Design of a Lower Limb Exoskeleton

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Abstract

Robotic lower limb exoskeletons have been built for augmenting human performance, assisting people with disabilities, studying human physiology, and re-training motor deficiencies. The main function of a powered exoskeleton is to assist the wearer by boosting their strength and endurance. Our project aims to develop an ergonomic, cost effective, yet powerful exoskeleton to aid the disabled and soldiers. We plan to use a light weight, but stiff material capable enough to handle the compressive stresses developed by the weight of the user. The links are driven using independent motors. Electric motors are used for the actuators due to their higher efficiency and lower weight. The system is fastened to the wearer using broad Velcro strips to employ universal compatibility and to avoid discomfort. The current system uses a pre-programmed microcontroller to actuate the motors. The speed and number of revolutions are determined in accordance with the human gait cycle. In order to obtain the required motion, sprockets are used along with simple cable-pulley system, thereby decreasing the overall weight of the system. The pace can be altered by suitably changing the voltage supplied to the motors using the driver circuit. The primary benefactors of the product will be the senior citizen, whose numbers are expected to shoot up to 70 percentages by 2050. So an ergonomic and cost effective exoskeletons market is expected to go nowhere but upwards. The links of our product are so designed to be 95 percentile human, so that it fits practically everyone. Provisions for small adjustments are also provided for additional comfort. The compact and vertical design not only creates an aesthetic appearance. It is also commendable that the existing technological exoskeletons rest a fortune and hence has not achieved a great appeal in the market. It is in this context that our cost effective exoskeleton becomes commercially important.

Keywords: Exoskeleton, Lower Limb, Gait Cycle, Paraplegia, Walk Assist

I. INTRODUCTION

As a method of providing walking assistance for paraplegic patients, exoskeleton-type assistive devices have recently received a great deal of attention, since these devices can provide full mobility similar to human walking. Since the ability to walk is an essential function of human beings, many paraplegic patients - who are unable to walk dream of walking again. Most of them have had critical accidents that caused their paralysis, and the possibilities of accidents are quite high in modern society. An exoskeleton to be an active mechanical device which is anthropomorphic in nature, and can be worn by a person and can act as an assistive device. Exoskeleton-type walking assistive devices have been developed for this reason and can achieve patient’s dream of walking, whereas wheelchairs only help them to move. These robotic systems provide active and repetitive controlled movements to help patients recover mobility, relieving the physical therapists from the onerous task of manual assistance and training. Since the first active exoskeleton appeared in the late 1960s, many novel robotic exoskeletons have been developed for the assistance and rehabilitation of human lower limb.

Inspired by science fiction, that has very persuasively been brought out in books and movies, researchers have, for quite some time, put in efforts to make an effective exoskeleton which can be used for assistance. Our focus is more on exoskeletons for the lower extremities and exoskeleton as an assistive device for rehabilitation. This is mainly because when we take a look around us, we realize that a small accident might lead to devastating results such as fractures, brain injury, spinal cord injury or at times even death. In worst case scenario, a person becomes a victim of paraplegia, which may lead to loss of locomotion. Such persons may never be able to walk again. As we attempt to uncover the major developments in the field of exoskeleton technology, we shall briefly touch upon performance augmenting exoskeletons followed by exoskeletons for rehabilitation. About 7%–10% of the world’s population have different kinds of disabilities. The population census stated that in the year 2010, 5.1% of the total...
population had difficulty in walking or moving (49% men and 51% women). A total of 39% of the disabled people suffer to diseases, 23% due to old age, 16% due to inheritance during pregnancy or at birth, 16% due to accidents, and 8% due to other reasons. For these causes, rehabilitation and increasing strength are possible methods to recover completely or partially. These wearable robots are metachromatic devices to increase human strength and resistance. They can be applied to recover the injuries, such as neurological and neuromuscular diseases, hemopoietic or muscular dystrophy, and muscle degeneration.

Now a day’s robotics will play an important role in therapy activities within rehabilitation treatment. In the last decade, the interest in the field has grown exponentially mainly due to the initial success of the early systems and the growing demand caused by increasing numbers of stroke patients and their associate rehabilitation costs. As a result, robot therapy systems have been developed worldwide for training of both the upper and lower extremities. This work reviews all current robotic systems to date for lower-limb rehabilitation, as well as main clinical tests performed with them, with the aim of showing a clear starting point in the field. It also remarks some challenges that current systems still have to meet in order to obtain a broad clinical and market acceptance.

