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Mechanical Design of the Hanyang Exoskeleton Assistive Robot(HEXAR)

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Abstract: This study developed a lower extremity exoskeleton system to enhance lower body strength. In this paper, selected the degrees of freedom (DOF) which actuated based on analyzed human motion, and analyzed the human joint function to design the joint modules of the exoskeletal robot. To improve the efficiency of the exoskeleton robot, a mechanical structure was designed on the basis of a semi-anthropomorphic architecture. The Hanyang EXskeleton Assistive Robot (HEXAR) has seven degrees of freedom per leg, two of which are powered by an electrical motor. Appropriately sized motors and gearing are selected, and put through a thorough power analysis. quasi-passive mechanisms were designed with compliance material for supporting the weight of external loads in the stance phase and absorbing/releasing the energy. This paper discusses design criteria considered in mechanical design for HEXAR.

Keywords: Exoskeleton, biomechanics, mechanical design, mechanism, electric motor.

1. INTRODUCTION

An exoskeleton robot system is a mechanical structure that is attached to the exterior of a human body to improve the muscular power of the wearer. Exoskeleton robots have been actively studied in the US, Japan, and Europe since the 1990s, and research is currently being conducted to identify their application in various industries, including military, medicine, and rehabilitation. Lower extremity exoskeleton robots can be categorized by muscle strength support as power assistance and power augmentation systems. Power assistance systems are exoskeleton robots that directly assist the power exerted by the human body, thereby giving the wearer greater strength [1]. EKSO and HAL exoskeleton robots are being developed mainly to assist persons who are aged, feeble, or disabled in their daily lives [2][3], whereas power augmentation systems are used to amplify the power of wearers, enabling them to perform tasks that they otherwise could not easily perform by themselves. The University of California at Berkeley has also been developing an exoskeleton system, referred to as the Berkeley Lower Extremity Exoskeleton (BLEEX). In addition, Lockheed Martin and SARCOS have developed the HULC and XOS, which are being designed for DARPA with the aim to offload the weight carried by soldiers onto the exoskeleton. These systems are driven by hydraulic actuators [4][5]. An exoskeleton called the Hanyang EXoskeleton Assistive Robot (HEXAR)–4 was developed in South Korea for industrial use. HEXAR-4 has two electric motors and operates through the muscle circumference sensor (MCRS) that is attached to the operators [6].

In this study we developed a lower exoskeleton system to carry a heavy load. To this end, we selected the degrees of freedom (DOF) which actuated based on analyzed human motion, and analyzed the human joint function to design the joint modules of the exoskeletal robot. We designed a exoskeleton robot through a semi-anthropomorphic architecture, and could bear the load on the ground to effectively. This paper focuses on the setup of the mechanical structure and design of HEXAR through the functions of each joint.

2. HUMAN BIOMECHANICS FOR A MECHANICAL SYSTEM

2.1 Background

Design requirements of exoskeletons can be determined by analyzing human motion since they are designed to perform similar tasks with the human body. In the application of human biomechanical data to design an exoskeleton robot, several assumptions are made:

- The size, mass, and inertial properties of the exoskeleton will be equivalent to a human
- The exoskeletons gait will be the same as a humans gait
- The exoskeleton will carry itself and the payloads.

The biomechanical data are used to determine the angles, torques, and power for the ankles, knees, and hips. These estimates can then be used to help in the design of joints and in the selection of actuators for the exoskeleton and to determine the total mean and peak power needed by the exoskeletal device. By estimating mean and peak power requirements, the power supply for the exoskeleton can be sized.

