Mechanical Design and Simulation of a Saddle-Assistive Device for Sit-to-Stand Transfer in Healthy Subjects

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Abstract: Assistive device equipment can improve the performance of sit-to-stand (STS), standing, and walking of people with lower limb disability. The motorized assistive device is usually expensive and the use of another assistive device also makes an excessive force in the upper and lower extremity during (STS) transfer, which is not desirable for patients. In addition, only a few number of the non-motorized assistive devices that support all three phases; namely, sit-to-stand, standing, and walking are available. Consequently, improving and creating the new technology seems essential in this case. In this paper, the design procedure of saddle-assistive device is described in order to make use of the linear actuator in (STS) transfer and walk. Experimental results orientation of the shoulder during (STS) was recorded in the lab. Then, based on this analysis and simulation, saddle-assistive devices(S-AD) were designed and prototyped. Function prototype of the (S-AD) was done in the lab on a healthy person in (STS) and walking and then was compared with (STS) in normal mode. It is proposed due to the integration of the three phases in one device. Other advantages are force reduction on lower limbs, creating conditions of stability, and independence for patients with lower limb disability.

Keywords: Experimental evaluation, Kinematic analysis, Lower limb force, Mechanism design, Motion disability, Sit-to-Stand, Saddle-assistive device

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1 INTRODUCTION

Human movement such as sit-to-stand (STS) is one of the most fundamental movements among daily living activities, especially for people with lower limb problems [1-3] Nowadays, a low percentage of elderly people in the hospitals and only 23 percent of the elderly can have daily life without help from caregivers [4]. Therefore, much attention has been paid towards the design and implementation of movement assistive devices with safe and reliable features to help patients and increase their life quality. In addition, assistive devices can help patients to improve and increase their body strength [5]. The lower limb consists of four major parts: a girdle formed by the hip bones, the thigh, the leg, and the foot. It is specialized for the support of weight, adaptation to gravity, and locomotion.

Sit to stand movement requires creating a torque about 40N.m in the knee [6]. Providing this torque is not available physically for the elderlies and patients with motion disability. Low mobility during STS causes weakness and loss of physical power [7]. It is also very important for people of this group to walk with the conditions of maintaining balance and not falling down [8], [9]. Providing the appropriate conditions during a walk and also for STS transfer creates the independence of these people. Trying to create an assisting system for standing and walking is essential with the lowest force applied to the upper and lower extremities and the use of the remaining physical strength.

To strengthen and assist sitting up to the standing movement, assistive devices are presented with different designs [10]. Efforts to STS transfer with knee strengthening with reinforced knees have been done with the help of pneumatic, hydraulic and electric actuators [11], [12]. Sit-to-stand with these devices requires a conventional walker. Walking imposes more restrictions for these devices because one needs to control the program of knee rotation independently. Due to the use of high torque on the knee, motors and actuators typically have a large size.

A few studies have been done on STS robot. Exoskeleton Hall [13] is a wearable robot which is used as an assistive device, increasing users' speed and power. Exoskeletons are usually heavy and inconvenient for the elderly, and rotational axis non-compliance of exoskeleton joint results in muscle pain in patients [14], [15].

A number of recent studies have considered robotic [16], [17] and power assistive device mechanism [18]-[20] as applications for sitting to standing and walking. Kinematic analysis of body movement and the shoulder trajectory in these studies have been considered [21], [22] and applied in the design of an assistive device. In these mechanisms, the weight of the upper extremity of the trunk is usually placed on the seat mechanism which brings about some restrictions [23]. Because it quickly causes exhaustion of the upper limb and affects the sustainability in STS and walking.

Assistive device movement facilitates walking [24], studies in a wide range prove. Most movement assistive devices are complex and expensive and somewhat cannot cover STS and walking.

In many of these researches, mechanical and powered mechanisms in the STS have been used. Such mechanisms support the patient in STS transfer from upper limb, however, they do not consider the role of body weight and forces on the lower and upper extremities. These forces cause pain in the shoulder in the long term. Therefore, this study aims at reducing these forces in the design of S-AD.