II. RELEVANCE

“Wheel chairs satisfies the need to move but exoskeletons promise the dream of walking”. Studies prove that more than 40% of the population are affected with problems regarding the lower limb. Current day systems of rehabilitation do not involve the active participation of muscles. It is in this scenario that the true relevance of an exoskeleton comes as its usage gives the effect of using a treadmill.

Our exoskeleton is so ergonomically designed that it efficiently distributes own and load weights. So the user can move without much effort. He can carry astonishing amount of weights, cover more distances and stride faster without fatigue for larger period of time. This proves to be of much importance in the military and in places where great physical tenure is needed.

III. EXOSKELETONS IN REHABILITATION

Exoskeletons play a major role in the rehabilitation of patients affected by spinal cord injury, or brain injury who have lost motor functions of the lower limb. Patients who have been wheel-chaired face a lot of problems with regard to their movement and also deal with many psychological issues. Also the human body is physiologically designed in a way such that it can stand, walk and move around, but a wheelchair user loses this ability and leads to having a negative impact on the body. To overcome such problems, exoskeletons play a major role in rehabilitation and enable a wheelchair-user to be independent of wheelchairs, enabling him to walk around. But with advances in technology, today we see some ground-breaking research and development in the field of exoskeletons and their application in rehabilitation has started to enter the field of commercialization. Some such exoskeletons are the ReWalk, eLEGS, Mind Walker, HAL, REX, Vanderbilt exoskeleton. Each one of them has a unique mechanism. Some use certain bio-signals to operate, while some use complex algorithms with a lot of sensor information. Some work as reciprocating gait orthosis while some employ the use of joystick to work.

A. Study of Robotic Leg Mechanism

In comparison with the industrial manipulators, the task of building an adaptable, autonomous walking machine is more difficult. Walking machines have more active degrees of freedom (DOF) than industrial robots. To enlarge the work-space of the legend, and thus enhance the machine’s ability to adapt to the terrain, each leg should have at least 3 DOF, which results in a total of 12 DOF for a quadruped or 18 DOF for a hexapod. All those joints must be controlled adequately in real time. This also means that the hardware and software systems must meet more critical requirements than those formulated for industrial robot controllers. Moreover, fully autonomous vehicles use only on-board controllers and so those controllers have to be miniaturized to an utmost extent. Mechanical structure of a walking machine should not only imitate the leg structure of living creatures (e.g., insects, spiders), but should also take into account the actuating systems properties (e.g., size, weight and power of the motors) and constraints (e.g., size of the body and the leg work-space).

However the ability to meet this need has been hampered by the lack of adequate joint mechanisms and controls. Joint technology is a key problem in the development of such systems, because hip and ankle joints require, at a minimum, pitch and yaw motion about a common center with remote location of actuation sources analogous to our muscles and joints. The lack of simple, compact, cost-effective and reliable actuator packages has also been a major stumbling block in current designs. Ineffective joint design leads to unwieldy vehicles that compensate for the instability of their simple joints by means of additional legs.

Following subjects are found important to study the leg mechanism.

Effectiveness of leg joints related to walking.

1) Locations of leg joints.
2) Movable extent of leg joints.
3) Dimension, weight and centre of gravity of a leg.
4) Torque placed on leg joints during walking.
5) Sensors related to walking.
6) Ground impact on leg joints during walking.
1) Effectiveness of Leg Joints Related to Walking
It is found that the walking was not affected even if there were no fingers and that the roots of the fingers and heel are more important for supporting the body weight. As far as the ankle joint and walking function are concerned, if the ankle joints were fixed
- there will be a lack of contact feeling with ground surface and the fore-and-aft.
- standing still is difficult if eyes were closed and
- when side crossing a sloped surface, the feeling of contact with ground surface stability will be weak.
As far as the knee joint, it is found that if the knee joints were fixed, walking up and down staircase is not possible.

2) Locations of Leg Joints
The location of leg joints affects the kinematic and dynamic properties of leg. These have been explained in detail in later part.

3) Movable Extent of Leg Joints
Again the length of the leg links and location of leg joints affect the movement and reach of the legs which determines the gait of walking on flat surface and up and downs of staircase.

4) Dimension, Weight and Centre of Gravity of a Leg
Placing the actuator at the knee joint adds various dynamic effects to the leg which have to be compensated for by the controller. This adds complexity to the control algorithms needed to move the leg. It also requires more powerful motors at the hip joint to move the added mass of the leg. Remote actuation, in which the actuators are located at the base of the leg, eliminates some of these problems, at the cost of increasing the complexity of the mechanism.

