Design, development and analysis of human exoskeleton for enhancing human capabilities

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Abstract. The study of the exoskeleton is widely recognized as the current challenge for robotic research. The exoskeleton helps us understand the complex gait cycles of the human locomotion. This paper aims to design a lightweight and easy to use powered dynamic exoskeleton with a higher weight carrying capabilities and produce gait cycles which imitate human locomotion. In this paper, we have proposed some novel mechanisms to overcome the limitations of heavy load-carrying capacities of the soldiers and also help with gait rehabilitation of patients with spinal cord injury, stroke, or neurological disorder. The exoskeleton is divided into the upper body and the lower body. The upper arm and the forearm are actuated by DC Geared motors and thus the upper limb can trace any path in the parasagittal plane. The thigh and calf segments are actuated by DC Geared motors to mimic the human gait cycle. The torques required to achieve this motion are discussed here.

1. Introduction

An exoskeleton is a wearable device powered by a system of actuators that enhance limb movement with increased strength and endurance. The design aims to control the movement of legs and hands to assist in carrying heavy loads by signaling the motors. A powered exoskeleton can prove to be a vital device to those who have lost control of their limbs.

A rigid, powered and mobile exoskeleton is designed for a person weighing a maximum of 100 kg and height 175 cm. The upper body of exoskeleton can lift a maximum of 5 kg of weight and the lower body of the exoskeleton can carry a maximum load of 40 kg. Gearboxes have been designed to increase the torque concentration of the actuators.

This exoskeleton design is inspired by HALEX (Human Assistive Lower Limb Exoskeleton) which is a lower limb exoskeleton developed for assisting humans in gait locomotion. [1]

2. Anatomy study of human body

2.1. Weight Measurement

The weight of human body parts is in a fixed proportion. The percentage of weight of the upper arm and forearm in human body weight is 2.63 and 1.5 respectively and that of thigh, shank, and the foot is 14.47, 4.57, and 1.33 respectively. [2]

2.2. Length measurement

A human has a fixed proportion of length for various parts. According to the study, the mean value of the forearm and upper arm is chosen to be 280 mm and 320 mm respectively. Similarly, the mean value of hip to knee and knee to ankle length is chosen to be 620 mm and 260 mm respectively. [3]
2.3. Degrees of freedom
In a human body, every joint has different degrees of freedom. The designed DOFs of the exoskeleton should be aligned with the natural DOFs of the human body to prevent undue stresses on human joints. Considering natural DOFs and the complexity of the design, 1 active DOF is provided each at the shoulder and the elbow for extension/flexion. Also, 2 DOFs (active DOF for extension/flexion and passive DOF for abduction/adduction) are provided at the hip and 1 DOF is provided at the knee (active) and ankle (passive) each.

3. Upper Body Exoskeleton

3.1. Torque Calculations
The calculations for torque are necessary to obtain the required drive. Motor selection and gear designing are dependent on the torque value at each joint. Considering,

\[ L_h = \text{Length of hand} \quad L_f = \text{Length of fore arm} \quad L_u = \text{Length of upper arm} \]
\[ W_h = \text{Weight of hand} \quad W_f = \text{Weight of fore arm} \quad W_u = \text{Weight of upper arm} \]
\[ W_{fl} = \text{Weight of forearm link} \quad W_{ul} = \text{Weight of upper arm link} \]
\[ W_{em} = \text{Weight of elbow motor} \quad W_{sm} = \text{Weight of shoulder motor} \]
\[ W = \text{Load on hand} \]

Maximum torque at the elbow can be calculated as,

\[ T_{\text{elbow}} = (W + W_h) \times \left(\frac{L_h}{2} + L_f\right) + (W_f + W_{fl}) \times \left(\frac{L_f}{2}\right) \]

Maximum torque at the shoulder can be calculated as,

\[ T_{\text{shoulder}} = (W + W_h) \times \left(\frac{L_h}{2} + L_f + L_u\right) + (W_f + W_{fl}) \times \left(\frac{L_f}{2} + L_u\right) + (W_u + W_{ul}) \times \left(\frac{L_u}{2}\right) + (W_{em} \times L_u) \]

3.2. Analysis
The trajectories that every human joint trace is different. Some of the human joints can be easily reproduced using various robotic joints like revolute and prismatic, whereas some human joints have complex motion which makes it difficult to reproduce using simple robotic joints. The analysis of the upper arm and forearm assembly is obtained for various trajectories using regression analysis.

