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Energy Efficient Autonomous Lower Limb Exoskeleton for Human Motion Enhancement

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***Abstract*—**The paper describes conceptual design, control strategies, and partial simulation for a new fully autonomous lower limb wearable exoskeleton system for human motion enhancement that can support its weight and increase strength and endurance. Various problems still remain to be solved where the most important is the creation of a power and cost efficient system that will allow an exoskeleton to operate for extended period without batteries being frequently recharged. The designed exoskeleton is enabling to decouple the weight/mass carrying function of the system from the forward motion function which reduces the power and size of propulsion motors and thus the overall weight, cost of the system. The decoupling takes place by blocking the motion at knee joint by placing passive air cylinder across the joint. The cylinder is actuated when the knee angle has reached the minimum allowed value to bend. The value of the minimum bending angle depends on usual walk style of the subject. The mechanism of the exoskeleton features a seat to rest the subject's body weight at the moment of blocking the knee joint motion. The mechanical structure of each leg has six degrees of freedom: four at the hip, one at the knee, and one at the ankle. Exoskeleton legs are attached to subject legs by using flexible cuffs. The operation of all actuators depends on the amount of pressure felt by the feet pressure sensors and knee angle sensor. The sensor readings depend on actual posture of the subject and can be classified in three distinct cases: subject stands on one leg, subject stands still on both legs and subject stands on both legs but transit its weight from one leg to other. This exoskeleton is power efficient because electrical motors are smaller in size and did not participate in supporting the weight like in all other existing exoskeleton designs.

***Keywords*—**Energy efficient system, exoskeleton, motion enhancement, robotics.

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I. INTRODUCTION

EXOSKELETON for human performance enhancement are wearable devices that can support and assist the user besides increasing their strength and endurance. The lower limb exoskeletons are now applied to several fields, including power augmentation for the military [1] or medical assistance [2], and rehabilitation [3]-[5]. In such devices, human provides control signals while the exoskeleton actuators provide required power for performing the task. A distinctive characteristic of exoskeletons compared to other robotic interfaces with haptic feedback is their close physical and cognitive coupling between the robot and the user [6]. In such design, the physical human-robot interfaces were developed, i.e. the mechanical and sensory components that mediate the transfer of physical interaction between the user and the exoskeleton [7].

On lower extremity exoskeletons, most previous researchers paid their attention in developing walking aid systems for gait disorder persons or aged people [8], [9]. One of those systems is the HAL (Hybrid Assistive Leg) developed by Yoshiyuki Sankai of University of Tsukuba and it was aimed at assisting human leg muscles during walking [10]. The system was based on electromyography (EMG) sensing of human muscles as the primary drive signals. The development resulted in several versions of HAL with the latest HAL-5 in 2009 [11]. The exoskeleton was motor powered on the hip and knee joints, leaving other joints free. The significance of their design is the implementation of EMG sensing which detects the muscle activities before actual limb movement. Motor driven joints approach was taken by other researches as well [12]. The developed Berkeley Lower Extremity Exoskeleton (BLEEX) was aimed at enhancing human strength and endurance for payload transport [13], [14]. The exoskeleton incorporates hydraulic actuation on all three sagittal joints and two coronal joints on the hip with all others joints free. The overall control design of BLEEX was to minimize interface between human and machine. Therefore, there was no sensor in direct measurement of human leg but includes all required sensors for determining the dynamics of the exoskeleton. The control system monitors the dynamics of the exoskeleton to determine operator's intention of motion. The significance of BLEEX is of the complex control network distributed throughout the exoskeleton and a custom designed onboard engine to power the hydraulic actuation system. Hydraulic actuation was implemented by various researchers. The ECUST Leg Exoskeleton Robot (ELEBOT) designed at East China University of Science and Technology (ECUST) shares the similar design goal as BLEEX but with a simplified system [15]. ELEBOT has the same approach of using hydraulic system as joint actuation. However, it was identified that only the knee joints would require substantial actuation support and therefore leaving all other joints free. The control of ELEBOT also came close to that of BLEEX by only monitoring stance phase and torque generated on the hydraulic actuators.

While the above exoskeleton designs require substantial power for operation on low efficiency, an exoskeleton design at Massachusetts Institute of Technology (MIT) attempted to lower the power requirement for load carrying [16]. The exoskeleton has only series elastic actuation at hip sagittal joints, variable damper at the knee joints and spring at ankle sagittal joints. The control is based on a state machine and

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monitors forces and orientation of the exoskeleton to determine the states. The Walking Assist Device designed at Honda Research and Development aims at increasing the lower extremity endurance of the elderly and those with weak legs [17]. By partially supporting the upper body weight, the user bears less weight on the lower limbs and requires less energy for motion. The device was a pair of non-anthropomorphic mechanical limbs attached to a seat. The whole device was fixed between the user's legs during operation. The walking assist device was only powered by electric motor at each of the knee joints and incorporates only pressure sensors beneath the shoes of the device. The control monitors the user's weight applied on the pressure sensors and provides the required force on both knees to achieve the predetermined weight reduction on both of the user's legs.