5) Torque Placed on Leg Joints During Walking
This is one of the most important aspects. The whole moment of leg depends upon the torque requirement on leg joints. If the actuators are not powerful enough to provide the required torque the expected gait cannot be achieved.

6) Sensors related to walking
Humans have three senses for sensing the equilibrium. One is the sensor to sense acceleration by ear drum; the second one is the sensor to sense the tipping rate by semi-circular canals and the third one is the sensor to sense the angles of joints movement, angle acceleration, muscular pressure and feeling of foot sole and skin. We also have the visual sensor which complements and alternates the sense of equilibrium mentioned above and also manages the walking information. Basing on this information, it can be concluded that a robot in its system needs a G-sensor, 6 axis force sensor and gyro meter to sense its own posture and joint angle sensor in order to grasp the leg movement when walking.

7) Ground impact on leg joints during walking
The ground reaction force is the impact force imposed on the foot during the walking. Human body is so designed to absorb the impact force with its soft skin tissues surrounding the foot, arch frame of bones forming the foot, and the roots of finger joints, and flexible movement of knee joint as the foot land the ground. As the walking speed increases, the reaction force becomes larger even with the human’s impact damper mechanism.

B. The Requirements for an Ideal Walking Machine
1) The machine must have a uniform velocity while the feet are in contact with the ground.
2) The stride must be long in relation to the physical dimensions of the walking machine to achieve adequate speeds.
3) The height and length of the stride must be controllable by the operator.
4) The height of the step should be large compared with the dimensions of the machine.
5) The ‘feet’ should have a high stride to return-time ratio.
6) A mechanism integral to the ‘legs’ must be provided for steering the body.
7) The body must be capable of moving either in the forward or reverse directions.
8) The inertia forces and torques must be balanced.
9) The energy lost in lifting the foot should be recovered in lowering the foot.

IV. LOWER LIMB MECHANISM
If one stops to consider for a moment it becomes immediately evident that the earth is literally crawling with walking machines. The locomotion of all organisms in nature is produced by a system of levers. In some cases, such as the caterpillar, the whole animal can be considered a single lever but, nevertheless, the motion can be reduced to a levered system. The fact that nature has confined herself to levered machines should be extremely significant to the designer of off-road equipment.
The successful design of a legged robot depends to a large extent on the leg design chosen. Since all aspects of walking are ultimately governed by the physical limitations of the leg, it is important to select a leg that will allow for a maximum range of motion and that will not impose unnecessary constraints on the walking gait chosen. The first stage of the leg design process therefore consists of a search for an optimal leg design.

V. DESIGN PROCESS

A. Gait Kinematics

1) Swing phase

![Free body diagram on swing phase.](image)

For 95 percentile human data
Mass of hip = 8.1 kg and mass of thigh = 5.8 kg
Total length of hip = 0.5m and length of thigh = 0.45m
Hip torque, $T_h = [8.1 \times 9.81 \times \cos(60) \times 0.35] + [5.8 \times 9.81 \times \cos(60) \times 0.858]$
$T_h = 38.31$Nm
Knee torque, $T_k = 5.8 \times 9.81 \times \cos(60) \times 0.358$
$T_k = 10.18$Nm

2) Stance phase

![Free body diagram on stance phase.](image)
Hip torque, $T_h = 50.6 \times 9.81 \times 0.25 \times \cos (60)$
$T_h = 69.49 \text{Nm}$

3) Step Climb

![Free body diagram on step climbing.](image)

Knee torque, $T_k = [40.6 \times 9.81 \times \cos (50) \times 0.5] + [8.1 \times 9.81 \times \cos (50) \times 0.15]$
$T_k = 135.6 \text{Nm}$

B. Motor Calculation

PMDC motor 12V 17W

Torque, $T = \frac{P \times 60}{2 \pi N}$ (5.1)
$= \frac{17 \times 60}{2 \pi \times 25}$
$T = 6.49 \text{Nm}$

Transmission ratio,
$\frac{N_2}{N_1} = \frac{t_2}{t_1}$ (5.2)

$N_1 = N_1 \times t_2$
$N_2 = 25 \times \frac{32}{18}$
$N_1 = 14.06$

Transmission ratio, $\frac{t_2}{t_1} = 1.778$

Torque, $\frac{T_2}{T_1} = \frac{N_1}{N_2}$ (5.3)

$T_2 = 1.778 \times \frac{25}{14.06}$
$T_2 = 11.53 \text{Nm}$

C. Sprocket and Chain

Pitch circle diameter, $P_d = \frac{P}{\sin\left(\frac{180}{t}\right)}$ (5.4)

