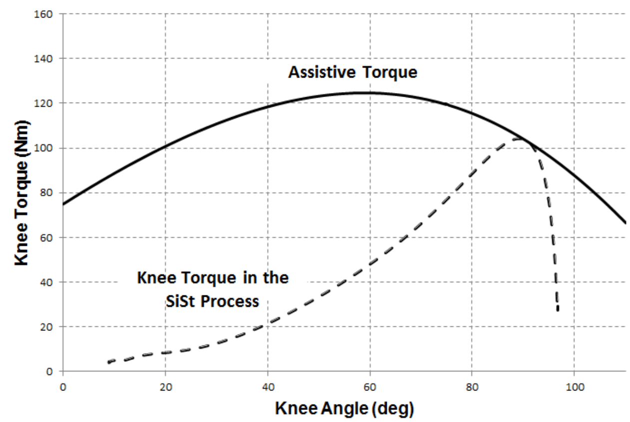
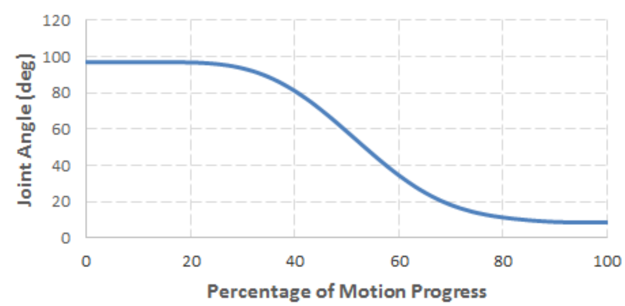
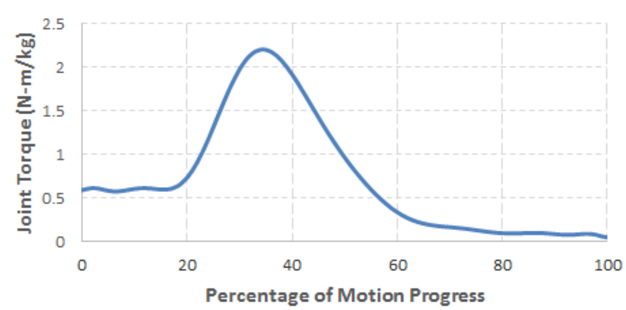


Fig. 3. Comparison of the assistive torque capacity of the SW-SiStA versus the Knee torque in the SiSt process for a 47kg person (drawn based on the data from [4]).



(a)



(b)

Fig. 4. The joint angle (a) and torque (b) trajectories of the knee in the SiSt process.

Based on such observation, it was determined that the control of the actuator force in the SiSt process can be provided with the combination of two two-way solenoid valves and two needle valves with adjustable orifices, as shown in the diagram in Fig. 5. The solenoid valves (2S020-1/8A, Sizto Tech Corporation, Palo Alto, CA) function as pneumatic switches that start/stop a certain phase, while the needle valves (PNV11-66, Pneumadyne, Plymouth, MN) enable the user to adjust the loading/unloading speeds for each individual user. This combination provides multiple advantages over the traditional proportional valve, including lower cost, improved reliability, and significantly reduced leakage and electric power consumption in operation. Further, each pair of solenoid valve – needle valve can potentially be combined into a single valve unit, reducing the complexity and volumetric profile of a future practical SW-SiStA device.

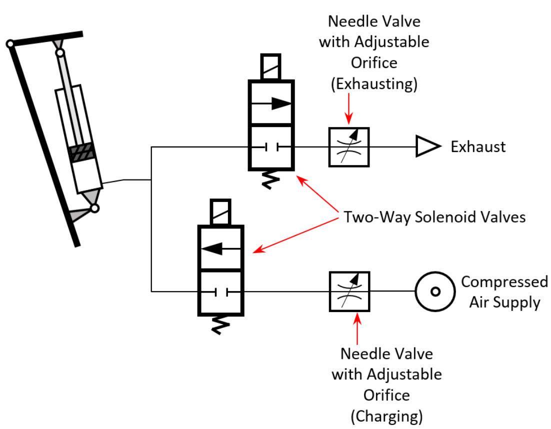


Fig. 5. The configuration of the pneumatic actuation system in the SW-SiStA.