Of features, an integrated assistive device helps sit to stand transfer and stability during walking for people with lower limb disability. These features should be based on the appropriate support from the path of the trunk in (STS) transfer and reduce force on the upper and lower extremities and propulsion force during walking. Accordingly, experimental data and simulations were used in this paper for the proposed design of the S-AD (Fig. 1). The results of the experiments provided in the three modes contain STS transfer, stability in standing and walking.

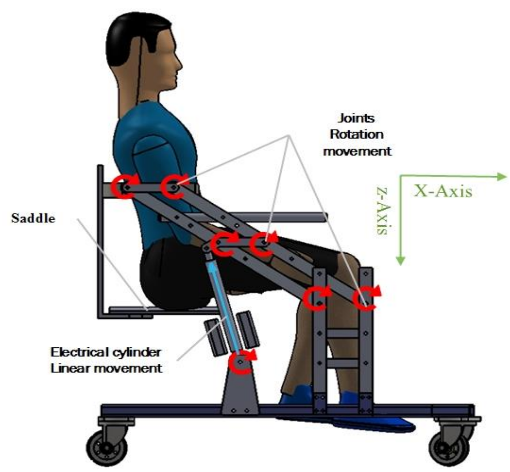

Fig. 1 Concept of saddle-assistive device mechanism

2 EXPERIMENTAL EVALUATION OF THE SIT-TO-STAND

To study the motion of STS, the VICON system with a frequency of 120 Hz along with 6 cameras is used [15].

By installing markers on certain parts of the body and sending and receiving infrared waves on it, motion recording is performed by the VICON system. The station VICON MXT40S is used for the analysis of

images from multiple cameras to show the marker position in the three-dimensional coordinates. In these experiments, output markers show the status movement of the body in the STS in 3 DOF. For recording data, markers are placed on vital parts such as hip, head, torso, legs, and ankles.
A healthy person with specifications as 80±2 kg weight and 176cm height entered the sitting to standing and walking trial voluntarily. Markers were bound to his body on the target points and in normal stand up from the chair (Fig. 2). The evaluation is divided into five main groups; which are, (1) sitting position in which the patient's initial coordinates are recorded, (2) the trunk bends forward (flexion), (3) the trunk bends backward (extension) in halfway, (4) full stance, and finally (5) walking. Sitting initial position was set by reference [25]. In this experiment, results are evaluated in the sagittal plane. To validate the data, this test was repeated in three stages.

Fig. 2 Sitting to standing, standing and walking in normal

Data extracted from the markers installed on the shoulder were exported to MATLAB 2015b and evaluated. The output of this evaluation is shown in Fig. 3 In this figure, the horizontal axis shows displacement in the direction of the axis X and the vertical axis shows the displacement in the Z-axis direction. The results show the position of marker shoulder at a height of 1125 mm in sitting. At maximum, the flexion and extension reached 1425 mm in amount and during walking this amount was fluctuating between 1380 to 1425 mm. S-AD mechanisms should be able to cover the trajectory of the shoulder during getting up.

3 DESIGN OF S-AD IN SIT-TO-STAND TRANSFER AND WALKING

Methods used to design mechanisms S-AD was carried out based on four steps. 1. An appropriate mechanism designed to track the movement of the shoulder in sitting to standing and walking. 2. Determining the linear actuator force to help the patient in STS transfer. 3. Determining the device dimensions in order to maintain the balance of the patients and prevent their collapse as an effect of a lateral load. 4. Kinematic analysis of S-AD to determine the angular velocity and angular acceleration of end effector during STS.

