Design of a Passive Gravity Balancing Robotic Architecture for Sit-to-Stand Function Rehabilitation for ALS Patients

Harshawardhan Kumar Unsasi[1], Srihari Rao Yarlagadda[1], Pranav Jhunjhunwala[1]
[1]Department of Mechanical Engineering, Columbia University, New York, NY, USA

I. Abstract

In this work, a passive gravity balanced robotic architecture for rehabilitation of sit-to-stand (STS) function in Amyotrophic lateral sclerosis (ALS) patients has been proposed. The robotic device has the following feature: 1) it is passive, it does not have any active actuators or control modules 2) it is gravity balanced, that is, it counterbalances the weight of the patient using springs 3) the device is modular, i.e, it can accommodate patients with different stages of disability. A 2 link planar serial mechanism with auxiliary parallelogram configuration has been employed to design the architecture. Using the Lagrangian approach, a general model was created for a single link mechanism with spring, which was further elaborated for the rehabilitation device. Using the model, spring constants and other design parameters for a gravity balanced system were obtained. Further, the design approach and the feasibility of the design has been illustrated.

II. Introduction

Amyotrophic Lateral Sclerosis (ALS) is a progressive neurodegenerative disease that affects the nerve cells responsible for controlling voluntary muscles. ALS is a rare disease, affecting around 2 in every 100,000 people worldwide. The disease gradually worsens over time, leading to muscle weakness, atrophy, and eventually paralysis. As ALS progresses, individuals may have difficulty in performing the sit to stand function which can hamper the ability of the patient to perform daily tasks and also can be life-threatening in certain cases. Currently, there is no cure for ALS, but there are treatments that can help manage symptoms and improve quality of life. One such treatment is use of rehabilitation and assistive devices to improve the quality of life of patients suffering from ALS. Rehabilitation can play a critical role in managing the disease, with interventions aimed at improving mobility, and maintaining function. While rehabilitation cannot cure ALS, it can help individuals with the disease maintain independence and improve their overall well-being.

However, very limited rehabilitative devices assisting in the sit-to-stand functionality have been reported in literature. Kamnik et al [1] proposed a three degrees of freedom (3-DOF) robotic mechanism providing support to the patient under the buttocks. The device is actuated by an electrohydraulic servo system capable of operating in multiple control modes. Another commercially available device to aid in sit to stand function is the TEK Robotic Mobilization Device [2]. It is a wheelchair mounted, mobile architecture which enabled the subjects to safely stand. Theses devices however rely heavily on active motor or actuators and are extremely complex. Due to the complex control and actuation systems involved, these devices are extremely expensive and inaccessible. Another limitation of these devices is that they move the subject through fixed trajectory rather than allowing the subject to move under their own control. Preventing patients from experiencing and practicing appropriate movement patterns can hinder the necessary changes in the nervous system that promote the relearning of typical movement patterns.

Gravity balanced devices have shown to improve motor learning capabilities [3]. Banala et al [4] proposed a device to assist subjects with hemiparesis to walk by reducing or eliminating the effects of gravity. Using the device for rehabilitative treatment, the range of movement increased by 45 % at the hip joint and by 85% at the knee joint.

In this work, an assitive gravity balanced passive robotics device is proposed which can be utilized to improve the sit-to-stand motor function learning of ALS patients by eliminating or reducing the effect of gravity. This device is designed for rehabilitative use, helping subjects regain and retrain control over their leg muscles. In the initial stages of treatment, most of the subject weight will be counterbalanced using the device. The gravity assistance from the device will be lowered as the treatment progresses. Use of this device in a progressive and systematic manner can lead to improved sit-to-stand motor function over time.

III. Solution Approach

Before we directly address the architecture we propose for the STS aid, we would like to first introduce a mathematical approach, parametric in nature, which can be used to design a gravity balancing mechanism in a n-link planar serial manipulator with 1-DOF gravity compensators.

Let us look at the 1 link serial manipulator with one gravity compensator, in this case a spring, discussed in the class before we generalize the approach to n-links. The one end of a spring is attached at the point A fixed at ground and another is attached at the point B located at the arm. The points A and B are located with length of h and b from the origin, respectively. The zero-length spring is adopted which

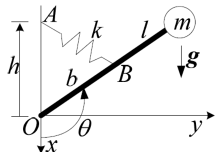

Fig. 1. 1 Link gravity balancing mechanism

has zero length at the zero deflection.If a non-zero length spring is utilized, computation of the spring constant is not easy and it is hard to obtain complete gravity balancing.
The total potential energy can be written as

$$V(\theta) = V_g(\theta) + V_k(\theta)$$

where θ represents the rotation angle of the link, $V_g(\theta)$ denotes the potential energy by the mass, and $V_k(\theta)$ denotes the potential energy by the spring.
Looking closely at the architecture, we can write down the following equations.

