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Design and Fabrication of a Low-cost Human Body Lower Limb Exoskeleton

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***Abstract*—Recent developments in exoskeleton technology have assisted humans in performing strenuous and fatiguing tasks. However, these exoskeletons are unable to reach masses due to their high cost. In this paper, design, fabrication and validation of a low-cost human body lower limb hybrid exoskeleton is presented. The exoskeleton provides assistive torque at the hip and knee joints which prevents strain on the limbs of the user. The exoskeleton is designed to work with joint actuators made of electric dc motors coupled with back-drivable custom gearboxes. A prototype of the same is fabricated and tested. The joint angle data required to mimic a walking gait cycle was collected by filming subjects walking on a treadmill with the help of a camera whereas joint torque data was obtained by performing inverse dynamics on a musculoskeletal model. The exoskeleton model was simulated in MATLAB Simulink. The torque profiles produced by the joint actuators are plotted and compared with required torque profiles. Percentage torque assists at the hip and knee joints are calculated and discussed.**

Keywords-exoskeleton; hybrid; torque assist; human motion analysis; musculoskeletal model

I. INTRODUCTION

Human exoskeletons have proved to benefit humans in different fields using power augmentation, strain reduction on muscles and reduction in joint torque requirements. Hence, these wearable devices have been implemented in areas such as rehabilitation, military and industries [1][2]. Researchers have worked on novel mechanisms to develop exoskeletons that augment power, reduce strain on muscles and reduce the joint torques need to be applied by a human to complete a task. H. Kazerooni and R. Steger [3] developed Berkeley lower extremity exoskeleton (BLEEX), an anthropomorphic, powered exoskeleton for human strength augmentation. They used hydraulic actuation system. An on-board internal combustion engine provided both electric and hydraulic power. Sang-Ho Hyon et al [4] developed XoR which is a light-weight lower-body exoskeleton prototype and uses hybrid pneumatic-electric drive. XoR was developed to achieve precise torque control, back-drivability and a desirable force/velocity profile as well as reduction in weight. This exoskeleton's design allows to augment operator's strength in rehabilitation applications and assist with postural control for disabled people.

Existing exoskeletons have incorporated hydraulic and pneumatic drives as well as systems consisting a combination of both pneumatic and electric drive. These drives however require fluid storage and a pump or a compressor which contribute to the bulkiness of the exoskeleton system. These problems were overcome through complete electric drive exoskeleton systems. Yoshiyuki Sankai developed Hybrid Assistive Limb (HAL) [5] for human strength augmentation and as an assistive gait device in rehabilitation. The torque requirements in this system are achieved through DC motors coupled with harmonic drives which work on strain wave gearing principle [7]. Harmonic drive facilitates compactness of exoskeleton system. HAL achieves human gait locomotion through predefined gait trajectories by controlling knee and hip joints.

These exoskeletons while being effective in assisting a human are costly. Hence, these systems fail to reach the masses in need. We have designed and fabricated a human body lower limb hybrid [6] exoskeleton driven by electric DC motors and springs. The main aim of this exoskeleton is to reduce the torque required to be applied at the leg joints like hip, knee and ankle by the wearer. The electric DC motors are coupled with a low-cost custom gearbox and act as joint actuators which apply torque at the hip and knee joints. Ankle joint of the exoskeleton uses a passive element that is a spring. A ratchet mechanism [9] can be used for locking the joint angles of the exoskeleton for a desired pose. The joint angles and joint torques were determined by performing human motion analysis on five human subjects. This data was fed to the exoskeleton system while a wearer was using it. This paper presents all the work done to develop the exoskeleton. Section

II presents the procedure followed for collection of the joint angles and joint torques by human motion analysis during walking gait cycle. Design of the gearbox for joint actuators is mentioned in section III. Section IV presents the overall design of the human body lower limb exoskeleton. Section V presents the details of fabrication of the exoskeleton. Section VI presents the electronic architecture of the exoskeleton system. Section VII presents the results in the form of percentage torque assist due to the exoskeleton. Section VIII presents the conclusion and mentions the possible future work.