The present paper introduces a conceptual design and partial simulation of a new exoskeleton that will enable to decouple the weight/mass carrying function of the system from the forward motion control which will reduce the power and size of propulsion motors and thus reduce the overall weight, cost and required electrical power for the system. Such lighter and cheaper devices are currently important engineering research area in medicine and military [18].

II. MECHANICAL STRUCTURE OF THE EXOSKELETON

Fig. 1 shows the conceptual sketch of the proposed exoskeleton structure in SolidWorks. In these figures, seat 1 is there to the rest subject's body and support its weight. Each exoskeleton leg has four degrees of freedom: two at the hip 2, one at the knee 3 and one at the ankle 4 to allow legs forward and lateral motions. Cushioned seat 1 in between subject crotch is connected to two parallel rigid pipes 5 at the back the object. A back panel 6 mounted onto the rigid pipes serves as a platform for control and power supply mounting. At hip level, the two parallel rigid pipes extend out to the two hip coronal joints. The link then continues to both sides of the hip 2 where sagittal and transverse joints are located, subsequently to the knee joints 3 and through the ankle joints 4 to the ground. Both exoskeleton legs are attached to subject legs using flexible cuffs 7. Single degree four-bar linkage mechanism 8 with rotary joints at the hip level provides hip-centered lateral rotation of the exoskeleton leg around vertical axis. The remaining three single-degree parallel axes rotary joints at the hip 2, knee 3, and ankle 4 provide freedom of flexion at the joints. Pneumatic cylinders 9 are used to block the motion at the knee joints 3 when necessary to support the weight.

Fig. 2 shows schematic diagrams of the exoskeleton. In these figures, 1 are adjustable telescopic members of the exoskeleton; 2 are dummy pneumatic cylinders that are able to inhibit the motion at the knee joints; 3 and 4 are the sensors to detect motion of subject thigh and shank; 5 are springs to support feet 6 of the exoskeleton; 7 and 8 are flexible belts to fasten exoskeleton to the subject thigh and shank. In the figures, M_1 and M_2 are motors driving the hip and knee joints of each leg; C_1 and C_2 are solenoid valves of the pneumatic cylinders 2 that are able to inhibit motions at the knee joints; S_1 and S_2 are flexible strips 3 and 4 with bonded strain gages that are able to sense the tiny motions of subject limbs; F_1 and F_2 are foot pressure sensors to sense the amount of pressure applied by the ground on the exoskeleton sole 6 during the walk. The pressure at the exoskeleton sole is generated due to the transmission of the weight forces via mechanical structure to the ground while the subject is resting on the seat.

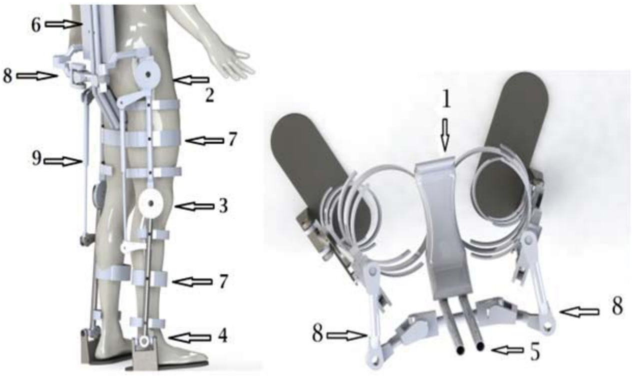

Fig. 1 Components of the exoskeleton

III. HUMAN-MACHINE INTERFACING AND CONTROL

The operation of all actuators, i.e. hip joint motors M_1, knee joint motors M_2 the knee motion inhibiting cylinders' solenoid valves C_1 and C_2, depends on the amount of pressure felt by the feet pressure sensors F_1 and F_2 (Fig. 2). The pressure on the feet depends on actual posture of the subject and can be classified in three distinct cases. If (case 1, Fig. 3 (b)) the subject is standing on one leg and the knee motion is inhibited, then the total subject body weight P_b is resting on the seat 1 (Fig. 1) and the weight is fully transmitted via stationary leg structure to the ground. The expected pressure reading from the corresponding foot sensors F (Fig. 4) will be at its maximum possible value $P=P_b$. However, the reading from other foot pressure sensor will be at zero value because it is not in touch with the ground. If (case 2, Fig. 3 (a)) the subject stands still on both legs, then the total subject body weight is almost equally shared by both leg structures and the expected pressure reading from both feet sensors will be about half of the maximum possible value $P=P_b/2$. If (case 3, Figs. 3 (c), (d)) the subject is in the stage of transiting the weight from, e.g. leg 1 to leg 2 while standing on both legs, then the reading from sensor F_1 will gradually reduce from its half value $P_b/2$ to zero while the reading from sensor F_2 will gradually increase from its half value $P_b/2$ to its maximum possible value P_b. The pressure reading P at the shoe-ground sensor F is due to both object's and exoskeleton's weights.