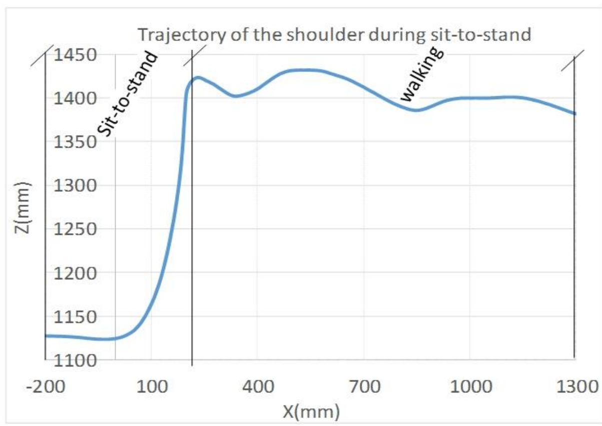

Fig. 3 The trajectory of sitting to standing based on the results of the laboratory gate

3.1 Mechanism design in compliance with the shoulder trajectory

The best mechanism that can be adapted to curve trajectory in Fig. 3 is the four-bar mechanism. This mechanism should be mounted on a main frame to provide the height of STS transfer (fig. 4). A link with fixed length is installed on the main frame with joint connection and the end of it is connected to the end effector. On the other hand, a linear actuator is attached to the main frame to provide the necessary force for standing up. The use of Sam6.1 software enables us to reach the maximum consistency with the mechanical mechanism by inserting the shoulder empirical STS points of the curve. This analysis showed that the actuator stroke length is 250mm.

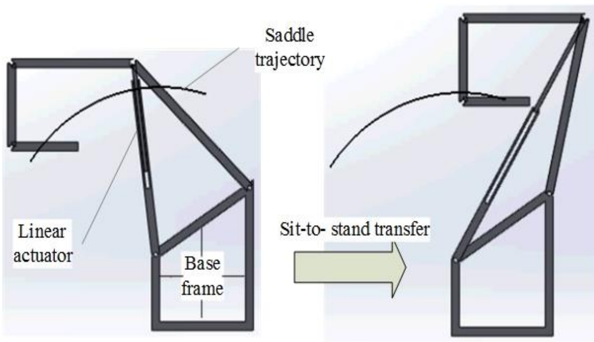

Fig. 4 4-link mechanism in accordance with the trajectory of the shoulder

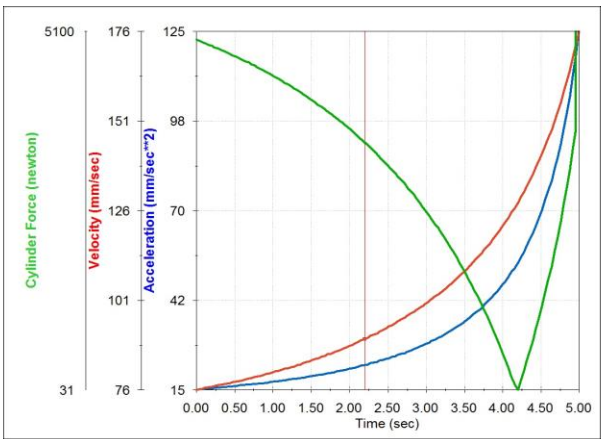

Fig. 5 The results of the simulations in determining the linear actuators force, velocity and acceleration saddle

3.2 Simulations in determining the cylinder force during STS

To determine the amount of force actuator in STS, critical points of mechanism moved to software SOLIDWORKS 2016 in the form of parts. In the motion study, the load of 4000 Newton, which is equivalent to half the weight of the patient, was placed on the center of gravity of the saddle in order to be used as an unknown force behind the actuator and set along the opening actuator to move mechanisms. Motion analysis is done from STS, then the result is extracted from the simulation, which includes force required actuators, velocity, and acceleration end effector. Setting up such mechanism needs 5100 Newton force for the linear actuators, the linear speed of 76-176 (mm/sec), and linear acceleration 15-125 (mm/sec^2). These values are obtained by opening speed 50 mm/s linear actuators (Fig. 5).

3.3 The balance of S-AD

One of the most important parameters for any assistive device is to create static equilibrium conditions. To calculate the static equilibrium conditions, the unknown force F1 is applied to the maximum height of the stand on the device (Fig. 6). The aim is to determine how much force is supposed to be applied on the walker in unsustainable conditions.