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A gait cycle is the period of time for one stride, that is, the time from one event (usually initial foot contact) to the next occurrence of the same event with the same foot. Fig. 1 shows the level ground walking condition. The locomotion on a level ground, under normal walking conditions, is simply distributed in the following stages: initial-contact (IC) period - heel strike to forefoot loading; midstance period (MS) - forefoot loading to heel strike; and weight propulsion (WP) period - heel raise to toe-off. From another point of view, stair ambulation (ascent/descent) has more details with regard to the normal walking conditions. Fig. 2 shows the stair walking condition. The stance phase of stair ascent is partitioned into three sequences: weight acceptance (WA), pull-up (PU), and forward continuance (FCN). Especially, the patterns for normal stair climbing show the dominant role of the knee during WA and PU, with supporting roles played by the hip and ankle. During FCN, the ankle plays the major role, with relatively little contribution from the knee and hip [7][8][9].

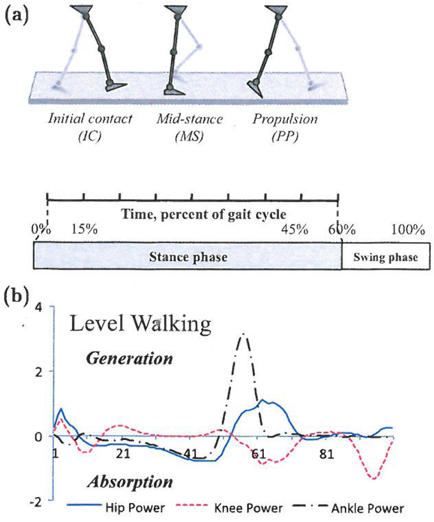


Fig. 1: (a) Phase of level ground walking, Stance phase is about 60% with respect to the gait cycle, and the swing phase is 40%. (b) Joint power during level walking, the sagittal plane axes move the legs in the direction the person is walking, they logically require the most power.

The description of anatomical human motion commonly used in medicine explains the movement between the bones and the range of motion of each joint in the three planes of the body, called anatomical planes. The anatomical planes that define the perpendicular axes around which rotation occurs are frontal, transversal, and sagittal planes. The three main joints are the hip, knee, and ankle, which respectively join the pelvis to the upper leg, the latter to the lower leg, and the lower leg to the foot. This common model places three axes of rotation at each joint, thus the model has a total of nine degrees of freedom per leg [10].

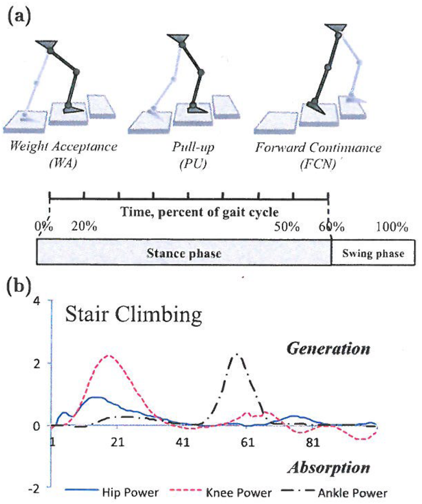


Fig. 2: (a) Phase of stair walking, stair climbing show the dominant role of the knee. (b) Joint power during stair walking, power generation of knee joint is greater than level walking.

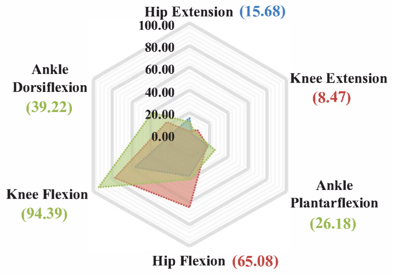
2.2 Gait Analysis

Gait analysis angle data are typically collected via human video motion capture. Torque and power data are calculated by estimating limb mass and inertia and applying dynamic equations to the motion data. In this study, gait analysis data from a 178-cm, 80-kg person were used to analyze the angle, torque, and power that, for developing HEXAR, are required for walking on level ground and stairs.