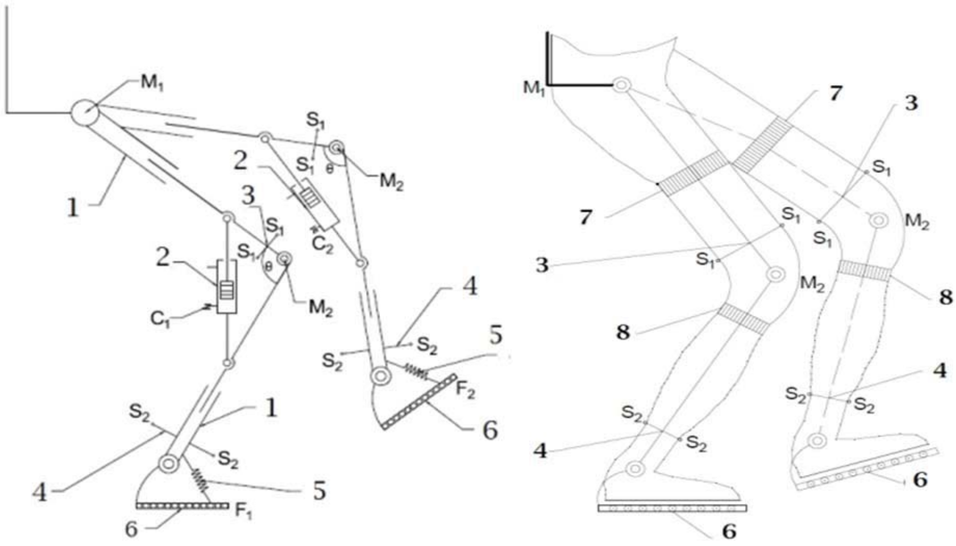

Fig. 2 Schematic drawing of the exoskeleton

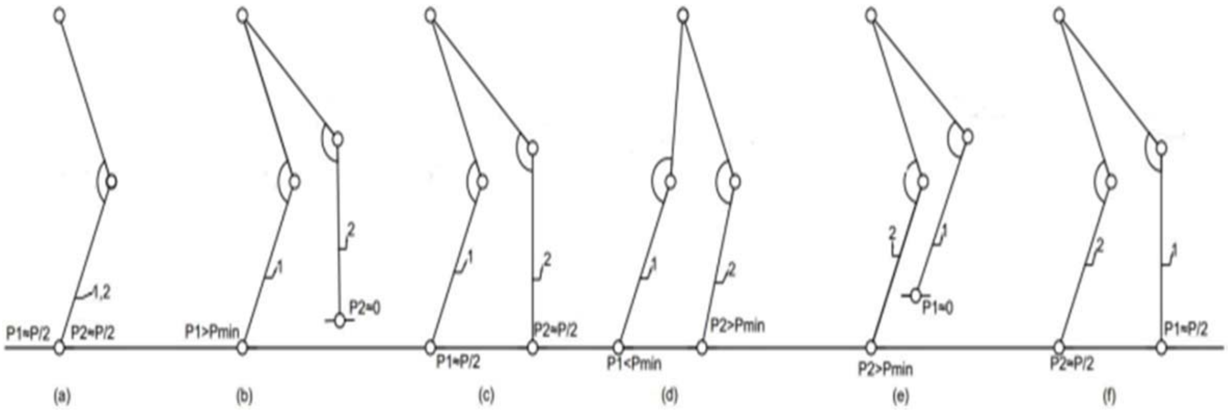

Fig. 3 Gaits of the exoskeleton

Several rules have been established to control the operation of the actuators during the subject walk. The first rule establishes a condition when the knee joint motion has to be inhibited, i.e. should be blocked by cylinder. Simultaneously, the hip and knee motors M_1 and M_2 have to be deactivated. At this condition the object puts its one foot on the ground and prepares to move the body in forward direction (leg 2 in Fig. 3 (c)). It is exactly the case when the exoskeleton is ready to carry the weight with no assistance from the leg muscles and the deactivated motors. The signal to initiate this action comes from the respective foot sensor; i.e., when the reading from the sensor is $P>0$ and it is growing. The cylinder is actuated and the motors deactivates when the contact with the ground is confirmed. This condition implies a stilt type of walk when the object's weight rests on the "rigid" leg while the object takes a step forward with another leg.

The second rule establishes a condition when the knee motion is unblocked; i.e., cylinder is deactivated and respective hip and knee motors M_1 and M_2 have to be reactivated instead. Obviously, it is the case when the reading of pressure sensors $P=0$, i.e. the foot is not in touch with the ground. Alternatively, if the foot is in touch with the ground it depends on gradually decreasing pressure signal from the foot sensors and the minimum allowed pressure value P_{min} that should initiate this action. At this condition the exoskeleton leg mechanism is ready to follow the intended motion of the object leg and to take a new step without hindering the leg motion (leg 1 in Fig. 3 (d)). Motors M_1, M_2 and flexible sensors S_1 and S_2 are used to execute this action (Fig. 2).

