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Design and prototyping of a semi-wearable robotic leg for sit-to-stand motion assistance of hemiplegic patients

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Abstract. With the increasing number individuals living with the long-term effects of stroke, it has become more important to provide accessible healthcare, in line with the UN SDG 3 on promoting good health and well-being. Hemiplegia, the paralysis of one side of the body, is a common side effect of stroke. The condition of hemiplegia provides unique challenges for afflicted individuals, including asymmetric body strength and limited mobility, especially in the sit-to-stand (STS) motion. High weight-bearing asymmetry also leads to poor mobility outcomes and increased fall risk for hemiplegic patients. To address these concerns, a semi-wearable sit-to-stand assist robot is proposed to provide assistive force, motion guidance, and stability during the STS motion. The proposed robot is a planar 2-DoF assistive robot attached to the hip of the user that acts as an extra support leg during the STS motion. The designed robot is semi-wearable, and is worn when needed during the STS motion, but can easily be detached when not needed. The robot was designed to reduce the weight-bearing asymmetry of hemiplegic users during sit-to-stand, to allow them to complete the motion in a more symmetric and stable manner. The design requirements and concept are outlined, along with the control scheme for device operation. Human experiments demonstrated the ability of the assist robot to reduce average weight-bearing asymmetry during the STS motion.

Keywords: SDG3, robotics and mechatronics, assistive robotics, hemiplegia, sit-to-stand, wearable robotics

1 Background

From 1990 to 2017, it was found that there has been an overall 3.1% increase in age-standardized stroke prevalence rate, and a greater number of people must live with the long-term impairments caused by stroke [1]. Motor impairment on one side of the body, i.e., hemiplegia or hemiparesis, is a common effect of stroke, with about 80% of survivors being affected [2]. Patients with hemiplegia experience problems in active movement and mobility. Maintaining mobility is critical in performing activities of daily living (ADL), and one important ADL impaired by hemiplegia is the sit-to-stand (STS) motion [3]. For impaired individuals, the assistance of a caregiver or the

use of large STS lifts is needed during the motion, as it is a significant fall risk [4]. Hemiplegia also affects how the STS motion is conducted, and significant asymmetry in leg weight-bearing and during the STS motion has been observed in hemiplegic individuals. Cheng, et al found that average weight-bearing asymmetry between the affected and non-affected legs during the STS motion is higher in hemiplegic patients, and that higher asymmetry was related to a greater risk of falls and poorer mobility outcomes [5]. Effort should be exerted to reduce weight-bearing asymmetry and help the patient perform the STS motion more symmetrically and avoid non-use syndrome. Reduction of weight-bearing asymmetry and more use of the paretic leg is critical for long-term mobility and quality of life of hemiplegic patients [3].

Devices have been developed to provide support and assistance for elderly or injured individuals in the STS motion, but not many have been designed to address the challenges faced by hemiplegic patients. External support devices, such as STS lifts, are sold commercially to aid in the STS transfer in hospitals or care facilities. However, they can be difficult to use in smaller home environments [6]. Wearable assistive devices, particularly exoskeletons such as ReWalk or other similar commercial exoskeletons, are also used to increase mobility of elderly or impaired users [7]. While these devices can provide beneficial assistive force, their cost is still prohibitive, making them not accessible for many people. Furthermore, such exoskeletons can take a long time to don and take off, making them inconvenient to use regularly, especially for hemiplegic users [8]. Other directions for the design of wearable assistive devices for STS have also been explored. Zheng, et al. developed a pneumatically actuated semi-wearable robotic device for sit-to-stand assistance that was designed to be easily detached after completion of the STS process [9]. Treers, et al. developed lightweight supernumerary robotic limbs for sitting/standing assistance [10]. These designs provide interesting directions for the development of STS assist devices, however they do not address the unique challenges presented by hemiplegia, such as asymmetrical loading of the legs, differences in muscle activation, and balance in the frontal plane.