In addition to the control valves, the SW-SiStA is also equipped with various sensors for joint position, foot plantar pressure, and actuator air pressure measurement. The joint position is measured through a linear potentiometer mounted in parallel with the actuator (LP-100F, Midori Precisions, Tokyo, Japan). Through the measurement of the actuator displacement, the joint angle can be calculated accordingly. The foot plantar pressure is measured with a force sensing resistor (FSR400, Interlink Electronics, Camarillo, CA). Such pressure signal functions as a trigger (when exceeding a certain threshold), indicating that the user is ready to start the SiSt process. Additionally, a pressure transducer (SDET-22T-D25-G14-U-M12, FESTO, Esslingen am Neckar, Germany) is used to measure the actuator air pressure, and the actuation force can be estimated accordingly. Note that the pressure transducer was installed for experimental evaluation only, and thus may be removed in a future practical device. Finally, the entire system is equipped with a carbon fiber air tank (Dura Pro SLP, Ninja Paintball, Crystal Lake, IL) to supply the compressed air, although the initial testing was conducted with an external air compressor for convenience in the experimentation.

A flow chart of the SW-SiStA operation is shown in Fig. 6, and the corresponding control algorithm is implemented in a microcontroller (dsPIC33FJ128MC802, Microchip Technology, Chandler, AZ). When the device is turned on, the foot pressure FSR signal is continuously read until it exceeds a preset threshold value, triggering the SiSt process. The assisted SiSt starts with the switching of the charging two-way solenoid valve to its ON position, which pressurizes the actuator chamber (its speed adjustable through the needle valve). Subsequently, the joint position is continuously read and differentiated with a digitally implemented practical differentiator (i.e., differentiator with embedded low-pass filter). If the joint extensional velocity exceeds a preset threshold, the controller transitions to the lifting phase (the charging valve switching to the OFF position, closing the actuator chamber). Note that the extension of the knee occurs simultaneously with the expansion of the actuator pressurized chamber, which in turn reduces its air pressure. As such, the actuator-generated assistive torque decreases with the extension of the knee, as a result of the underlying pressure dynamics in the actuator (i.e., no control action required). After a certain period of time (its duration is a tunable parameter), the exhausting two-way valve switches to its ON position (connecting to the atmosphere) to exhaust the air in the actuator. Such exhausting action further accelerates the decrease of the air pressure to ensure that the assistive torque reduces to zero when the user reaches the final standing posture.

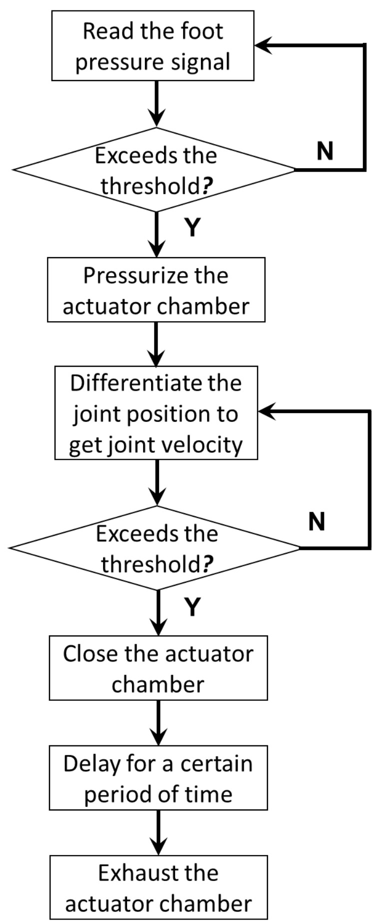


Fig. 6. Flow chart of the SW-SiStA's control process.

IV. HUMAN SUBJECT EXPERIMENT

Human subject experiments were conducted to evaluate the performance of the SW-SiStA in assisting human users during the SiSt process. The experiments were conducted at the Exoskeleton and Prosthetic Intelligent Controls Lab at the Georgia Institute of Technology, and the protocol was approved by the Georgia Institute of Technology Institutional Review Board. Five healthy subjects (four males and one female) with an average age of 22 ± 1.10 years, body mass of 74 ± 3.74 kg, and height of 1.78 ± 0.072 m were recruited for a single day of experimentation. Each subject was fitted to the SW-SistA through two adjustable shank straps on the device. The subjects were asked to perform ten trials of a sit-to-stand motion without assistance, followed by ten trials of the sit-to-stand motion with the SW-SiStA assistance, as shown in Fig. 7. During all trials of both conditions, surface electromyography (EMG) sensor data (Biometrics Ltd., UK) were collected using a bilateral arrangement of three EMG electrodes: vastus lateralis (VL), vastus medialis (VM), and rectus femoris (RF). Conventional motion capture equipment (VICON Motion Systems, USA) as well as one force plate per foot (Bertec Corporation, USA) were used to calculate inverse dynamics. Joint kinetics and kinematics data were calculated using measured ground reaction forces and marker data (Nexus 2.7, VICON Motion Systems, USA). To ensure that lower limb muscles predominantly performed the sit-to-stand motion, the chair did not have armrests, and each subject was requested to fold their arms by their trunk. Additionally, the trunk remained upright to minimize initial momentum by the subject. After the experiment, synchronized kinematic, kinetic, EMG, and device torque data were analyzed. EMG signals were processed with conventional methods by initially taking off the offset voltage, 20 ~ 400 Hz band-pass filter, full wave rectification, and 6 Hz low-pass filter to generate a smooth envelope of EMG activity.