Based on the rules discussed above, the following control strategy for the walk is proposed:

- Motors M_1 and M_2 of each leg are actuated only and only if the pressure reading from the corresponding pressure sensors at the foot either zero or keeps decreasing until $P \leq P_{min}$ (second rule) in order to pick up the leg from the ground and take a step
- Cylinders solenoid valves C_1 and C_2 are actuated only and only if the pressure reading from the corresponding pressure sensors at the foot become be $P>0$ and keeps increasing (i.e. confirm the ground touch, first rule).

The control strategy for the motors M_1 and M_2 is aimed to make sure that the exoskeleton structure will follow the subject's leg physical motion without hindering it. The set of sensors S_1 and S_2 (flexible strips with bonded strain gages) are

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attached to the links of the exoskeleton (Fig. 2). When the subject limbs commence the motion the limbs will touch and bend the strips. The sensors will detect in real time any intended tiny motions of the subject's limbs and send the signals to the PID controller. The controller will react immediately by activating hip and knee motors M_1 and M_2 in order to move the links of the exoskeleton away from the object limbs and thus to restore the original shape of the strips. The set point of the PID controller is zero signals from the sensors. The PID controller can provide fast system response and accurate positioning of the exoskeleton links with respect to subject's limps. As a result, object limp can move free with no obstruction from the exoskeleton.

The system operational or logic flow chart is shown in Fig. 4. If the common switch is on, then the system starts receiving data from pressure F sensors (Fig. 2). If $P > 0$ that means that the foot is in contact with the ground. If the value of P is growing that means the subject is stepping of that foot and the motors have to be deactivated and the cylinder has to be activated. This is weight supporting condition for the exoskeleton. If instead P is decreasing that means the subject is transmitting the weight from this leg to another one and if $P \geq P_{\min}$ then motors should be kept deactivated and the cylinder is activated to support the weight. If $P \leq P_{min}$ that means the limit is reached and the subject is ready to move this leg one step forward. Therefore, the cylinder valve is deactivated to allow the motion of the exoskeleton components. In this condition the reading of strain gages S_1, S_1', and S_2, S_2' and operation of both motors M_1 and M_2 are initiated. By comparing the reading from the pair of sensors S_1, S_1', and S_2, S_2' the sense of motors rotation can be established. For example, if the reading $S_1 > S_1'$ the rotation of M_1 can be set in clockwise direction. Conversely, if $S_1 < S_1'$ then the rotation of M1 can be set in counterclockwise direction. Same is true for the data received from sensors S_2, S_2' that control the sense of rotation of motor M_2. The speed of motor rotation is controlled by the motor driver and PWM signal received from the microcontroller. PWM is selected to be proportional to the absolute difference between the readings of the pair of sensors, i.e. $| S_1 - S_1' ||S_2 - S_2'|$. It is very effective way of monitoring the speed of the motor response to the object intention to move a limb. The higher is the pressure applied by the user to the strip the higher is the acceleration of the motor to restore the shape of the strip with attached strain gages. It is in a way an implementation of proportional control strategy for the motor speed control. The microcontroller operates in loop continuously checking the status of all sensors, making decision and actuating either cylinder valves or the motors as long as the common switch is on (Fig. 4).

IV. COMPUTER SIMULATION OF HUMAN-MACHINE INTERFACE WITH MATLAB\SIMULINK

The main control system for the exoskeleton is divided into four subsystems where each subsystem is responsible for the sensing and actuation of each joint. For simulation purpose, the subject movement is taken from the recorded data of typical human lower limb movement during walking. Fig. 5 shows the top layer of the program that controls the overall logic of the exoskeleton motion.

The "Subject Movement" block provides the data to simulate the subject movement input to the individual joint controller which runs a closed-loop control algorithm to control the movement of its actuator

Figs. 6 and 7 show the second layer of the simulation program for hip and knee joint respectively where the closed-loop controller is implemented. The controller setup is identical for both hip and knee joint except for the addition of inhibition logic for knee joint. The controller consists of a "PID" block, "DC Motor" block, "Load Torque" block and "Sensor" block. The "PID" block calculates the desired output to be applied to the actuator, "DC Motor" block simulates the response of the DC motor towards the voltage applied, "Load Torque" block calculates the static and dynamic loads acting on the joint actuator and "Sensor" block simulate the electrical signal given by the sensing system in response to the subject movement. The DC motor model is constructed based on classical DC motor equivalent circuit as well as on the closed loop simulation technique based on the motor torque-current and speed-voltage relations. The load for the joints are constructed and calculated based on the dynamic model derived based on classical Lagrangian mechanics [19]. To simplify the code management, each torque component is grouped into a separate function block.