II. HUMAN MOTION ANALYSIS

A setup was done for human motion analysis using a video camera. Subjects between ages 20 and 25 were chosen for the analysis. The heights of the subjects varied between 165 cm to 180 cm and the weights varied between 55 kg to 90 kg. The subjects were made to walk on a treadmill with speed of 5 km/hr with no incline which is the average human walking speed. A Nikon D3200 video camera on a tripod of height 1 m was placed at a distance of 4 m normal to the sagittal plane of the walking subjects. The walking gait cycles of these subjects were recorded at 25 frames per second. The videos were analysed by tracing the white markers on the joints of human subjects on a video analysis software called Dartfish Pro to obtain joint angles during the walking gait cycle. Hip and knee joint angles during the mid-stance and mid-swing position are showed in Fig. 1. Similarly, a total number of six important poses during a walking gait cycle were analysed for joint angles, namely heel strike, foot flat, mid-stance, heel off, toe off and mid-swing.

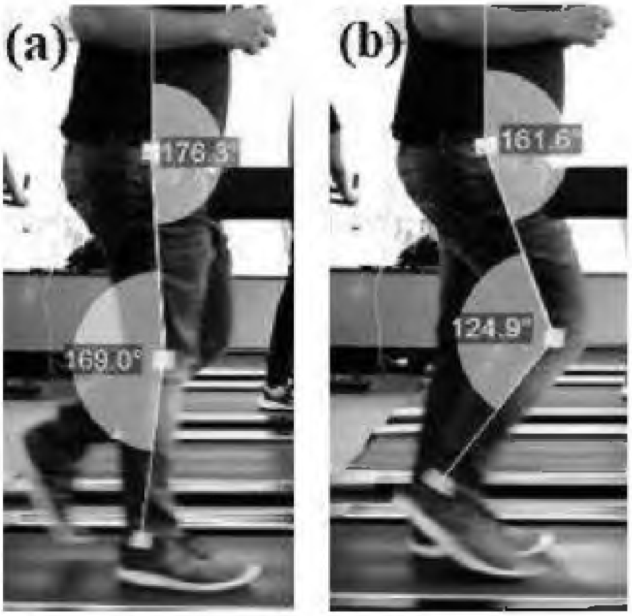

Figure 1. Hip and knee joint angles in a walking gait cycle during (a). foot flat pose and (b). mid-swing pose.

The average hip and knee joint angles were plotted against time named as hip_flexion_r and knee_angle_r respectively and are shown in Fig. 2. This data was further used to drive the exoskeleton.

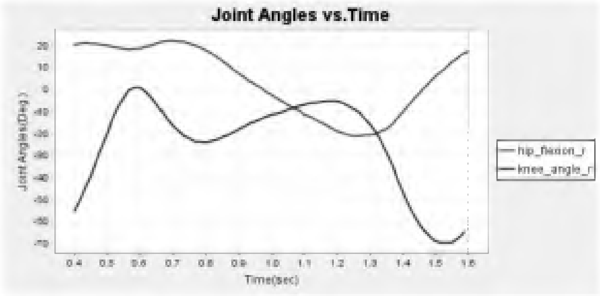

Figure 2. Plot of hip and knee joint angles (deg.) v/s time (sec.).

For obtaining the joint torques required during walking, a musculoskeletal model was simulated in OpenSim 4.0 using available joint angle data as shown in Fig. 3.The exoskeleton is to be designed for a wearer with maximum weight of 80 kg and height of 180 cm. Thus, the weight of the musculoskeletal model was set to 80 kg and the height was set to 180 cm. Ground reaction forces applicable during the walking gait cycle like friction force and reaction due to weight were applied to the model. [10] After performing inverse dynamics on the musculoskeletal model, the values of hip and knee torques were plotted against time as shown in Fig. 4.