There is a dearth of assistive devices for hemiplegic individuals, and the increasing number of post-stroke patients means there is a need to develop interventions to aid in the care of hemiplegic patients, in line with the UN Sustainable Development Goal 3 of Good Health and Well-being [11]. Therefore, the objective of this study is to develop an STS assist robot for hemiplegic patients that can provide support and reduce the weight-bearing asymmetry of the legs during the STS motion.

The current research expands on previous work done on the concept and design of the STS assist robot [12]. Another method for determining the target STS path is presented, along with initial experiments on a fabricated prototype to assess the effectiveness of the assist robot.

2 Sit-to-Stand Assist Robot Design

A semi-wearable sit-to-stand assist robot for hemiplegic patients is proposed to address the unique challenges posed by their ailment, such as their asymmetrical body strength and reduced coordination. Furthermore, the design is focused on maintaining

the physical capabilities of the hemiplegic person, as exercise, especially of the paretic leg, is important for their overall quality of life [3]. The design concept for the STS assist robot can be seen in Fig. 1a. The STS assist robot is a planar 2-DOF assistive robot attached to the user at the hip to provide stability and assistive force throughout the STS motion. It acts as a support leg to compensate for the loss of strength of the hemiplegic limb and perform the STS motion more symmetrically. The robot will work in coordination with the human user and should provide assistive force while still allowing the user to exert force and effort to perform the motion on their own. The robot provides motion assistance by guiding the user along the correct STS motion path and facilitating more use of the affected leg and more symmetrical execution of the motion. The structure and actuation of the robot will provide stability to the user in the frontal and sagittal planes during the STS motion. The designed robot is semi-wearable, meaning it is worn when needed during the STS motion, but can be easily detached when not needed. A gait belt is used as the interface between the robot and the user and provides a stable point for application of assistive force.

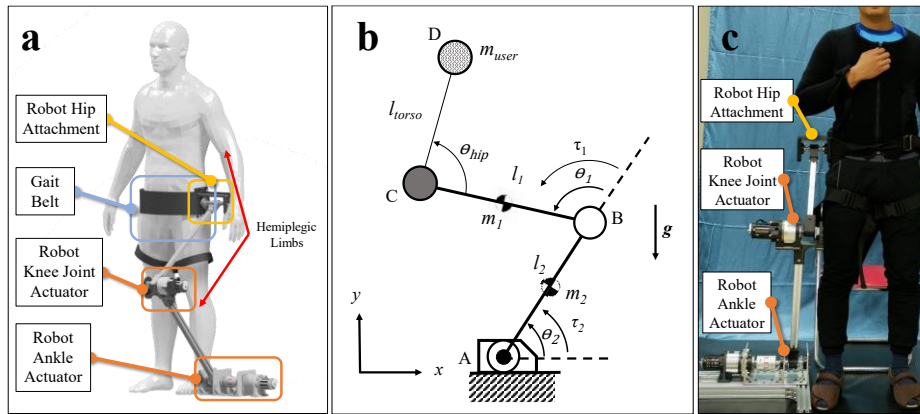


Fig. 1. (a) Model of the assist robot. (b) Schematic diagram of the assist robot with a user. (c) Image of the fabricated prototype being worn by a user.

Fig. 1b shows the schematic diagram of the proposed assist robot attached to a user used to estimate the load to be supported by the actuators. The base of the robot was assumed to be fixed to the ground during the motion and in line with the user's feet. The robot ankle, knee joint, and hip attachment are represented by points A, B, and C, respectively. Point D represents the center of mass of the user at the torso. The relative position vectors of the points, D_C , C_B , and B_A , were calculated using Eqs. (1) to (3). The estimated actuator torques, τ_1 and τ_2 , were calculated using Eqs. (4) and (5). q is the proportion of total body mass to be supported by the robot, taken to be 10%, as this allows the asymmetry between the affected and unaffected side to be reduced from the range of a hemiplegic faller to the range of a hemiplegic non-faller [5]. Link lengths of 350 mm for l_1 and 600mm for l_2 were used in the calculations. θ_{hip} values and the estimated position of point C at the hip throughout STS motion path were calculated using measurements by Nuzik et. al. [13]. Inverse kinematics was used to

obtain an initial estimate of θ_1 and θ_2 needed to reach point C during the STS motion. The user was assumed to have a mass of 62.5 kg, and masses of 2 kg for m_1 and m_2 were assumed. The effects on inertia on the assist robot limbs were neglected. Based on the calculations, about 25 N·m for τ_1 , and 60 N·m for τ_2 would be needed.

