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Abstract. Designers typically have to consider diverse requirements when choosing actuators for assistive exoskeletons. In general, it is recommended to avoid oversizing actuators to produce lighter and more transparent systems. However, certain decisions may rely on the application context or design philosophy. The torque and power demands of the exoskeleton can be met by selecting the appropriate size of the actuator. This contribution considers one case study to better match actuator capabilities to paraplegic patient requirements. It presents a method for assessing different actuator characteristics using a variety of motors and reduction gears. This methodology uses an application-oriented requirement to show how various design decisions affect the lower limb exoskeleton (LLE) actuator. An LLE for paraplegia patients is used as a case study to demonstrate the process.

INTRODUCTION

Exoskeletons are being investigated for their potential to give physical aid in various applications, from facilitating daily activities to boosting military personnel's endurance. Several assistive exoskeletons provide physical aid by tracking the wearer's motions and intelligently adding or supplementing missing forces [1] The device may be required to generate significant contact forces to adjust the forces. These two situations result in opposed actuation needs: large forces are generally generated utilizing high-ratio transmission gears, which may reduce the effectiveness of force modulation [2] High gear ratios are also more expensive, larger, and heavier.

To choose a small actuator that best fulfils the needs of the exoskeleton while minimizing the drawbacks of competing demands, appropriate actuator selection criteria must be developed. The exoskeleton design process tends to be somewhat cautious, which could lead to the actuator being oversized. These aspects provided the driving force behind this work, which provides a basic framework to assist in actuator selection with the purpose of accurately matching the actuator's capabilities to the LLE for paraplegia patients. This study emphasizes the importance of selecting the motor and the gear reduction ratio in relation to the application requirements. Electric motors may frequently produce torques many times greater than their stated torque [3] giving users much more practical options for size and weight. We present the case study of an LLE intended to help individuals with paraplegia strengthen their viewpoint.

LOWER LIMB EXOSKELETON: CASE STUDY

The lower limb exoskeleton utilized as a case study in this article is intended to help patients who are paraplegic. Paraplegia is the medical term for an impairment of the lower extremities' motor or sensory function. One of the worst limitations is the lack of mobility caused by paraplegia. The inability to stand and walk has profound physiological impacts on the body that go beyond limited mobility, such as muscle atrophy, bone mineral loss, recurrent skin diseases, an increased risk of urinary tract infections, muscle stiffness, and compromised lymphatic and vascular circulation [4].

According to the World Health Organization, between 250,000 and 500,000 people worldwide suffer from spinal cord injury (SCI). Loss of full or partial control over body limbs and sensory faculties is one of the signs of SCI. One of the most critical stages in enhancing medical care and rehabilitation services for SCI patients is the provision of assistive devices to allow patients to carry out their daily tasks.

It is imperative to develop solutions to help and support people with gait disorders in their locomotion to give them a better quality of life and enable them to carry out their day-to-day responsibilities. Exoskeletons and other assistive robotic devices are crucial in solving mobility problems. Wearing an exoskeleton is a user-oriented robotic technology that can support or replace limb functions. Fig. 1 illustrates the significant applications of the LLE.

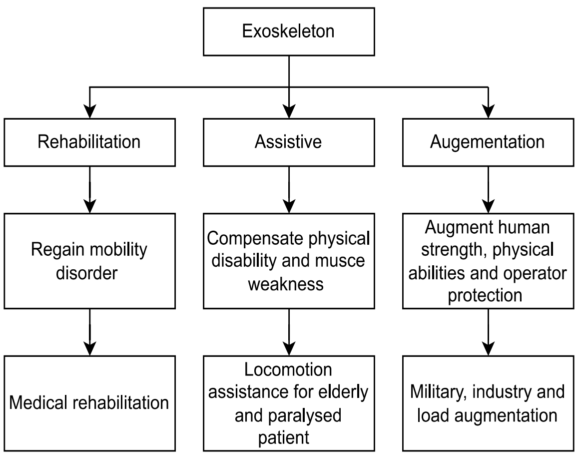

FIGURE 1. Types of Exoskeleton Technology

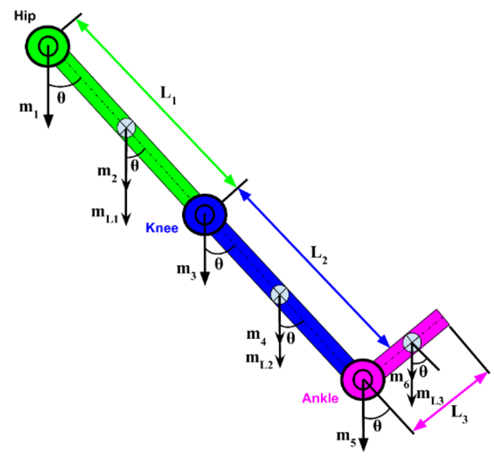

FIGURE 2. Free Body Diagram of Leg

The hip, knee, and ankle joints constitute the LLE. Any joint's maximum degree of freedom (DoF) depends on how the LLE is employed. In this study, paraplegic individuals are considered to wear exoskeletons. We will consider one DoF for each leg's hip and knee joint, respectively. The passive ankle joint is enough to serve our purpose for paraplegic patients. Two actuators are connected on each side, aligned with the hip and knee joints, and can generate the required torques for the corresponding leg segment. The range of motion (RoM) and required torque for different joints for different activities are shown in Table 1.