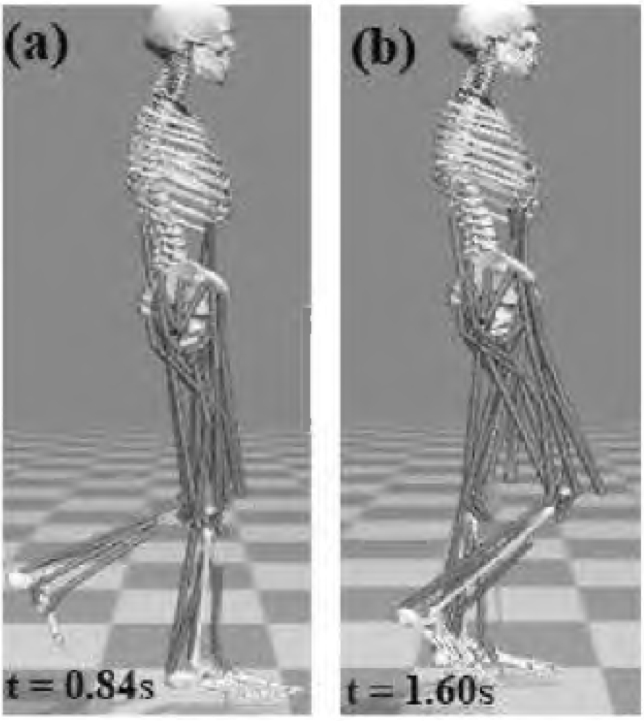

Figure 3. Musculoskeletal model walking according to collected joint angle data (a). foot flat pose (b). mid-swing pose.

III. GEARBOX DESIGN

After studying the plot demonstrating the variation of joint torques with time and comparing it with the experimental results obtained by Mehdi Jokar et al [8], electric DC motors are selected, and appropriate gearboxes are designed to fulfil the demands of torque requirements for hip and knee joints. Hip joint requires torque value of approximately 60 N m and the knee joint requires approximately 40 N m. These values are required for a subject weighing 80 kg with a height of 180 cm to walk. The aim is to reduce the joint torque needed to be applied by a human during walking by applying external torque using joint actuators.

RS 550 - 12V high torque DC motor coupled with a P60 planetary gearbox (26:1) from Banebots is selected as the joint actuator. However, the peak output torque of this actuator is 7.128 N m which is not sufficient for the application. Hence, a compound gearbox and a simple gearbox are designed for hip and knee joints respectively. Gearbox for the hip joint is a two stage compound gearbox with 3:1 gear reduction ratio at each stage, where driving pinion has 25 teeth and driven wheel has 75 teeth, which results in a total gear reduction ratio of 9:1. Gearbox for the knee joint is a simple gearbox with one driving pinion (25 teeth) and a driven wheel (125 teeth). The gear reduction ratio is 5:1.

The resultant peak output torques at the joint actuators are determined by multiplying the output torque of the motor that is 7.128 N m with the gear reduction ratio.

As a result,

$$\text{Obtained hip torque} = 7.128 \times 9 = 64.152\ N\ m$$

And,

$$\text{Obtained knee torque} = 7.128 \times 5 = 35.64\ N\ m$$

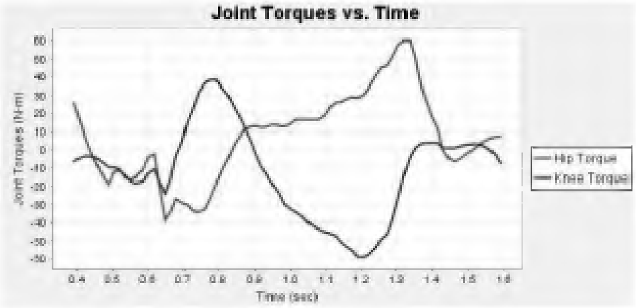

Figure 4. Plot of hip and knee joint torques (N m) v/s time (sec.).