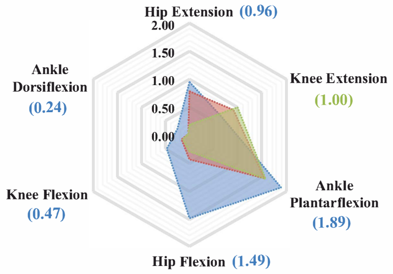
To determine the necessary joints to actuate, the power applied by a human for each axis was examined. As the vast majority of gait work is done in the sagittal plane, the ability to move in the coronal and transverse planes during human gaits would be overshadowed by the sagittal-plane function. It is reasonable that the considerations based solely on kinematics and kinetics in the sagittal plane should capture the dominant characteristics of the hip, knee, and ankle joints functions during the stance phase [12]. Therefore, the design of the exoskeleton focused on the analysis of data of the sagittal plane.

Joint moment and power were normalized to body weight, BW. For the purpose of the exoskeleton design, peak values were analyzed for the angle, moment, and power, which represented the hip, knee, and ankle joint, respectively, see Fig. 3. The difference between the positive power, i.e., power-absorbing energy, and negative power, i.e., constantly dissipating energy, was analyzed. Thus, the functional properties of each joint can be set through the power analysis. In order to walk forward, the greatest positive power occurs at the ankle joint when the stance switches to the swing phase at 60% of the step cycle. The ankle absorbs energy during the first half of the stance phase and releases energy just before toe-off. The most notable difference between normal walking and stair ascent is the role reversal of the knee joint from power absorber to power generator. For stair descent, power absorption of the knee joint is about 2.3 times higher than in level walking.

(a) Joint Angle (unit: °)



(b) Joint Moment (unit: Nm/BW)



(c) Joint Power (unit: W/BW)

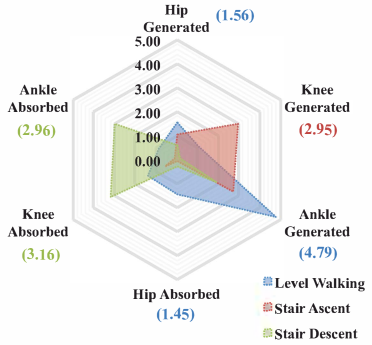


Fig. 3: (a) Peak values of joint angle. (b) Peak values of joint moment. (c) Peak values of joint power. Gait analysis data from a 178-cm, 80-kg person with 30-kg payloads on back.

3. HARDWARE DESIGN CRITERIA

3.1 Structure for an Exoskeleton Robot

This research focused on the load carrier that performs the anti-weight function of the load while walking on a level surface or climbing steps. When the exoskeleton is operated at ground level, the leg in the stance phase is only required to support load bearing along the z-axis direction, which is perpendicular to the ground. During the transition from the heel strike to the stance phase, an energy-conservative ankle joint can simultaneously perform load-bearing functions against the weight of the total system and the gait propulsion function.HEXAR has hip, knee, and ankle joints like humans, but they differ from those of humans. HEXAR has seven degrees of freedom per leg and one degree of freedom in the waist joint. There are many possible architectures that can be used for a lower extremity exoskeleton design. Exoskeleton robot mechanism structures can be classified as anthropomorphic, which is designed so that the rotation axis of the robot joint is in alignment with the rotation axis of the human joint; semi-anthropomorphic, which has a robot joint functionally similar to the human joint; and non-anthropomorphic, in which the robot joint is in misalignment with the human joint [1]. To increase the efficiency of the designs characteristics and operability, semi-anthropomorphic architecture was selected.

Before designing a joint or actuator, information on the desired range of motion for each joint is needed. To avoid potentially harming the operator, the range of motion for the exoskeleton joint should be limited to less than that of human flexibility. Thus, gait analysis angle data, as described in the previous section, provide a minimum bound, and data on human factors yield the maximum limit.