$$\mathbf{D}_C = l_{torso} \begin{bmatrix} \cos(\theta_{hip} + \theta_1 + \theta_2) \\ \sin(\theta_{hip} + \theta_1 + \theta_2) \end{bmatrix} \quad (1)$$

$$\mathbf{C}_B = l_1 \begin{bmatrix} \cos(\theta_1 + \theta_2) \\ \sin(\theta_1 + \theta_2) \end{bmatrix} \quad (2)$$

$$\mathbf{B}_A = l_2 \begin{bmatrix} \cos \theta_2 \\ \sin \theta_2 \end{bmatrix} \quad (3)$$

$$\tau_1 = m_1 \mathbf{g} \times \left(\frac{\mathbf{C}_B}{2} \right) + q m_{user} \mathbf{g} \times (\mathbf{D}_C + \mathbf{C}_B) \quad (4)$$

$$\tau_2 = m_2 \mathbf{g} \times \left(\frac{\mathbf{B}_A}{2} \right) + m_1 \mathbf{g} \times \left(\frac{\mathbf{C}_B}{2} + \mathbf{B}_A \right) + q(m_{user} \mathbf{g}) \times (\mathbf{D}_C + \mathbf{C}_B + \mathbf{B}_A) \quad (5)$$

Based on the estimated torque requirements, two Turnigy Aerodrive SK3-5065 BLDCs with 1:30 and 1:100 gear reduction for actuators 1 and 2, respectively, were selected for actuation. The robot prototype was controlled using an ODrive v3.6 BLDC Motor Controller together with an Arduino Mega microcontroller. Fig. 1c shows the fabricated prototype being worn by a user.

3 Control Scheme of the STS Assist Robot

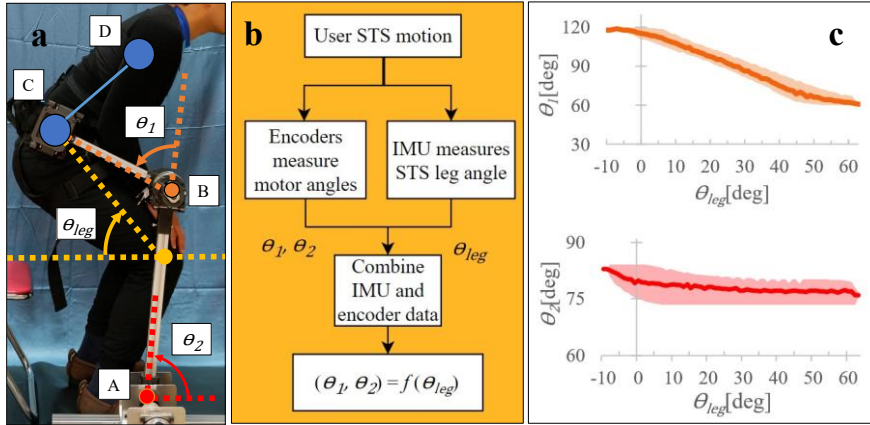


Fig. 2. (a) Image of the assist robot worn by a user with relevant angles marked. (b) Process diagram for obtaining target STS path. (c) Target actuator angles vs leg angles during the STS motion for one test subject, with deviation from average marked by shaded area.

To determine the output position of the assist robot actuators, it is necessary for the STS motion of the user to be tracked in real time. Treers, et al. measured the angle of the user’s thigh with respect to the horizontal, called the leg angle, using an accelerometer and related it to the output force profile of an assistive device during the STS motion [10]. This method showed that the leg angle can be used to determine the progression of an individual through the STS motion, and that the leg angle corresponds to the position of an individual during the STS motion.