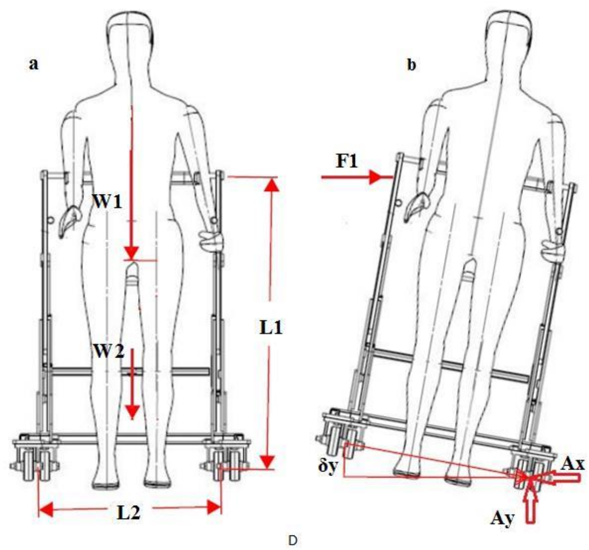

Fig. 6 (a) Forces affecting the static balance and (b) its equivalent reaction

Using the law virtual work, the walker is assumed to have a distance equal to δy from the ground. In this case, the user's weight W1 and the device weight W2 are placed vertically. The distance vertical force is considered from the wheel axle L1 and its lateral is L2. Considering the width of the device as 660 mm and the fact that average height from the ground to the shoulder is between 1300 mm to 1450 mm, we can write:

L1=2*L2
δy=Virtual displacement
δU=Virtual work

$$\delta U = -\frac{(W1 + W2)\delta y}{2} + F1(2\delta y) = 0$$

$$-\left(\frac{(W1 + W2)}{2} + 2F1\right)(\delta y) = 0 \text{ and } (\delta y) \neq 0 \Rightarrow$$

$$F1 = \frac{(W1+W2)}{4} \quad (1)$$

Considering the weight of 80 kg for the user and weight of 46 kg for the device, the amount of force needed to unbalance the device will be equal to 309 N. This shows that the device is highly safe against imbalance. As a result of calculation and the analysis of motion simulation analysis using the software and calculation, the amount of force cylinder, main components, and the range of motion mechanism are determined (Fig. 7).

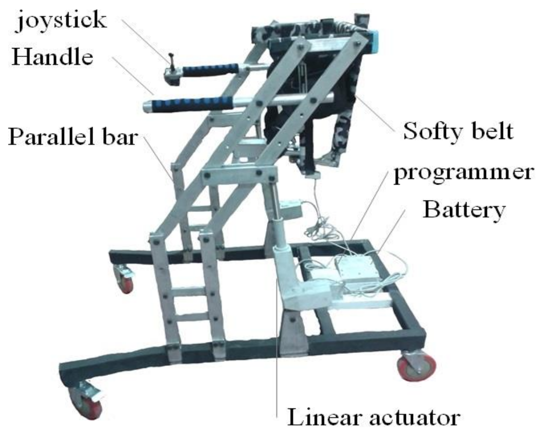

Fig. 7 The prototype of S-AD

This assistive device has two degrees of freedom in the sagittal to follow the path trunk while using a four-link mechanism during stand-up. In the use of standard actuators, the speed and acceleration of the STS transfer are set to be 50 mm/s so that patients can be transferred at an acceptable and controllable level. Here, two linear actuators with maximum 6000 N force and a four-bar mechanism were used for STS. It is also possible for users to have comfortable STS via a joystick mounted on the levers of the device. In this situation, by opening the cylinders' activation four-bar mechanism, the user can easily stand up through the saddle. Throat width of entrance in this assistive device is proportional to the width of the wheelchair so that the patient with motion disability can sit on the saddle. Linear actuators used in the device are rechargeable and controllable. The safety belt was used to avoid falls.