3.2.1. Vertical Line Trajectory. A vertical line of length of 500mm at a distance of 400mm from the shoulder is chosen as the trajectory for analysis.

| Equation for Elbow | Equation for Shoulder |
|--------------------|-----------------------|
| Angular Displacement \( \dot{\theta} \) | \(-0.0541t^2 - 0.8952t + 136.49\) | \(0.0287t^2 + 0.2599t - 62.973\) |
| Angular Velocity \( \theta' \) | \(-0.067t + 1.7175\) | \(0.0574t + 0.2599\) |
| Angular Acceleration \( \theta'' \) | \(-0.067\) | \(0.0574\) |
3.2.2. *Horizontal Line Trajectory.* A horizontal line of length of 380mm starting from 200mm from the shoulder and collinear with the shoulder is chosen as the trajectory for analysis.

3.2.3. *Circular Trajectory.* A circle of diameter 350mm, center at 350mm horizontally apart from the shoulder is chosen as the trajectory for analysis. The trajectory starts from uppermost point of the circle in anti-clockwise direction.

**Table 2. Equations for Horizontal Trajectory**

| Equation for Elbow          | Equation for Shoulder          |
|-----------------------------|--------------------------------|
| Angular Displacement $\theta$ | $-0.035t^2 + 1.7175t + 71.028$ | $0.015t^2 - 2.0768t - 0.7122$ |
| Angular Velocity $\theta'$  | $-0.067t + 1.7175$            | $0.03t - 2.0768$            |
| Angular Acceleration $\theta''$ | $-0.067$                      | $0.03$                      |

**Figure 1.** Regression Analysis of Vertical Trajectory

**Figure 2.** Regression Analysis for Horizontal Trajectory
Table 3. Equations for Circular Trajectory

| Angular Displacement $\theta$ | Equation for Elbow | Equation for Shoulder |
|--------------------------------|--------------------|-----------------------|
| Angular Velocity $\dot{\theta}$ | $-0.0397t^3 + 1.8929t^2 - 21.808t + 124.12$ | $0.0242t^3 - 0.8524t^2 + 4.5579t - 20.915$ |
| Angular Acceleration $\ddot{\theta}$ | $-0.1191t^2 + 3.7858t - 21.808$ | $0.0726t^2 - 1.7048t + 4.5579$ |

Figure 3. Regression Analysis for Circular Trajectory

4. Lower body exoskeleton

4.1. Gait analysis

An ideal kinematics appearance of the human gait cycle for walking centers of physiotherapy, orthopedics, and development of exoskeleton as a reference data for the kinematic joint parameter is the purpose of this study [4]. A person walking on a treadmill and the legs moving in parasagittal plane was video recorded. The angles of the hip ($\theta_1$), knee ($\theta_2$), and ankle ($\theta_3$) of the right leg at equal intervals of time were measured by analyzing each frame in this video.

By quadratic regression,

$$(\theta_1) = -0.1915t^2 + 2.0252t + 172.8344$$

$$(\theta_2) = 4.1370t^2 - 11.3538t + 161.3970$$

$$(\theta_3) = -0.0168t^2 + 3.0867t + 41.3745$$

Figure 4. Distribution of reference axes on the lower limb exoskeleton [6]
4.2. Dynamic analysis
Using data from the proposed mechanisms and from Minchala et al [5], torque values for lower limb exoskeleton were obtained by using the following formulae,
\[ \tau = \frac{d}{dt} \left( \frac{\partial L}{\partial \dot{q}_i} \right) - \frac{\partial L}{\partial q_i} \]  \hspace{1cm} (6)
\[ L = K - P \]  \hspace{1cm} (7)
Where \( i \) represents the DOF, \( q_i \) represents the generalized coordinates (articul coordinates \( \theta_i \)), \( \tau \) represents torque applied to joint \( i \). Also, K, P and L represent the kinetic energy of the system, potential energy of the system and Lagrangian function respectively.
The torque values for the lower limb exoskeleton were acquired by using the data from the propound mechanics and from Minchala et al. [6]