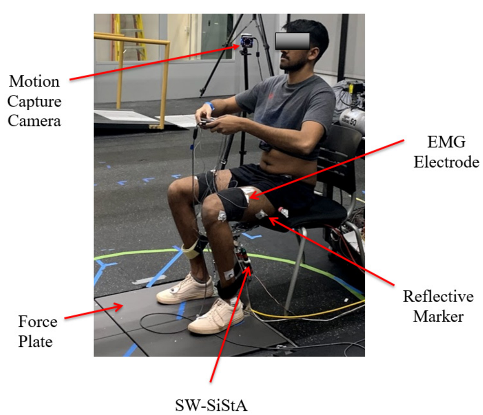


Fig. 7. Experimental setup.

Figures 8~12 display the primary results obtained from the experiments. In the experiments, the SW-SiStA was able to generate significant torque output (up to 30 N-m) to assist the human users' SiSt motion (Fig. 8). The device acted with a torque profile that was similar to the biological torque typically exibited by the knee joint with a peak torque roughly 20-30% that of the biological knee joint during the SiSt process [10]. As the assistance was provided in a way consistent with the human motor control, the resulted joint motion is natural, as can be clearly observed from the joint angle trajectories shown in Fig. 4. The effectiveness of the assistance was determined based on a comparison of muscle activation of using the SW-SiStA compared to no SW-SiStA assistance. With the SW-SiStA providing assistance, the peak EMG of the quadricept muscles were reduced by 18-30%. Specifically, we measured the vastus lateralis, vastus medialis and rectus femoris shown in Figs. 10~12. Each muscle exibited reduced EMG activation levels when using the SW-SiStA compared to no SW-SiStA assistance. This clearly demonstrates the device effectiveness as reduced effort was needed to stand when the assistance was provided by the SW-SiStA.

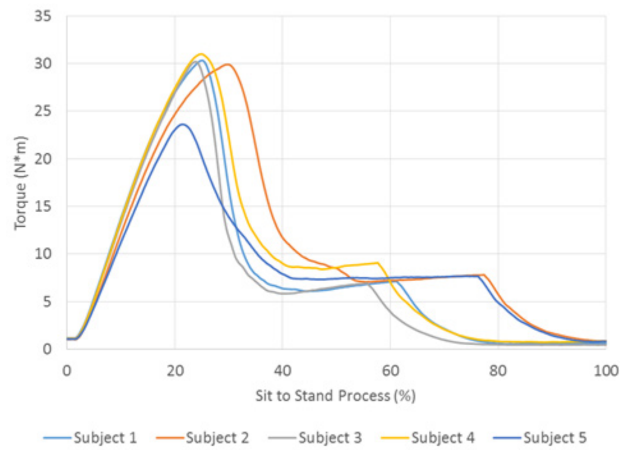


Fig. 8. SW-SiStA torque across the SiSt process.

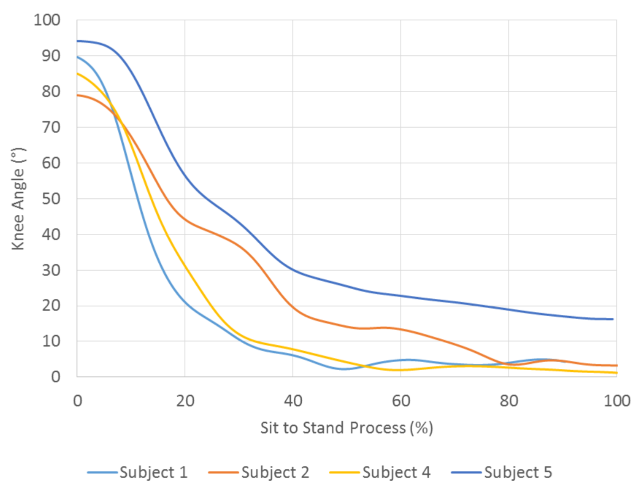


Fig. 9. Knee angle across the SiSt process.