4 MOTIONS AND FORCES MEASUREMENTS

Information needed to measure force and movement in use of S-AD are sitting, standing and walking position of the healthy Subject. Also, determining the maximum foot reaction force on the ground and on handle walker was needed during STS and walk. For this purpose, a 6-axis force sensor (KISTLER) was used to measure the vertical and propulsions force. Moreover, a load cell tensile and compression (DASEL) was used to measure the force on the hands. This sensor is installed properly on the S-AD handle.

In the experiment of the movement assistive device, force sensor with appropriate design on the handle S-AD was installed. The sensor is connected to a computer through a cable interface. Two force plates were used with a length of 60 cm, these force plates can record information in three-axis force and torque. These sensors are connected to the computer and simultaneously can register information's force and the displacement in the transition from sitting to standing and walking.

The test was performed on a healthy person. For this test, two modes were considered to compare the results. The first mode: a healthy person from the chair (STS) start transferring, then start walking on the force plate. The second mode: a healthy person from the saddle of S-AD start a transition from (STS) to help of line actuator (Fig. 8). After standing with the S-AD, start walking on the force plate. In all these steps, a healthy person does not separate from the saddle.

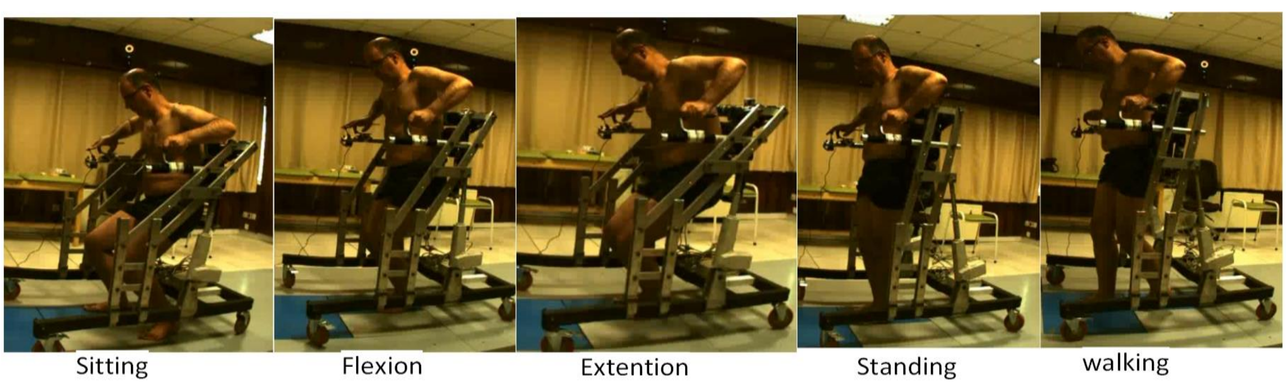

Fig. 8 Sit-to-stand (a): in normal (b): using walker (c): using S-AD

5 RESULTS AND DISCUSSION

Fig. 9 shows vertical reaction force (Fz) and propulsion force (Fx) during STS from the chair and walking on healthy subjects. The results measured in the sagittal plane and the subject weight is 800 N. The results show that the vertical force applied to the force plate in sitting position is zero. With the start of the sitting to standing, this force increased to reach the maximum 800 N. In standing, fluctuations force reached 900 N in a moment which re-balanced and returns to 800 N. In walking, this force remains constant with small changes in the range of 800 N. To create propulsion, force (Fx) of 125 N maximum is required. Normally, the time for sitting to standing is 1.6 s and leaving the force plates is 3s.