5. Design of exoskeleton

5.1. Upper arm module
In a human body, the shoulder or the Glenohumeral joint permits three degrees of freedom. It can perform abduction/adduction, extension/flexion and internal/external rotation. There is minimal translational motion in this joint.
An exoskeleton must incorporate the changes during the entire motion. The exoskeleton, if designed for all three degrees of freedom would become quite bulky and difficult to carry. Hence the degree of freedom is restricted to one. The exoskeleton is made to perform extension/flexion. Power is transmitted using DC motor coupled with a gearbox and miter bevel gears are used to reduce lateral dimension.

5.2. Forearm module
The elbow joint permits two degrees of freedom which are extension/flexion and pronation/supination. The extension/flexion movement occurs in the parasagittal plane around a coronal axis.
The forearm exoskeleton is designed to serve one degree of freedom. Only extension/flexion is achieved using a DC Motor coupled with a gearbox and miter bevel gears are used to reduce lateral dimension.

![Figure 5. Shoulder module](image)
5.3. **Hip module**
The rotational movement of the human hip is possible because of the ball and socket hip joint. It allows movement in 3 planes namely parasagittal, coronal and transverse. The hip module of this exoskeleton allows rotational movement in the parasagittal and coronal planes. The hip flexion/extension in parasagittal plane is active DOF and is controlled by a DC motor whereas the hip abduction/adduction in coronal plane is passive DOF.

5.4. **Knee module**
As the torque required at the knee joint is 21.68Nm, the gearbox provided a reduction of 5:1. Hence, the weight of knee and tibia part is kept optimum.
5.5. Ankle module
It should be compliant with the motion of wearer’s foot. It should be light weight so as to not pose any high torque requirement for upper joint modules. It should assist the wearer during the gait locomotion.

![Ankle module](image)

Figure 9. Ankle module

5.6. Standard Motor
DC Geared RS 550 (12 V) Motor is used. Peak specifications of motor are 7.86 oz.-in/A, i.e. 0.055 Nm/A torque, 17100 RPM and 76% efficiency. For 5A current, torque will be 0.275 N-m.

5.6.1 Motor alignment for upper limbs. The motor at the shoulder joint has to be perpendicular to the arm links for power transmission. However, this protrudes out of the assembly by increasing the width of the exoskeleton. To avoid this, the motor is located parallel to the shoulder clavicle. The power transmission is achieved using a pair of mitre bevel gears. This reduces the lateral dimensions of the exoskeleton and avoids protrusions. For this alignment, Mitre gears with 18 teeth and 0.6 modules are used with both the motors.

5.7. Gearbox
RS 550 motor does not provide sufficient torque hence gearboxes were self-designed. Planetary Gearboxes of 0.6 modules are used to obtain reduction in upper limbs whereas Compound Gearboxes of 1.25 modules is used in lower limbs.

| Joint   | Torque (N-m) | Design Reduction Ratio | Gearbox Stages |
|---------|--------------|------------------------|----------------|
| Elbow   | 26.06        | 125:1                  | 3 – 5:1, 5:1, 5:1 |
| Shoulder| 57.9         | 216:1                  | 3 – 6:1, 6:1, 6:1 |
| Hip     | 47.53        | 9:1                    | 2              |
| Knee    | 21.68        | 5:1                    | 1              |

Table 4. Specification of self-developed gearboxes

6. Conclusions and Future Scope
A human power amplification exoskeleton will be available to the soldiers, rescue workers, trekkers or the physically disabled. The exoskeleton will be easy to operate and will assist the user for carrying the load up to a maximum of 5 kg by the upper limb and 40 kg by the lower limb. The exoskeleton can bear the static human weight of 100 kg. The self-weight of the full-body exoskeleton is 20 kg.

By using composite materials, the self-weight of the exoskeleton can be further reduced. The use of composite materials can help in increasing strength. The load-carrying capacity can be increased by incorporating higher torque motors. Strain Wave Gearing or Harmonic gearing, which provides maximum output torque with minimum size and weight, can be implemented. Electro-myographic sensors can be used to predict real-time intentions of the user and assist accordingly.
References

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