Fig. 8 shows the detail of the "Sensor" block. The "Cantilever Beam" block is constructed from the mathematical model of strain gauges' responses to the deflection of cantilever beam that is to which it is bonded. The thigh or shank movement of the human object will result in the displacement of the deformable material (beams) which will further result in the deformation of the strain gauges. Foil type strain gauge can be attached to the deformable materials such as Low Density Polyethylene (LDPE) sheet to achieve the measurement with maximum sensitivity. The block receives the input from the movement of the thigh or shank which will create the deflection of the cantilever beam. Depending on the beams length and thickness, materials properties of the material and the position of strain gauge on the cantilever beam, the amount of strain of each gauge can be calculated as a result of this deflection. Once the strain is calculated it can be converted to output voltage by means of Wheatstone bridge circuit. In order to follow closely the subjects leg motion, the output voltage from Wheatstone bridge is then compared to the zero voltage reference to generate the error for the PID controller. The PID controller then instantly applies the output to the joint DC motor to actuate and drive the exoskeleton link in order to follow the subject movement with accuracy and fast response.

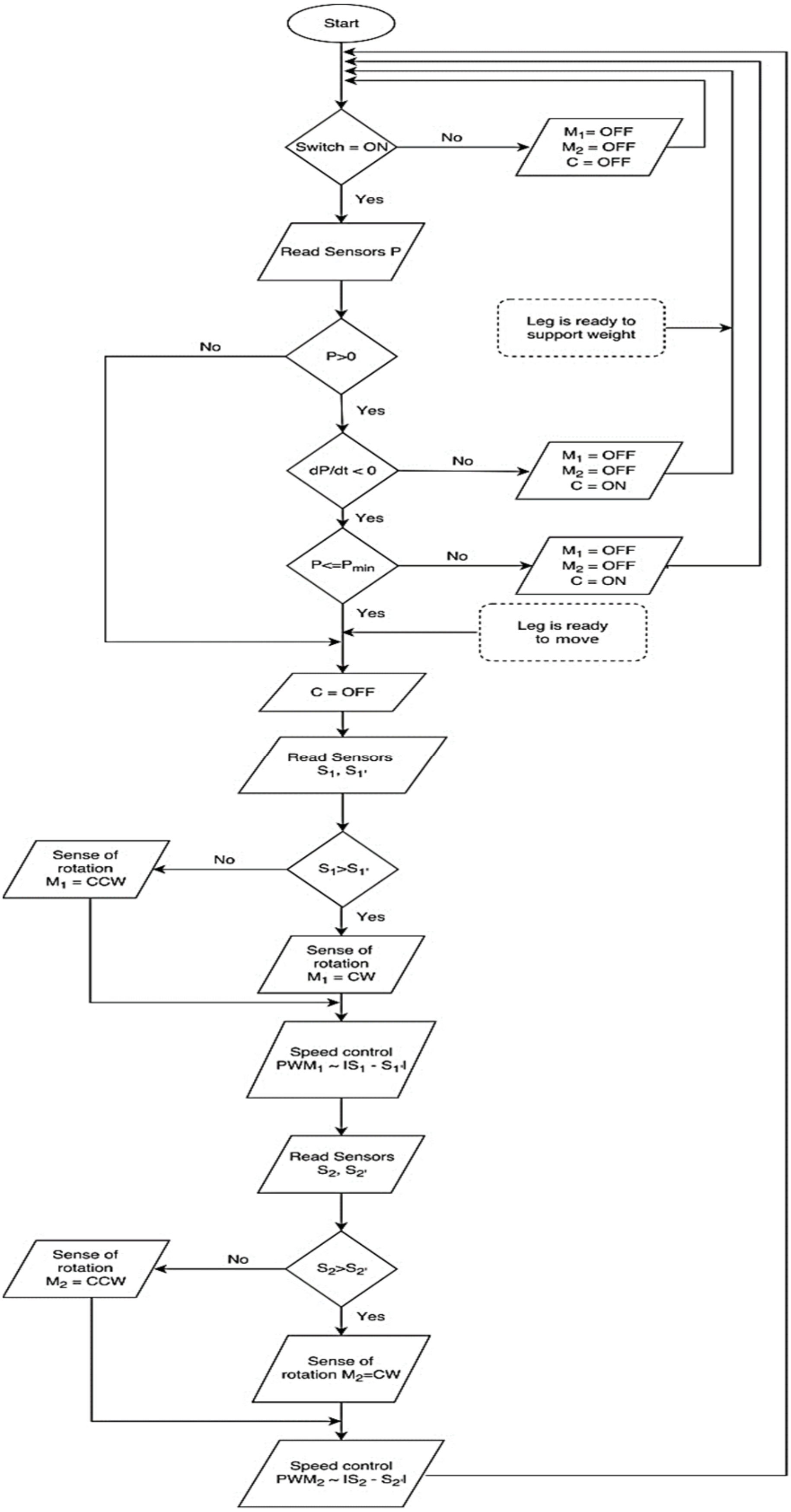

Fig. 4 Flow chart of controller operation

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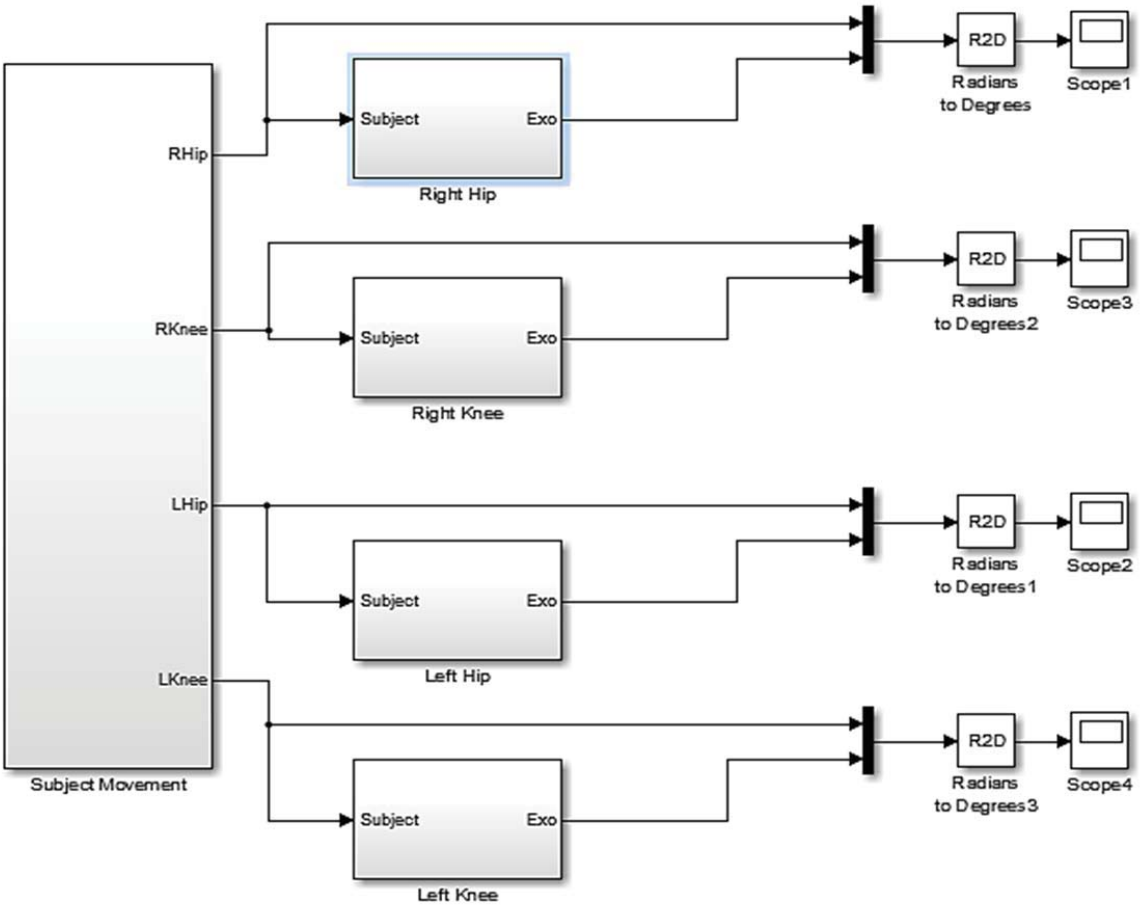