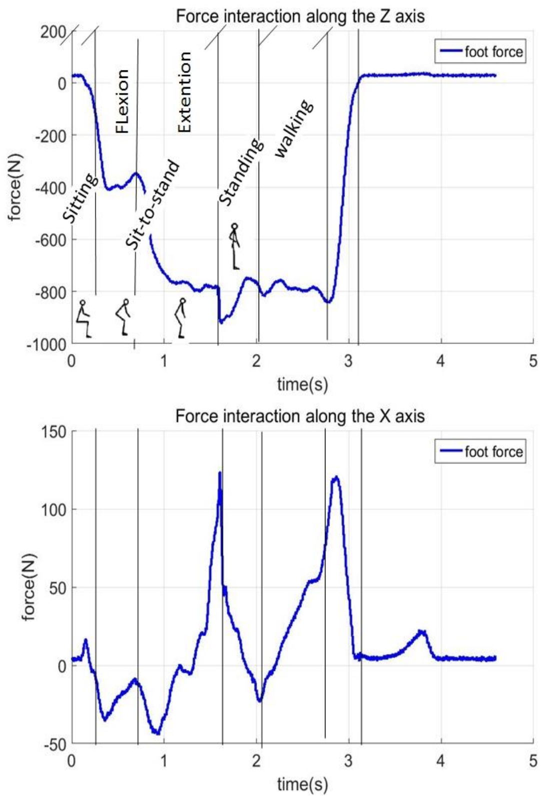

Fig. 9 Vertical and Propulsion reaction forces in STS transfer from the chair and walk

Vertical and propulsion reaction forces during STS and walk using the S-AD is shown in Fig. 10 The results show that the vertical force (Fz) applied on force plates is zero in sitting position on the saddle. STS transfer is done with the help of the saddle of assisting device, which increases from zero to 630 N. In full standing, this force remains in the range of 630 N with some fluctuation. At the start of walking, this force reduced and reached to 570 N. The time for STS in support of the (S-AD) is 20 s. Propulsion force (Fx) in sitting to standing was obtained -10N and in walking was obtained average 20 N.

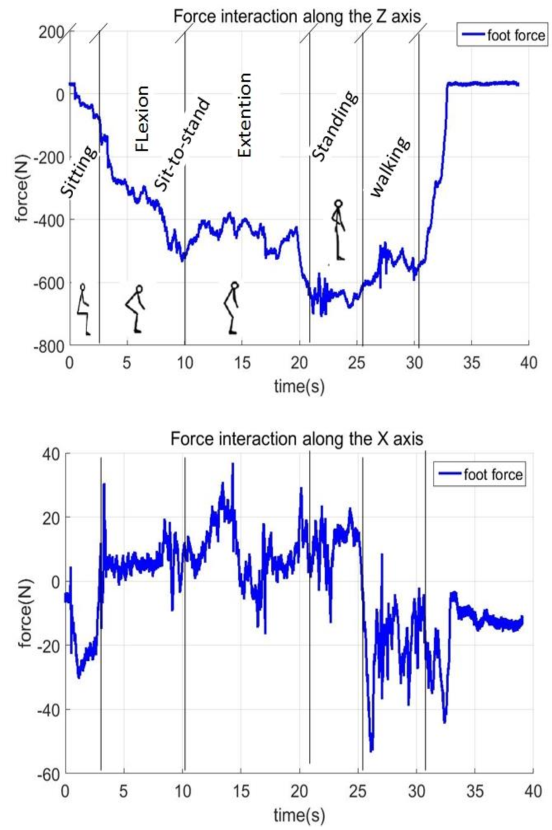

Fig. 10 Vertical and Propulsion reaction forces in STS transfer and walk using S-AD

By measuring the force on the handle of the S-AD the results were obtained with helping load cell (Fig. 11). This force is applied in STS 10N, during standing -2N and during walking up to 9N.

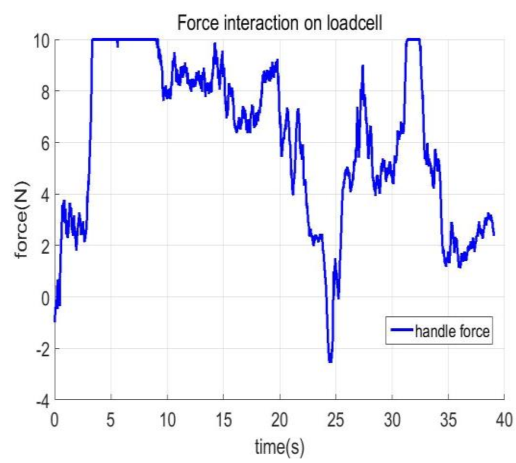

Fig. 11 Reaction forces on the handle S-AD in sitting, sitting to standing transfer and walking