We developed an under-actuated exoskeleton robot system consisting of seven degrees of freedom per leg. Based on the gait power analysis in the previous section, only the hip and knee extension/flexion joints were initially actuated on HEXAR. Ankle dorsiflexion/plantarflexion absorbs energy during the first half of the stance phase and releases energy just before toe-off. To satisfy this function, quasi-passive mechanisms were designed with compliance material for supporting the weight of external loads in the stance phase and absorbing/releasing the energy. The remaining joints were selected to be passive with mechanical limitations because ROM, moment, and power were low.

3.2 Actuator Selection

In order to select and size the actuator, several assumptions were made. The first assumption was that the size, mass, and inertial properties of the exoskeleton were equivalent to those of a human. The second was that human and exoskeleton joints move with the same axis. The third was that the total weight of the exoskeleton was 21-kg and the maximum external loads permitted were 35-kg.

BLDC motor's specifications can be selected by the current and torque characteristics. The motor produces the following torque, which is proportional to the motor current i, such that $T = k_t i$, where k_t is the motor torque constant. For the steady-state torque-speed relationship, the voltages around the loop are summed and rearranged for by the following Eq. (1):

$$i = \frac{V - v_b}{R} = \frac{V - k_v \omega}{R} \tag{1}$$

where v_b is the motors back-EMF in the armature, V is the voltage applied to the motor, k_v is the back-EMF constant, R is the motors resistance, and ω is the angular velocity. Substitute this value of into the following equation for the maximum theoretical torque:

$$T_{max} = \frac{k_t}{R} \left(V_{max} - k_v \omega \right) \tag{2}$$

Therefore, the required torque must be less than T_{max} from the motor winding. The final limit of the motors capabilities is the current limit, I_p. I_p is based on the maximum current density in the winding and is available for a maximum duration of 10 seconds. If the lowest of these is I_p, the maximum torque T_p, the winding can be produced the torque at any motor speed and is calculated by

$$T_p = k_t I_p \tag{3}$$

The required joint torque T_{req} and speed ω_{req} are the gait analysis data discussed in the previous section. The selected motors are pancake shaped, and a component-type harmonic drive was selected in order to minimize joint modules weight and width. With a harmonic drive gear ratio N, the required motor torque T and ω are calculated by Eqs. (4∼5)

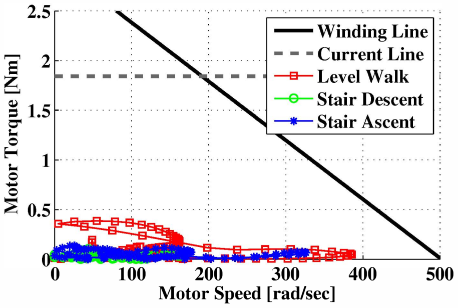
$$T = \frac{T_{req}}{N} \tag{4}$$

$$\omega = \omega_{req} N \tag{5}$$

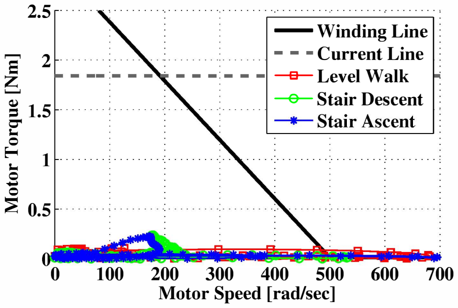
It can be seen from Fig. 4 that the required motor torque-speed characteristics for HEXARs joints were calculated and plotted for various walking environments. Stair ascent and descent with the required torque curve was lower than the current and winding line torque. However, the required torque-velocity curve for level walking for the knee joint exceeded the short-term operation limit of the actuator with the transition from extension to flexion. In order to satisfy the required torque, only upgrading the motor should be needed. However, this research did not consider this aspect because of the short timeframe available for actuating the motion. The parameters of the electrical motors selected to power the flexion joints to HEXAR are shown in Table 1.