For the proposed STS assist robot, the leg angle of the user, θ_{leg} , is related to the user’s hip position during STS, where the assist robot is attached to the user. The hip position corresponds to specific actuator angles of the assist robot, θ_1 and θ_2 , needed to reach that position. The relationship between leg angle and hip position varies between users. To determine this relationship for a particular user, the user is asked to do their target STS motion while wearing the unactuated assist robot. An Inertial Measurement Unit (IMU) is used to measure the user’s leg angle in real time. As the STS motion is done, the leg angles of the user are measured together with the actuator angles which are measured using the assist robot motor encoders, and a relationship between the leg angles and target actuator output angles is obtained.

This process only needs to be conducted once for each user, and the obtained relationship allows the assist robot actuator output angles can be controlled in real time during the STS motion as a function of the IMU-measured leg angles, $f(\theta_{\text{leg}})$. This method allows individualized target STS paths to be generated for each user. Fig. 2b summarizes the methodology to relate the user STS motion to the target assist robot motion. The obtained relationship between the user’s leg angles and actuator angles is loaded into the microcontroller which is used for real-time control of the robot. The IMU readings of the leg angle are used to command the actuators to go to the target angles, based on the relationship. The target output angles are commanded to the assist robot using PID position control, and actuator encoders provide feedback for the actual position of the robot. The progress of the human throughout the STS motion is monitored by the IMU every 20 ms, updating the target actuator output angles.

4 Experiment Design and Methodology

Initial assessment of the capacity of the designed assist robot to reduce weight-bearing asymmetry of the designed robot was done with healthy test subjects wearing a hemiplegia simulation suit (Sakamoto Model Corporation), which consists of hard plastic splints fastened with elastic straps to the ankle and knee of one leg to prevent bending of the joints, as seen in Fig. 3a. This restriction to one leg causes the subject to generate force asymmetrically between the left and right sides. A total of four ($N=4$, 4 male) healthy test subjects were recruited for the experiments (age: 28 ± 3.96 years, body mass: 64.31 ± 3.13 kg, height: 175.75 ± 4.32 cm). The experiments conducted were approved by the Tokyo Institute of Technology Human Subjects Research Ethics Review Committee (Permit No. 2022302). The experiment consisted of two phases, calibration, and STS measurement. During the calibration phase, the target STS path of the robot was determined. The subjects were asked to wear the unactuated assist robot, and then do the STS motion normally 10 times, to obtain the target

assisted STS motion path. In the STS measurement phase, the test subject was asked to complete three sets of STS motions: normal, with the hemiplegic restriction, and with the hemiplegic restriction and assist robot. For each set, the test subject was asked to do the STS motion at least five times. Ground reaction forces under the left and right feet during the STS motion were measured using 60 cm \times 90 cm embedded force plates (Kistler Group, USA) under the left and right foot (with assist robot, as needed). Motion data of the left and right shoulders were also recorded using a motion capture system (Motion Analysis Corporation, USA) to determine the timing of the start and end of the STS process. Average weight-bearing asymmetry between the left and right legs during the STS motion as a percentage of body weight was analyzed.

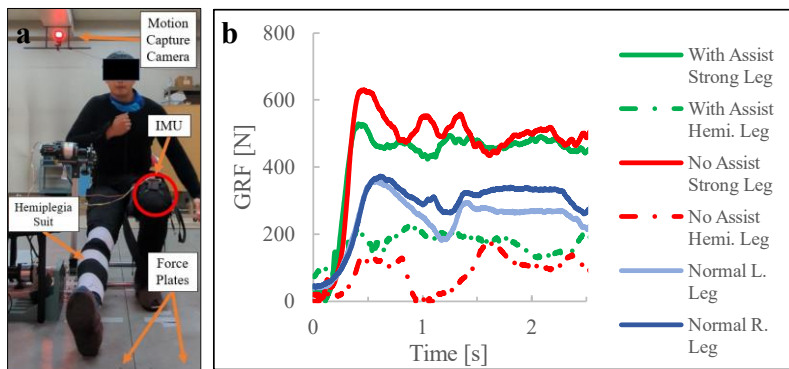


Fig. 3. (a) Experiment setup with user wearing assist robot and hemiplegic restriction. (b) Ground reaction forces (GRF) of STS motion of one test subject during the experiment.