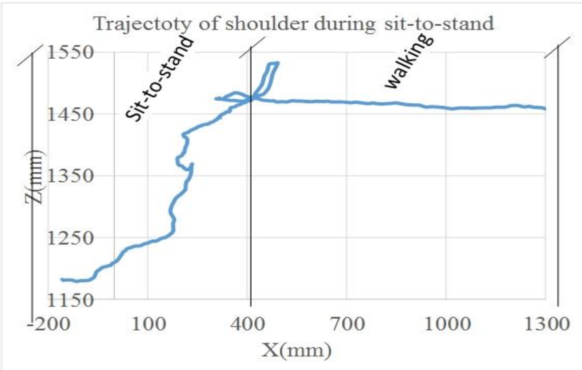

Fig. 12 The trunk trajectory during STS and walk in the sagittal plane in the use of S-AD

This, as well as the trajectory of the trunk in STS transfer and during walking, can be seen in Fig. 12. Sitting height according to height adjustment of Saddle is located higher in comparison with Fig. 3. The trajectory of STS shoulder matched with it and was observed that is needed to move forward more. During walking, the shoulder height corresponded but in this case the movement fluctuations in the sagittal plane has declined.

6 CONCLUSION

The preliminary design of an assistive device with high stability was presented for disabled subjects. The overall kinematics of this device was based on the analysis of the problems of standing up and walking people with lower limb movement. Accordingly, the trajectory of the four-link mechanism adapted to the trunk trajectory using experimental measurements, and the necessary driving force was calculated for the linear actuator during STS.
This device, with force plasters installed on the ground floor, force sensors on handle, and markers on the body entered the STS and walk test. The goal was to measure vertical and propulsion forces and trunk trajectory during STS and walk. To this end, the results were compared to sitting and walking of a healthy subject. The results showed that the use of S-AD reduces the force arriving on the lower and upper extremities in STS transfer and during walking considerably. Hence, it is expected to be useful for the independence of the elderly subjects, because it supports STS transfer and walk well and it prevents the subjects' collapse.

REFERENCES

[1] Alexander, N. B., Schultz, A. B., and Warwick, D. N., "Rising from a Chair: Effects of Age and Functional Ability on Performance Biomechanics". Journal of Gerontology, Vol. 46, No. 3, 1991, pp. M91-M98.

[2] Hughes, M., Schenkman, M., "Chair Rise Strategy in the Functionally Impaired Elderly", Journal of rehabilitation research and development, Vol. 33, No. 4, 1996. pp. 409-412.

[3] Vose, J. G., et al., "Optimization of Lower Extremity Kinetics during Transfers Using a Wearable", Portable Robotic Lower Extremity Orthosis: A Case Study, in Converging Clinical and Engineering Research on Neurorehabilitation. 2013, Springer, pp. 99-102.

[4] Organization, W. H., "The World Health Report: 2001: Mental Health: New Understanding", new hope. 2001.

[5] Hirvensalo, M., Rantanen, T., and Heikkinen, E., "Mobility Difficulties and Physical Activity as Predictors of Mortality and Loss of Independency in Community Living Older Population", Journal of the American Geriatrics Society, Vol. 48, 2000, pp. 493-498.

[6] Ivlev, O., "Soft Fluidic Actuators of Rotary Type for Safe Physical Human-Machine Interaction", in Rehabilitation Robotics, 2009. ICORR 2009. IEEE International Conference on. 2009. IEEE.

[7] Kong, K., Jeon. D., "Fuzzy Control of a New Tendon-Driven Exoskeletal Power Assistive Device. in Proceedings of the IEEE/ASME", International Conference on Advanced Intelligent Mechatronics (AIM 2005), 2005.