$$V_g(\theta) = -mgl\cos\theta$$

$$V_k(\theta) = \frac{kS^2(\theta)}{2}$$

$$\mathbf{A} = \begin{pmatrix} -h & 0 & 0 \end{pmatrix}^\top \quad \text{and} \quad \mathbf{B} = \begin{pmatrix} b\cos\theta & b\sin\theta & 0 \end{pmatrix}^\top$$

Here A and B(h and b in substance) are the parameters that are introduced. A is the coordinate location of the spring that is attached to the rigid frame and B is the other end of the spring that is attached to the link or any auxiliary which resembles the link in orientation .

$$S^2(\theta) = |\mathbf{BA}|^2 = h^2 + b^2 + 2bh\cos\theta$$

$$V_k(\theta) = C + kbh\cos\theta$$

$$V(\theta) = C + kbh\cos\theta - mgl\cos\theta$$

$$k = \frac{mgl}{bh}$$

Now let us start to generalize the approach for n links.Consider an n-link manipulator. Let l_i be the length of link i. It is assumed that the mass of each link, m_i, is located at a distance of l_{ig} from the origin of the i frame, respectively. θ_i represents the rotation angle of link i with respect to the i-1 frame.

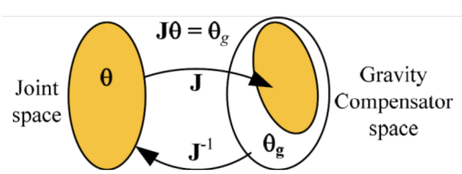

Fig. 2. Joint space vs Gravity compensator space

$$V_g = -\sum_{i=1}^{n} m_i g \cdot p_i^0$$

$$V_k = \sum_{j=1}^{p} C_j + a_j k_j b_j h_j \cos\theta_{gj}$$

Here, p is the number of gravity compensators present in the system. It is very inturive that each gravity compensators contributes to a cosine term and a constant term.One can look at the one link serial manipulator case to see how it happens.

$$\theta_g = J\theta$$

$$V(\theta, \theta_g) = V_g(\theta) + V_k(\theta_g) = \text{const}$$

$$V(\theta) = V_g(\theta) + V_k(J\theta) = \text{const}$$

$$\frac{\partial V(\theta)}{\partial \theta_i} = \frac{\partial V_g(\theta)}{\partial \theta_i} + \frac{\partial V_k(J\theta)}{\partial \theta_i} = 0$$

$$\begin{pmatrix} \frac{\partial V_g(\theta)}{\partial \theta_1} \\ \frac{\partial V_g(\theta)}{\partial \theta_2} \\ \vdots \\ \frac{\partial V_g(\theta)}{\partial \theta_n} \end{pmatrix} = \begin{pmatrix} f_{11}(\theta) & f_{12}(\theta) & \cdots & f_{1p}(\theta) \\ f_{21}(\theta) & f_{22}(\theta) & \cdots & f_{2p}(\theta) \\ \vdots & \vdots & \ddots & \vdots \\ f_{n1}(\theta) & f_{n2}(\theta) & \cdots & f_{np}(\theta) \end{pmatrix} \begin{pmatrix} V_{g1} \\ V_{g2} \\ \vdots \\ V_{gp} \end{pmatrix}$$

$$\lambda = \begin{pmatrix} \lambda_1 & \lambda_2 & \vdots & \lambda_n \end{pmatrix}^T$$

$$\lambda_i(\theta) = \sum_{j=1}^{q} d_{ij} \sin(J_{j1}\theta_1 + J_{j2}\theta_2 + \cdots + J_{jn}\theta_n)$$

$$\theta_{gj} = J_j\theta$$

$$\frac{\partial V_k(J\theta)}{\partial \theta} = -J^T MK$$

$$K = \begin{pmatrix} k_1b_1h_1 \\ k_2b_2h_2 \\ \vdots \\ k_qb_qh_q \end{pmatrix}^T \in \mathbb{R}^{q\times 1}$$

$$f(\theta)V_{gmax} - J^T MK = 0$$

IV. Design

Our proposed rehabilitation device is a 2 link planar serial manipulator with auxiliary parallelogram configuration. It has 2 springs, one attached to the first link and the other attached to the auxiliary link to drive the second link. The auxiliary parallelogram is used to locate the center of mass of the entire system and then springs are then attached to gravity-balance the device in all configurations. The system is completely passive, i.e it does not have any active elements like actuators. Fig 3 shows the rehabilitation device with a subject seated on it. As the patient tries to stand, the pre-loaded springs assist the patient in standing up by providing the necessary forces and counterbalancing the weight of the patient or the gravity as shown.

The proposed architecture is a 2 DOF mechanism, designed to follow the trajectory of the subject rather than following a predetermined motion path. Allowing a subject-determined path enables the patient to experience appropriate movement patterns which promote relearning of typical muscle movements.