TABLE I. JOINT ACTUATOR SPECIFICATIONS

Joint	Specifications				
	Motor	*Gearbox Type*	*No. of Stages*	*Gear Reduction Ratio*	*Output Peak Torque (N m)*
Hip	Banebots RS 550 with P60 26:1 gearbox	Compound	2	9:1 (3:1 at each stage)	64.152
Knee	Banebots RS 550 with P60 26:1 gearbox	Simple	1	5:1	35.64

A summary of specifications of the joint actuators with designed gearboxes is presented in Table I for clear understanding. These obtained peak torque values are for ideal conditions. They are difficult to achieve when mimicking a walking gait cycle. However, these joint actuators are cheaper to develop as compared to existing harmonic gearboxes and also assist the user as discussed in further sections.

IV. DESIGN OF EXOSKELETON

The exoskeleton is designed to have 8 DOFs, 4 on each leg. Out of which 4 DOFs are active and remaining are passive. Hip flexion and knee joints are provided with actuation as discussed in earlier section. Hip abduction and ankle joints are given passive assistance using springs. A load carrying frame is provided at the back of exoskeleton which can carry extra load such as a bag pack.

The battery and the electronic circuits are mounted on this frame. The frame acts as a torso for the exoskeleton on which the hip joint actuators are mounted. The knee joint actuators are further connected to hip joint actuators using linkages with adjustable lengths. The ankle joints are connected to the knee joints using similar linkages. The load carrying frame at the back of the exoskeleton transfers the extra weight kept on it to the ground through the radial ball bearings mounted for hip abduction DOF. This ensures that the burden of the weight is not taken by the wearer of exoskeleton. Detailed design of individual components is previously presented by the authors in [11]. A CAD model of the exoskeleton is shown in Fig. 5.

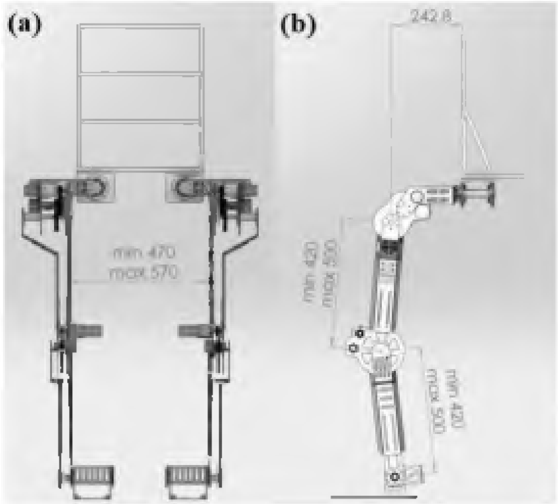

Figure 5. CAD model of exoskeleton (a). Front View (includes minimum and maximum width of the wearer in mm) (b) Left side view (includes minimum and maximum dimension of adjustable linkages, and distance between the back frame and hip joint in mm).

V. FABRICATION

The gearboxes of the exoskeleton were manufactured by laser cutting aluminium according to the designed model. Bearing casings, brackets and linkages were fabricated by CNC bending after laser cutting. The aluminium shafts used in the gearboxes and in the passive DOFs were manufactured with the help of CNC turning. [12][13]

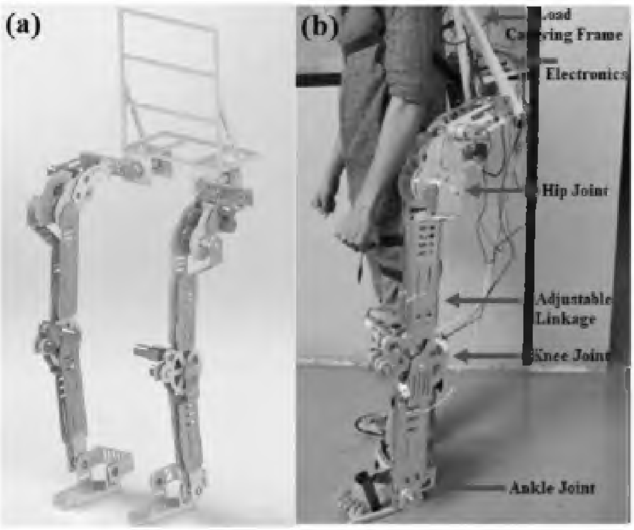

Figure 6. (a). CAD rendering of the exoskeleton (b). Fabricated exoskeleton prototype on a wearer.