Pitch, $p = 12.70 \text{mm}$

So $P_{d1} = \frac{12.70}{\sin\left(\frac{180}{18}\right)}$ (5.5)
$= 73.13 \text{mm}$

$P_{d2} = \frac{12.70}{\sin\left(\frac{180}{32}\right)}$ (5.6)
$= 129.56 \text{mm}$

Centre distance
Optimum centre distance (30 to 50)$p$

i.e. minimum 381mm and maximum 635mm

But due to space limitation we have chosen centre distance as 250mm
Pitch line velocity of the smaller sprocket, 
\[ V_1 = \frac{\pi d_1 N_1}{60} \] (5.7)
\[ V_1 = \frac{\pi \times 0.07313 \times 25}{60} \approx 0.0957 \text{ m/s} \]

Load on the chain, 
\[ W = \frac{\text{Rated power}}{\text{pitch line velocity}} \] (5.8)
\[ W = \frac{17}{0.0957} \approx 177.58 \text{N} \]

**D. Chain Design**

For ISO chain number 08B
- Roller diameter = 8.51mm (maximum)
- Width between inner plates = 7.75mm (maximum)
- Transverse pitch = 3.92mm
- Breaking load for a simple type = 17.8KN (minimum)
- From Lingaiah data book,
  - Factor of safety = 7

Number of chain links, 
\[ K = \frac{t_1 + t_2}{2} + \frac{2x}{p} + \frac{([2t_2 - t_1]^2 - p)^2}{2\pi} \] (5.9)

In order to accommodate the initial sag in the chain, value of center distance is reduced by 5 to 10 mm.
\[ x = 250 - 5 = 245 \text{mm} \]

Pitch of the chain, 
\[ p = 12.70 \]
\[ k = \frac{18+32}{2} + \frac{245}{12.70} + \left[ \frac{32-18}{2\pi} \right]^2 \times 12.70 \] (5.10)
\[ = 63.84 \approx 64 \text{mm} \]

Length of chain, 
\[ L = k \times p \] (5.11)
\[ = 64 \times 12.70 \approx 812.8 \text{mm} \]

Design power = rated power * service factor
- Load factor \((k_1)\) for variable load with heavy shock = 1.5
- Lubrication factor \((k_2)\) for drop lubrication = 1
- Rating factor \((k_3)\) for continuous service = 1.5
\[ k_s = k_1 \times k_2 \times k_3 = 2.25 \] (5.12)

Design power = \[ 17 \times 2.25 = 38.25 \text{KW} \]

**E. Bearing**

SKF 6203 deep groove roller ball bearing.
- Inside diameter, \(d\) = 17mm
- Outside diameter, \(D\) = 40mm
- Width, \(B\) = 12mm
- Ball radius, \(r\) = 0.6mm

Axial force \(F_a\) : Static load carrying capacity \(C = 617.5 \text{N} \)
\[ = \frac{4750}{617.5} = 0.13 \]
So, \(e = 0.31 \)

From table 24.51, the values of constants
\[ X = 1 \]
\[ Y = 0 \]

Equivalent bearing load, \(P = [X \times V \times F_a + Y \times F_a] \times k_s \) (5.14)
For mild shock \(k_s = 1.25 \)
\[ P = (1 \times 1 \times 1962) \times 1.25 \]
\[ P = 2452.5 \text{N} \]

Dynamic load carrying capacity, \(C = 9560 \text{N} \)
Life in millions of revolution, \(L_n = \left( \frac{C}{P} \right)^3 \) (5.15)
\[ L_n = \left( \frac{9560}{2452.5} \right)^3 \approx 59.23 \text{ million revolutions} \]
VI. DRIVING AND CONTROL MECHANISMS

A. PMDC motor

In a dc motor, an armature rotates inside a magnetic field. Basic working principle of DC motor is based on the fact that whenever a current carrying conductor is placed inside a magnetic field, there will be mechanical force experienced by that conductor. All kinds of DC motors work in this principle only. Hence for constructing a dc motor it is essential to establish a magnetic field. The magnetic field is obviously established by means of magnet. The magnet can be any type i.e. it may be electromagnet or it can be permanent magnet. When permanent magnet is used to create magnetic field in a DC motor, the motor is referred as permanent magnet dc motor or PMDC motor. These types of motors are essentially simple in construction. These motors are commonly used as starter motor in automobiles, windshield wipers, washer, for blowers used in heaters and air conditioners, to raise and lower windows, it also extensively used in toys. As the magnetic field strength of a permanent magnet is fixed it cannot be controlled externally, field control of this type of dc motor cannot be possible. Thus permanent magnet dc motor is used where there is no need of speed control of motor by means of controlling its field. Small fractional and sub fractional kW motors now constructed with permanent magnet.