4. HARDWARE DESIGN OF THE HEXAR

Fig. 5 shows the HEXAR exoskeleton assisting the muscular strength of the lower extremities by arranging the joint mechanism and joint functions. HEXAR consists of a torso harness that connects the waist joint, hip joint, knee joint, and ankle joint modules, which combine the quasi-passive and active mechanisms. The active mechanism is provided to the hip and knee joints for extension/flexion movements; the ankle and other side-joint modules use a quasi-passive mechanism.



(a) The hip joint motor



(b) The knee joint motor

Fig. 4: The required motor torque for the hip as calculated from the gait analysis data for walking.

Table 1: Electric motor selected for HEXAR

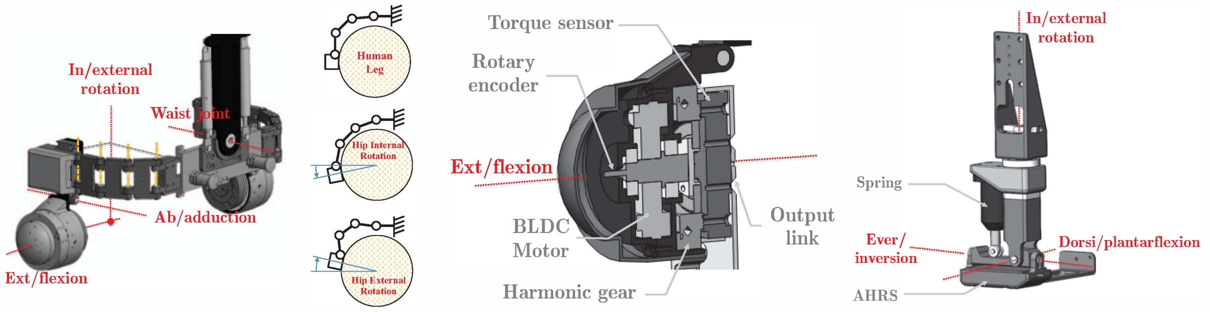
Index	Value	Unit
Motor torque constant, k_t	0.061	Nm/Amp
Back-EMF constant, v_b	6.39	$V/KRPM$
Motor resistance, R	0.615	Ω
Current limit, I_p	30.2	Amp
Transmission ratio, N	100	-
Efficiency	90	$\%$

4.1 Torso Harness Module

The torso harness module links the exoskeleton to the wearer through a shoulder strap and belt. The battery, main controller, and payload holder mount to the rear side of backbone frame. A force-torque sensor mounted between harness and frame to measure the human-robot interaction force for control algorithm. An attitude heading reference system (AHRS) attached to measure the orientation of the upper body with respect to gravity. The torso harness module is connected to the hip joint module through the backbone, which consists of the constant force mechanism at the waist joint, and the waist joint module bears the total weight of the upper mechanism through the constant force mechanism.

4.2 Hip Module

The hip joint module consists of a sliding part to adjust the link length and three degrees of freedom joints, which include two passive and one active joint mecha-



(a) Hip module (b) Knee module (c) Ankle module

Fig. 6: Rotational joint axis and components for each joint modules.

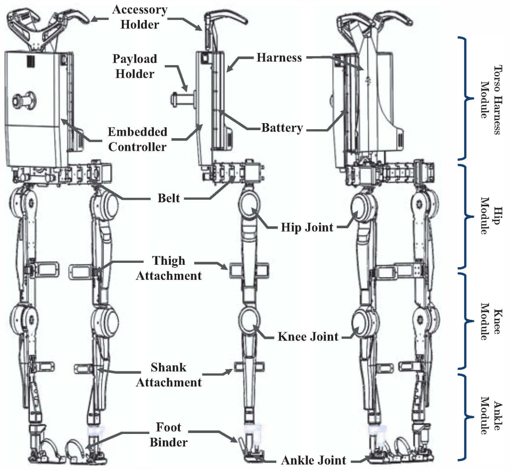


Fig. 5: HEXAR model with major components.