The load carrying frame was fabricated by welding aluminium tubes of square cross section according to the design. Springs were used with radial ball bearings to produce passive DOFs for hip abduction and ankle joint. A fabricated prototype of the exoskeleton is demonstrated in Fig. 6. Considering the ergonomics for maximum user support, velcro straps were used to strap the exoskeleton on the wearer. Weight of the exoskeleton including batteries is 15 kg which is less as compared to the existing exoskeletons such as XoR (30 kg) and HAL (23 kg).

VI. ELECTRONIC ARCHITECTURE

Closed loop control as shown in Fig. 7 is used for the smooth operation of exoskeleton. STM 32 is used as the master controller. Motor driver used in this system is VNH 5019. The exoskeleton is driven in position control mode which means that the motor driver receives commands in the form of angular inputs through PID control from the master controller. Motor driver drives the motor according to these control signals. The feedback of the angular position of the motor is given to the master controller with the help of a rotary encoder connected to the joint actuator. Any error in the angular position of the motor is compensated by the master controller by sending appropriate signal to the motor driver. The system is powered by 12 V Lithium Polymer battery having capacity of 16000mAh. Considering the power consumption of joint actuators, the exoskeleton should work for 48 minutes in one full battery capacity. However, practically the exoskeleton works for 36 minutes.

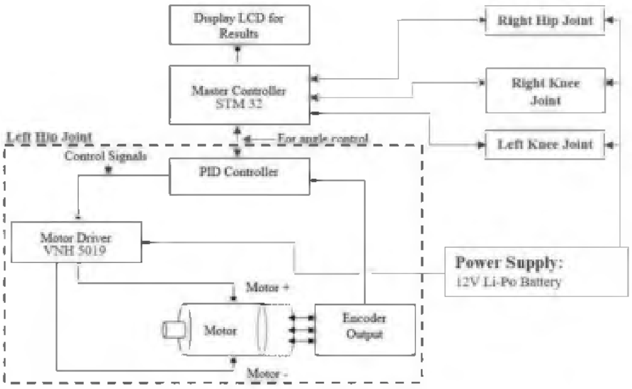

Figure 7. Electronic architecture of the exoskeleton.

VII. RESULTS AND DISCUSSION

The exoskeleton was simulated in MATLAB Simulink as shown in Fig. 8. [14] The back frame and the linkages were assigned weights and inertial properties as when a wearer is wearing the exoskeleton and walking. Angles obtained earlier were used as input for the motion of exoskeleton. The torque profiles produced by the hip and knee joint actuators were plotted against time. A plot of required and obtained torque profiles at the hip joint is represented in Fig. 9. A similar plot for the knee joint is represented in Fig. 10. The joint actuators do not provide the exact maximum values of torque required at the hip and knee joints. However, Fig. 9 and Fig. 10 suggest that the joint actuators produce torque profiles similar to the required torque profiles. [15] Hence, it is evident that there is a finite percentage of assist in torque at the joints due to the exoskeleton.