5 Results and Discussion

The individual motion paths generated during the calibration phase were able to reliably follow the STS motions for all the test subjects, and an example of the generated actuator output angles vs leg angles for one test subject can be seen in Fig. 2c. The results of the human test subject experiments for the three sets of STS motions, normal, with hemiplegic restriction, and with hemiplegic restriction and assist robot, are summarized in Table 1. A graph of ground reaction forces (GRF) exerted during one STS motion for all three conditions of one test subject can be seen in Fig. 3b.

The restriction on one leg of the test subjects to simulate hemiplegia was able to induce an asymmetric force generation condition on the test subjects. Test subjects 1 and 2 demonstrated a very high degree of average weight-bearing asymmetry with the restriction on one leg, at 80.9% and 71.8%, respectively. Test subjects 3 and 4 exhibited a high degree of force asymmetry at 45.5% and 46.8%, respectively.

While wearing the assist robot, average weight-bearing asymmetry during STS was significantly reduced for test subjects 1 and 2, at 55.7% and 46.4%, a roughly 25% decrease in asymmetry for both. Asymmetry was slightly reduced for test subjects 3 and 4 with the assist robot, at 43.8% and 44.6%, respectively, about a 2% decrease. These results show that the assist robot can facilitate greater use of the restricted side.

Table 1. Summary of STS experiment results with human test subjects.

Test Subject		Duration (s)	Ave. Asymmetry (%BW)
1	Normal	1.22	1.3
	Hemiplegic	1.39	80.9
	Hemi. w/ robot	2.45	55.7
2	Normal	1.37	3.2
	Hemiplegic	1.88	71.8
	Hemi. w/ robot	2.93	46.4
3	Normal	1.30	4.4
	Hemiplegic	1.45	45.5
	Hemi. w/ robot	2.79	43.8
4	Normal	1.79	1.5
	Hemiplegic	2.71	46.8
	Hemi. w/ robot	2.88	44.6

The restriction also caused a slight increase in time taken to conduct the STS motion, however this time was still within hemiplegic STS speed of about 3.3 s. in literature [14]. The experiment could not fully simulate overall weakness or cognitive impairments of a hemiplegic patient, so the test subjects could still utilize motion strategies that a hemiplegic individual would not be able to. An increase in time taken to complete the STS motion while the assist robot was worn can be observed, due to the designed speed for the assist robot being based on the average speed of a hemiplegic individual, but it was still within the STS time taken by hemiplegic individuals.

Overall, the experiments demonstrated the capability of the robot to reduce average weight-bearing asymmetry when one leg is limited in force generation capacity.

6 Conclusion

The design, prototype, and initial experiments with a novel planar 2-DoF robotic leg for assistance in the STS motion of hemiplegic individuals was presented. The robot was designed to address the unique requirements provided by the asymmetrical body strength condition of hemiplegic individuals by providing stability in the frontal and sagittal planes and by reducing weight bearing asymmetry of hemiplegic users during the STS motion to facilitate more use of the paretic leg. The design of the robot and the method for generating the target STS motion path allowed the assist robot motion to be easily adjusted for users of different sizes. A prototype of the assist robot was fabricated and experiments with healthy human test subjects were conducted while having their motion restricted to simulate the asymmetric weight-bearing of hemiplegic individuals. The experiments demonstrated the capability of the assist robot to reduce average weight-bearing asymmetry during the STS motion when one leg is limited in force generation capacity. The proposed device can aid in improving mobility of hemiplegic patients, and further work to improve the assistive capacity of the device and robustness versus falls will be done to develop an effective and accessible assist robot, in line with the UN SDG 3 on promoting good health and well-being.

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