The working principle of PMDC motor is just similar to the general working principle of DC motor. That is when a carrying conductor comes inside a magnetic field, a mechanical force will be experienced by the conductor and the direction of this force is governed by Fleming’s left hand rule. As in a permanent magnet dc motor, the armature is placed inside the magnetic field of permanent magnet; the armature rotates in the direction of the generated force. Here each conductor of the armature experiences the mechanical force F = B.I.L Newton where B is the magnetic field strength in Tesla (weber / m²), I is the current in Ampere flowing through that conductor and L is length of the conductor in meter comes under the magnetic field. Each conductor of the armature experiences a force and the compilation of those forces produces a torque, which tends to rotate the armature.

B. Stepper Motor

A stepper motor or step motor or stepping motor is a brushless DC electric motor that divides a full rotation into a number of equal steps. The motor's position can then be commanded to move and hold at one of these steps without any feedback sensor (an open loop controller), as long as the motor is carefully sized to the application in respect to torque and speed.

DC brushed motors rotate continuously when DC voltage is applied to their terminals. The stepper motor is known by its property to convert a train of input pulses (typically square wave pulses) into a precisely defined increment in the shaft position. Each pulse moves the shaft through a fixed angle.
Stepper motors effectively have multiple "toothed" electromagnets arranged around a central gear-shaped piece of iron. The electromagnets are energized by an external driver circuit or a microcontroller. To make the motor shaft turn, first, one electromagnet is given power, which magnetically attracts the gear's teeth. When the gear's teeth are aligned to the first electromagnet, they are slightly offset from the next electromagnet. This means that when the next electromagnet is turned on and the first is turned off, the gear rotates slightly to align with the next one. From there the process is repeated. Each of those rotations is called a "step", with an integer number of steps making a full rotation. In that way, the motor can be turned by a precise angle.

Arduino mega 2560

Arduino is an open-source prototyping platform based on easy-to-use hardware and software. Arduino boards are able to read inputs - light on a sensor, a finger on a button, or a Twitter message - and turn it into an output - activating a motor, turning on an LED, publishing something online. One can tell the board what to do by sending a set of instructions to the microcontroller on the board. To do so people use the Arduino programming language (based on Wiring), and the Arduino Software (IDE), based on processing.

Over the years Arduino has been the brain of thousands of projects, from everyday objects to complex scientific instruments. A worldwide community of makers - students, hobbyists, artists, programmers, and professionals - has gathered around this open-source platform, their contributions have added up to an incredible amount of accessible knowledge that can be of great help to novices and experts alike.
D. Driving Circuit for DC Motor

An ‘H bridge’ is used to control the motion of dc motor on either direction along with the help of relays and controlled by Arduino mega 2560. An H bridge is an electronic circuit that enables a voltage to be applied across a load in either direction. These circuits are often used in robotics and other applications to allow DC motors to run forwards and backwards.

![Structure of an H bridge](image)

H bridges are available as integrated circuits, or can be built from discrete components. The term H Bridge is derived from the typical graphical representation of such a circuit. An H bridge is built with four switches (solid-state or mechanical). When the switches S1 and S4 (according to the first figure) are closed (and S2 and S3 are open) a positive voltage will be applied across the motor. By opening S1 and S4 switches and closing S2 and S3 switches, this voltage is reversed, allowing reverse operation of the motor.

![The two basic states of an H bridge](image)

Using the nomenclature above, the switches S1 and S2 should never be closed at the same time, as this would cause a short circuit on the input voltage source. The same applies to the switches S3 and S4. This condition is known as shoot-through.

VII. CONCLUSION

Man has made tremendous advancements in the field of machinery which is available in various forms and for various purposes. The majority of these machines involve locomotion and the predominant form of locomotion incorporated in these machines is the wheeled locomotion. Wheeled locomotion, though being very versatile lacks certain specialized capabilities. Walking as a form of locomotion for machines is being explored only for the past few decades but still the achievements are far from perfection. Bipedal walking is now a focus of foremost research as it poses a challenge in front of the technological capabilities of man.

The exoskeleton developed has proven to be most effective in assisting and replicating gait. The ergonomic design allows its usage for long periods of time, without any risk of fatigue or injury. The present market trends are favorable for such the product and the demand is forecasted to go nowhere but up owing to its low cost and simplicity. Thus the exoskeleton becomes not only a novel idea, but also a noble product ready to hit the market.

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