nisms as shown in Fig. 6a. One of the passive joints has a single axis for abduction/adduction joint motion, and the other one is configured in a series chain to rotate in a similar axis to the internal/external rotation. The series chain structure consists of four hinge joints that have the same axis for the internal/external rotation joint in both the human and robot. Because of that structure, it is possible to bear the external loads with operate the internal/external rotation. The hip joint module is then combined with the actuated knee joint module

4.3 Knee Module

Knee and hip flexion joint module is comprised of an active mechanism that uses an electrical BLDC motor, which can produce extension/flexion motions in the sagittal plane and in a harmonic drive combination as shown in Fig. 6b. The motors are pancake shaped, having a large diameter and small width; CSD harmonic drives were chosen based on the smallest width and height. Miniature rotary encoders are connected with rotor to measure motor angle which can calculate the joint angle. A torque sensor is then placed between the output link and harmonic gear.

4.4 Ankle Module

The ankle joint module was designed to minimize the torque generated by the loads by designing it so that the ankle joint of the exoskeleton is close to the ground. Design to be used for ankle joint is shown in Fig. 6c. Especially, joint mechanism was designed like ball-socket joint through the crossover the three axes. In addition, a mechanism using springs was developed to compensate for the torque generated in the stance phase and to generate propulsion force in the toe-off phase. The required spring constant was the gait data analysis for angle and moment. The spring constant, k_{sp}, was 1.61 Nm/deg when total weight of the exoskeleton was 21-kg. The AHRS attached to measure the orientation of the foot by using in control algorithm.

4.5 Controller Module

The controller structure is composed of a main controller, a sensor control unit (SCU), and a motor control unit (MCU). The main controller includes a FPGA programed to serve as communication and ADC for subcontrollers. To implement the control algorithm, the main controller communicates with the other control units to obtain the sensor signal and send the command. The SCU is responsible for acquiring the sensor signal and transmitting it to the main controller by converting it to a communication signal. The MCU performs the joint feedback control and sends commands to the actuator. Fig. 7 shows that all controllers were connected by the CAN communication network, each with a specific ID.

4.6 Full Bodoy Design

Fig. 8 shows the HEXAR design. The backpack encloses the battery, embedded controller, and payload.

5. CONCLUSION

We developed HEXAR to enhance lower body strength to enable humans to carry heavy loads. Biomechanical data on the characteristics of human joints and to determine the exoskeleton joint parameters were analyzed for the robot design. Range of motions for the

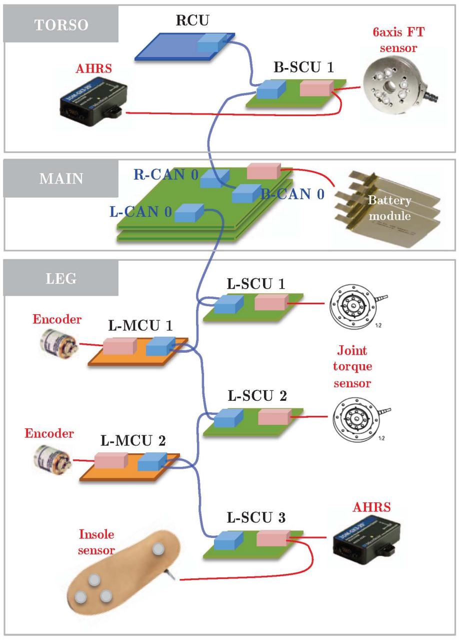


Fig. 7: The controller communication architecture.

Fig. 8: Full body design.

exoskeleton robot were established based on the limitations of human motions, and the joint functions were determined based on the power analysis. The actuator sizes were determined from the required joint torque and speed curves.

To this end, HEXAR was designed using a minimized actuator and a newly designed passive mechanism. Its total weight was 21-kg. Its architecture was configured with a controller, including a battery, which means that HEXAR can be used for five to six hours. Finally, we implemented the control laws for cooperative work between human and robot. HEXAR has been demonstrated to support weights up to 35-kg and can walk at a speed up to 6 km/h.

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