[8] Cheng, Y. Y., et al., Can Sit-To-Stand Lower Limb Muscle Power Predict Fall Status? Gait & posture, Vol. 40, No. 3, 2014, pp. 403-407.

[9] Viteckova, S., Kutilek, P., and Jirina, M., "Wearable Lower Limb Robotics: A Review", Biocybernetics and Biomedical Engineering, Vol. 33, No. 2, 2013, pp. 96-105.

[10] Nagai, K., Nakanishi, I., and Hanafusa, H., "Assistance of Self-transfer of Patients Using a Power-Assisting Device. in Robotics and Automation", 2003. Proceedings. ICRA'03. IEEE International Conference on. 2003. IEEE.

[11] Mefoued, S., et al., "Sit-to-Stand Movement Assistance Using an Actuated Knee Joint Orthosis", in Biomedical Robotics and Biomechatronics (BioRob), 2012 4th IEEE RAS & EMBS International Conference on, 2012. IEEE.

[12] Yan, T., et al., "Review of Assistive Strategies in Powered Lower-Limb Orthoses and Exoskeletons", Robotics and Autonomous Systems, Vol. 64, 2015, pp. 120-136.

[13] Kawamoto, H., et al., "Power Assist Method for HAL-3 Using EMG-Based Feedback Controller", in Systems, Man and Cybernetics, 2003. IEEE International Conference on, 2003. IEEE.

[14] Salah, O., et al., "Development of Parallel Manipulator Sit to Stand Assistive Device for Elderly People", in 2013 IEEE Workshop on Advanced Robotics and its Social Impacts, 2013. IEEE.

[15] Chang, S. R., et al., "Improving Stand-to-Sit Maneuver for Individuals with Spinal Cord Injury", Journal of neuroengineering and rehabilitation, Vol. 13, No. 1, 2016, pp. 1.

[16] Salah, O., et al., "Anfis-Based Sensor Fusion System of Sit-to-Stand for Elderly People Assistive Device Protocols", International Journal of Automation and Computing, Vol. 10, No. 5, 2013, pp. 405-413.

[17] Jun, H. G., et al., "Walking and Sit-to-Stand Support System for Elderly and Disabled. in Rehabilitation Robotics (ICORR)", 2011 IEEE International Conference on, 2011. IEEE.

[18] Rea, P., Ottaviano, E., and Castelli, G., "A Procedure for the Design of Novel Assisting Devices for the Sit-to-Stand", Journal of Bionic Engineering, Vol. 10, No. 4, 2013, pp. 488-496.

[19] Médéric, P., et al., "Design of a Walking-Aid and Sit to Stand Transfer Assisting Device for Elderly People. in 7th Int", Conference on Climbing on Walking Robots (CLAWAR'04), Madrid, Spain. 2004.

[20] Rea, P., Ottaviano, E., "Analysis and Mechanical Design Solutions for Sit-To-Stand Assisting Devices", 2016.

[21] Nuzik, S., et al., "Sit-to-Stand Movement Pattern: A Kinematic Study", Physical therapy, Vol. 66, No. 11, 1986, pp. 1708-1713.

[22] Schenkman, M., et al., "Whole-Body Movements During Rising to Standing from Sitting", Physical Therapy, Vol. 70, No. 10, 1990, pp. 638-648.

[23] Takai, A., et al., "Estimation and Minimization of Nody Load During Sit-to-Stand Movement for Rehabilitation", Journal of System Design and Dynamics, Vol. 7, No. 4, 2013, pp. 488-503.

[24] Matsuura, D., et al., "Efficiency Improvement of Walking Assist Machine Using Crutches Based on Gait-Feasible Region Analysis", Mechanism and Machine Theory, Vol. 84, 2015, pp. 126-133.

[25] Tully, E. A., Fotoohabadi, M. R., and Galea, M. P., "Sagittal Spine and Lower Limb Movement During Sit-to-Stand in Healthy Young Subjects", Gait & posture, Vol. 22, No. 4, 2005, pp. 338-345.