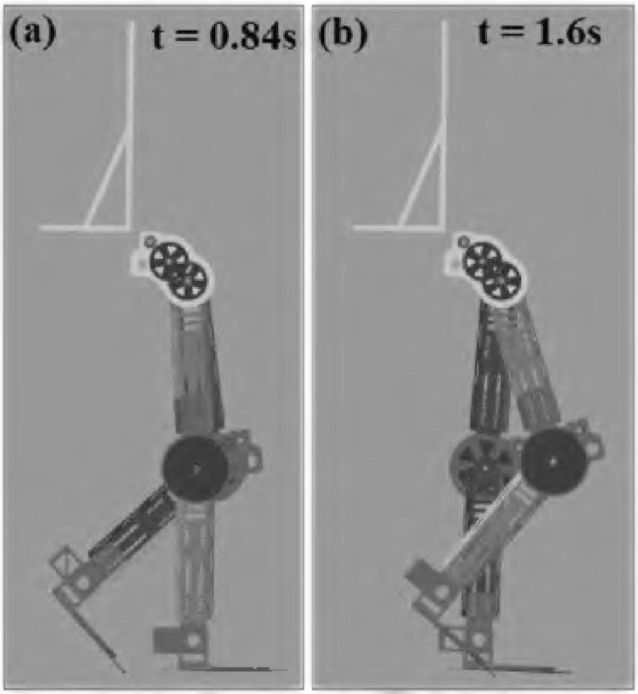

Figure 8. Simulation of the exoskeleton in MATLAB Simulink (a) foot flat pose (b) mid-swing pose.

It is clear from Fig. 9 that maximum difference between the required and obtained torques is at the peak torque requirement which occurs at 0.78 seconds and 58 N m torque is required. Torque produced by the joint actuator is 24 N m, which is 41% of the peak required torque. Thus, there is a minimum of 41% torque assist at the hip joint. For knee joint, the maximum difference between the required and obtained torques occurs at about 1.2 seconds with peak required torque value of 55 N m, as can be seen in Fig. 10. The joint actuator is able to produce 28 N m at that moment which is about 51% of the peak required torque. As a result, a minimum of 51% torque assist is obtained at the knee joint. The maximum torque assist on both the joints will be 100% as the required and obtained torque profiles overlap at some instances.

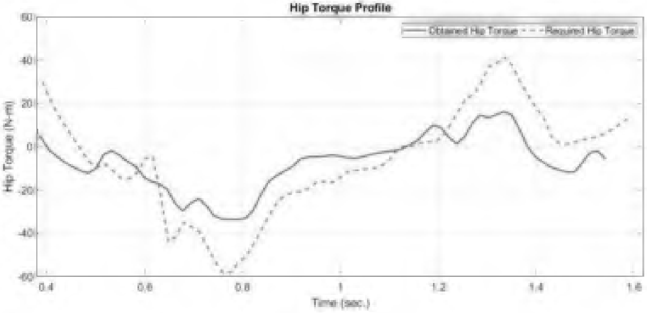

Figure 9. Plot of required and obtained hip torque (N-m) v/s time (sec.)

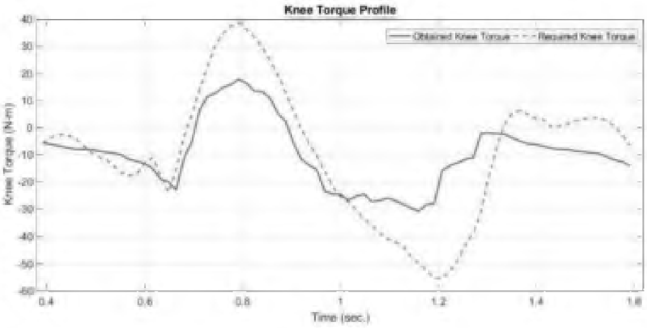

Figure 10. Plot of required and obtained knee torque (N-m) v/s time (sec.)

VIII. CONCLUSION AND FUTURE SCOPE

A low-cost lower limb hybrid exoskeleton with custom made back-drivable gearbox, as compared to the existing hybrid exoskeletons which are driven on harmonic drive, was designed, fabricated and tested. The weight of exoskeleton (15 kg) is less as compared to many of the existing exoskeletons. The exoskeleton provides minimum 41% torque assist at the hip joint and 51% at the knee joint which allows the wearer to apply comparatively low torque at these joints and prevent strain.

The current model of exoskeleton works on a pre-defined walking gait cycle. It does not assist the user in running, jumping or following any other gait cycle. To solve this, data related to these different gait cycles can be collected and fed into the system provided the actuators are selected according to the highest torque requirement of these gait cycles. Electromyographic sensors can be used to sense the intention of the wearer and implement a gait cycle accordingly Also, gears used in the gearboxes are spur gears which produce backlash. Hence, use of helical gears is proposed for future prototypes. The capacity of the power source can be increased for longer test runs. Alternate renewable sources of power supply may also be implemented.

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