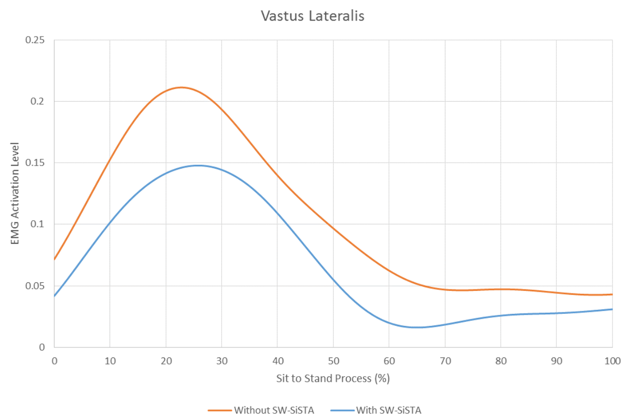


Fig. 10. Lower limb EMG activity for Vastus Lateralis.

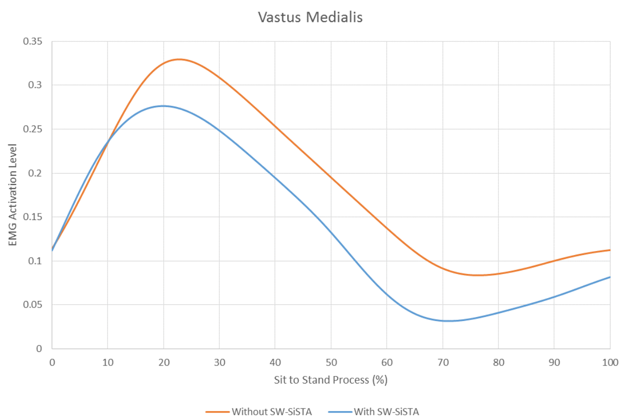


Fig. 11. Lower limb EMG activity for Vastus Medialis.

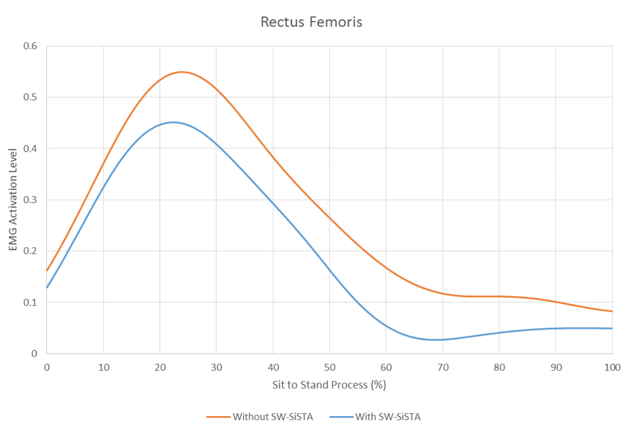


Fig. 12. Lower limb EMG activity for Rectus Femoris.

V. Discussion and Conclusions

This paper presents the design, control, and experimentation of a novel robotic device that assists mobility-challenged individuals during their sit-to-stand (SiSt) process. With a unique semi-wearable design, the device can be easily detached after the completion of the SiSt process, and thus will not cause extra burden to the user during the subsequent ambulation. Pneumatic actuation was adopted to power the joint motion, providing the advantages of low cost and high force/power density compared with the motor-based actuation. With careful design calculation, the device is able to provide full knee torque for a 47kg person. To reduce the complexity of the device control, a simple solenoid valve was utilized in combination with two adjustable needle valves, providing the capability of personalized adjustment without utilizing expensive proportional valves. After the device is fabricated, its performance was experimentally tested in the assistance of human subjects, and the results show a natural motion under the device assistance as well as a significant reduction in the muscle activities.

For the future works on the SW-SiStA, the authors plan to conduct device testing on mobility-challenged older adult subjects to characterize its performance on the target users. The authors also plan to improve the user interface of the device (e.g., developing an automatic detaching mechanism), making the SW-SiStA more convenient to use in the mobility-challenged users' daily life.

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