Fig. 5 Top layer of exoskeleton simulation program

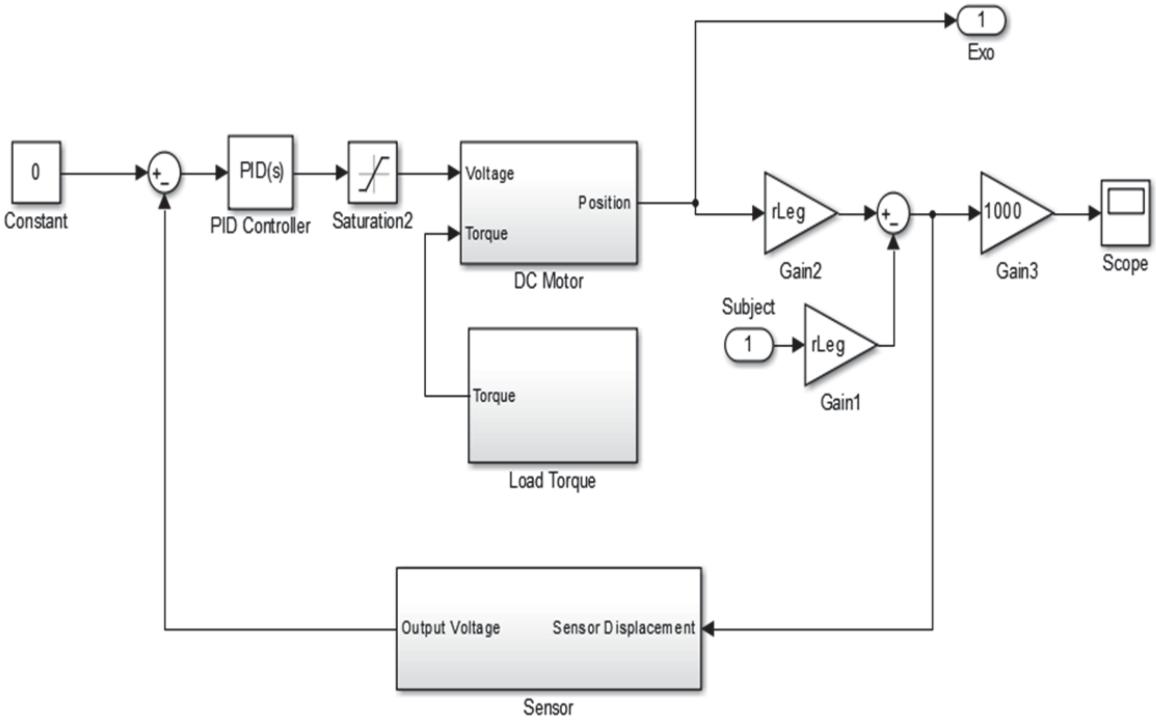

Fig. 6 Closed-loop controller for hip joint

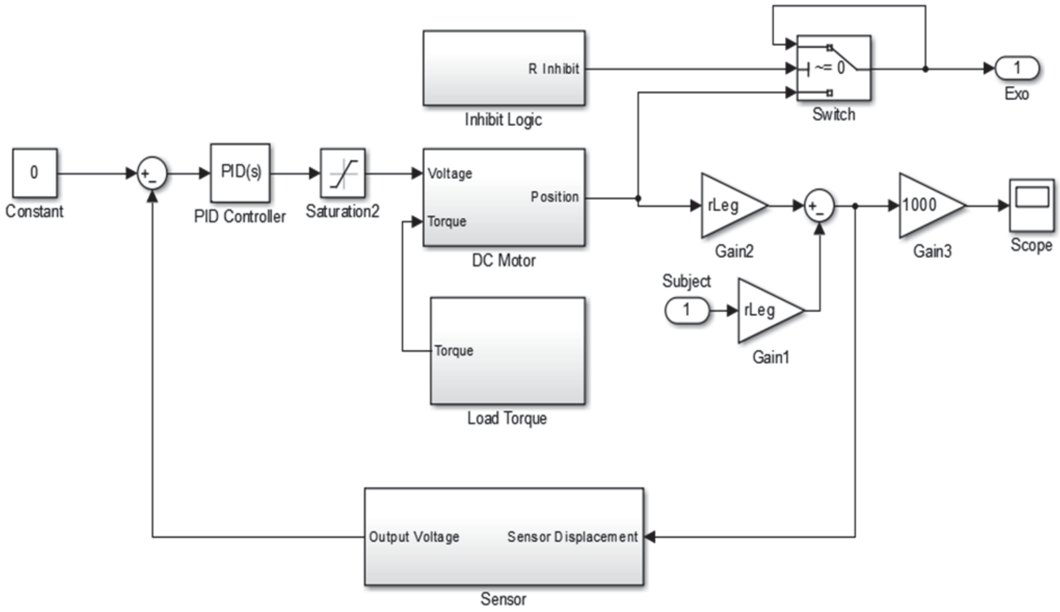

Fig. 7 Closed-loop controller for knee joint

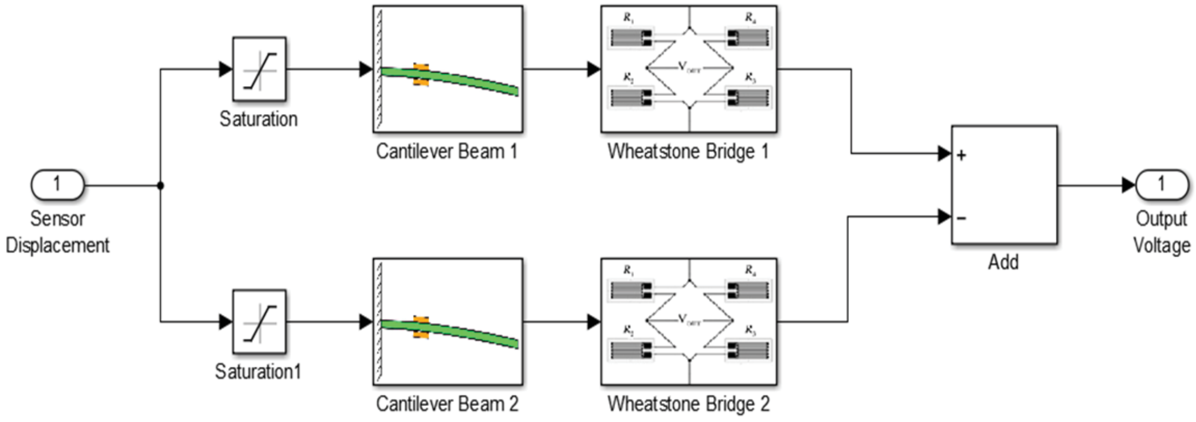

Fig. 8 Simulink model of the sensing subsystem

The parameters used in the simulation work are shown in Table I.

TABLE I
SIMULATION PARAMETERS

Symbol	Quantity	Value
	Mechanical Parameters	
r_{leg}	Length of leg (thigh and shank)	0.4 m
m_{thigh}	Mass of thigh	4 kg
m_{shank}	Mass of shank	3 kg
m_{knee}	Mass of knee	1 kg
m_{ankle}	Mass of ankle	0.5 kg
	Motor Parameters (Maxon DCX32L 24V)	
K_t	Torque constant	27.3 mNm/A
R	Terminal resistance	0.331 Ω
L	Terminal inductance	0.103 mH
J	Rotor inertia	72.8 gcm^2
b	Viscous friction	5.17x10^{-3} mNm/rad/s
	Sensor Parameters	
h	Thickness of cantilever beam	5 mm
x	Strain gauge distance	35 mm
l	Length of cantilever beam	70 mm
G	Gauge factor	31

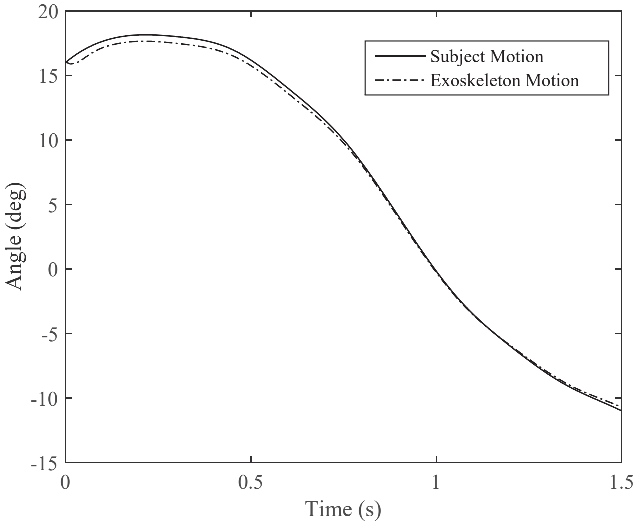

Fig. 9 Hip joint angle during leg swinging motion

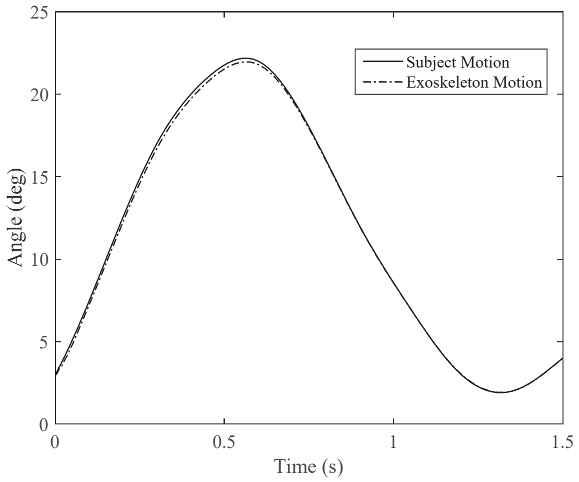

Fig. 10 Knee joint angle during leg swinging motion

V. CONCLUSION

The paper describes the methodology of mechanical design and effective control of a new exoskeleton system to enhance walk capabilities of people. It also can be used for rehabilitation of people with leg injuries. The core idea is to use exoskeleton to decouple weight carrying capabilities of the legs from its body advancing capabilities. This has been done by special logic and intelligent management of electrical motors and motion inhibiting passive pneumatic cylinders operation. The operation is managed and controlled by the microcontroller which receives the necessary data from the strain gauge sensors located at the subject's thighs and shanks and the pressure sensors located at the feet. The paper also demonstrates the MATLAB\Simulink modelling of the exoskeleton leg dynamic behavior that proves fast and precise response to the human motion intentions. This approach in exoskeleton design enables the user to focus on just forward motion that takes much less muscle tension and leave to the exoskeleton to carry the heavy body weight. This makes the exoskeleton more power efficient because electrical motors are smaller in size and did not participate in supporting the weight like in all other existing exoskeleton designs. The motors just provide a synchronous fast motion of the exoskeleton leg in response to human intention to take a step.

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