Fig. 3. Proposed gravity balanced robotic architecture

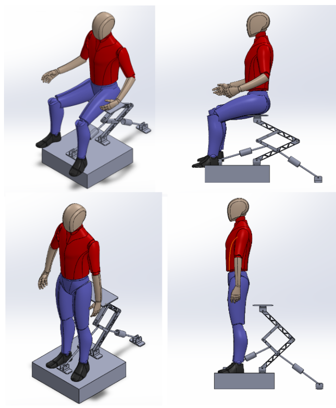

Fig. 4. Sit and stand configurations of the robotic device

V. Results

As we have modelled our rehabilitation device as a 2 DOF planar serial manipulator with 2 springs, one attached to the first link and the other attached to the auxiliary link of the auxiliary parallelogram, we can use our general approach to find the mathematical condition to render the system as a passive gravity balancing mechanism.

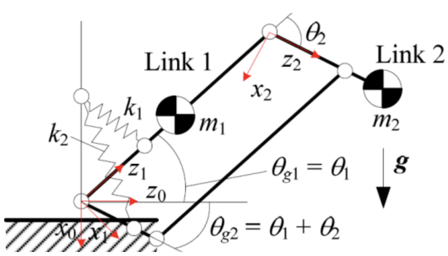

Fig. 5. Our Architecture- 2 link gravity balancing mechanism

$$V_g = -\sum_{i=1}^{2} m_i g \cdot P_i^0 = -(m_1 g l_{1g} + m_2 g l_{2g})c_1 - m_2 g l_{2g} c_{12}$$

$$\begin{pmatrix} \frac{\partial V_g}{\partial \theta_1} \\ \frac{\partial V_g}{\partial \theta_2} \end{pmatrix} = \begin{bmatrix} s_1 & s_{12} \\ 0 & s_{12} \end{bmatrix} \begin{bmatrix} m_1 g l_{1g} + m_2 g l_{2g} \\ m_2 g l_{2g} \end{bmatrix} = f(\theta) V_{gmax}$$

$$\lambda = \begin{pmatrix} s_1 & s_{12} \end{pmatrix}^\top$$

$$J = \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix}$$

$$M = \begin{bmatrix} a_1 s_1 & 0 \\ 0 & a_2 b_{12} \end{bmatrix}, K = \begin{pmatrix} k_1 b_1 h_1 \\ k_2 b_2 h_2 \end{pmatrix}$$

$$\frac{\partial V_k}{\partial \theta} = -\begin{bmatrix} a_1 s_1 & a_2 s_{12} \\ 0 & a_2 s_{12} \end{bmatrix} \cdot \begin{pmatrix} k_1 b_1 h_1 \\ k_2 b_2 h_2 \end{pmatrix}$$

$$k_1 = \frac{m_1 g l_{1g} + m_2 g l_1}{b_1 h_1}, \qquad k_2 = \frac{m_2 g l_{2g}}{b_2 h_2}$$

For these values of the k_1 and k_2, the system is completely gravity balanced. One can observe that the mass of the subject(patient) is also taken into account. One very important aspect we need to look at is that we have assumed the free length of the spring is 0. If that's not the case, the system cannot be completely gravity balanced. However, we can reasonably make it close to a gravity balanced setup.

VI. Conclusion and Future Extensions

In this report, we present the design and analysis of a 2 link planar mechanism with 2 - 1 DOF gravity compensators. To make the system gravity balanced, appropriate mathematical constraints were derived. These constraints take into account the gravitational forces acting on the mechanism and ensure that they are balanced at all times.

Furthermore, we briefly discuss a rigorous mathematical approach that generalizes inertia redistribution for planar serial manipulators with 1 DOF gravity compensators. This approach involves redistributing the inertia of the system to achieve perfect balance. This technique can be applied to n-links mechanisms and provides a systematic way to design and analyze complex mechanisms with gravity compensators.

Overall, our work demonstrates the importance of designing gravity-balanced mechanisms, especially in applications where precise positioning and stability are crucial. The mathematical constraints and techniques presented in this report can serve as a useful tool for designing and analyzing similar mechanisms in the future.A SolidWorks model with all reasonable physical constraints is modeled as a proof of concept.

The proposed mechanism is highly modular and customizable, and can be easily extended to n-links without loss of generality. This makes the design flexible and adaptable to a wide range of applications.

Although the proposed mechanism is currently planar, it can be modified to incorporate a spacial aspect, which would increase its flexibility and allow for factors such as platform stability and smoothness of transition to be considered. With these modifications, the design could be more versatile and serve in a wider range of applications.

Furthermore, by incorporating design changes, the architecture proposed can be transformed into a mobile mechanism that can aid patients around the clock. This would require the addition of non-passive elements such as motors and drives to provide the necessary mobility.Overall, the proposed mechanism has a great potential for further development and can be modified to serve in a wide range of applications, including medical and industrial applications. With the addition of non-passive elements, the mechanism can become more sophisticated and useful.

VII. References

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