TABLE 1. RoM and Joint Torque Requirements for Different Activities

Activity	**Range of Motion**		**Joint Torque**	
	Hip (˚)	**Knee** (˚)	**Hip** (**Nm**)	**Knee** (**Nm**)
Walking	-10/30	-10/60	65	40
Stair Climbing	15/70	10/90	40	90
Stair Descent	20/45	15/90	50	105
Sit to Stand	-10/90	10/105	50	70
Forward Bending	-5/40	10/70	40	60

The torque required for each joint is determined using the free body schematics of the various joints presented in Fig. 2. Force acting on the hip and knee is shown using the downward arrow. As the ankle joint is considered a passive joint, we will get the required torque for the hip (T_1) and knee (T_2) joint as given in Eq. 1.

The task of the LLE is to provide motion assistance to paraplegic patients. Knowledge of the joint trajectory is obtained by the range of motion of each joint for different activities given in Table 1. Equation 1 provides the torque necessary to actuate the hip and knee joints and follow the specified trajectory.

$$T_1 = sin\theta\left[(m_2+m_{L1})g\left(\frac{L_1}{2}\right)+m_3g(L_1)\right]+sin\theta\left[(m_4+m_{L2})g\left(L_1+\frac{L_2}{2}\right)\right] + sin\theta[m_5g(L_1+L_2)] + sin\theta[(m_6+m_{L3})g(L_1+L_2)] + cos\theta\left[(m_6+m_{L3})g\left(\frac{L_3}{2}\right)\right] \quad (1)$$

$$T_2 = \sin\theta\left[(m_4+m_{L2})g\left(\frac{L_2}{2}\right)\right]+\sin\theta[m_5g(L_2)]+\sin\theta[m_6g(L_3)]+\cos\theta\left[(m_6+m_{L3})g\left(\frac{L_3}{2}\right)\right]$$

The design of an exoskeleton should be ergonomic, cozy, light, sturdy, adaptable to various users, and secure. The significant parts of the exoskeleton are the actuators. So, the selection of actuators and the optimal gear reducer is crucial in exoskeleton design. Typical application requirements of actuators include high torque, less power consumption, and the ability to work under loading conditions.

TYPES OF ACTUATORS

According to the energy source used as input, actuators can be categorized. In exoskeleton applications, there are primarily three different types of actuators: hybrid, electric, hydraulic, and pneumatic actuators.

Figure 3 depicts various actuator types predominantly used for the LLE.

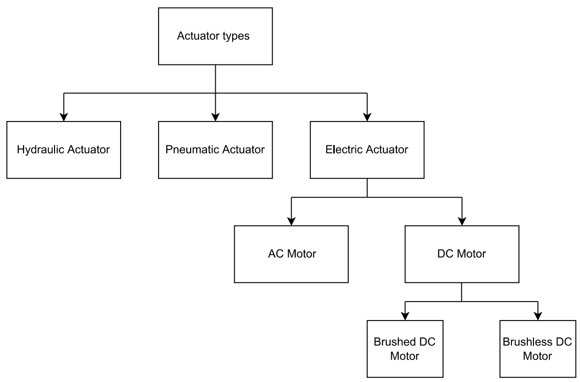

FIGURE 3. Types of Actuators

Hydraulic Actuators

A cylinder or fluid motor that employs hydraulic power to facilitate mechanical operation is known as a hydraulic actuator. A linear, rotational, or oscillatory motion results from mechanical motion. Since liquids can seldom be compressed, a hydraulic actuator can generate significant force. The excellent power density of the hydraulic system allows hydraulic actuators to manage massive loads, which is why they are the focus of a lot of research. The evolution of the hydraulic system in the exoskeleton is nonetheless constrained by the usage of conventional hydraulic systems, which are frequently centralized, inefficient, and bulky.

The centralized hydraulic system in Raytheon's XOS prototype [5] was mounted outside the exoskeleton, restricting the robot's range of motion. The centralized hydraulic system driven by a gas engine was employed to actuate the BLEEX prototype [6]. They switched to electric actuators in their later designs from hydraulic actuators. The architecture of the BLEEX electric motor actuation is described along with a comparison to the hydraulic actuation system initially developed. The exoskeleton joints of the HULC prototype [7] were powered by fluid through a centralized hydraulic system, in which an electric motor drives the hydraulic pump. The power density was increased due to the compact, centralized hydraulic power unit (CHPU) for the exoskeleton developed by [8]. Hydraulic systems with centralized control demonstrate their outstanding power density. However, they also have a number of shortcomings, including poor efficiency and a bulky design, that further limit the development of the exoskeleton. The centralized hydraulic system requires a consistent energy supply to function. The control valves release energy, which causes energy loss owing to valve throttling. In his comparison of the LLE actuators, Hollerbach shows that hydraulic actuators have superior torque-to-mass ratios [9].

The revolutionary hydraulic actuating system (HAS) for hip and knee joints is proposed by [10] and is based on an electric-hydro static actuator. Each HAS united a high-speed micro pump, a particular tank, an electric servo motor, and other parts into a module. Here, the mass of all the cylinders and sensors is included in the weight of the four HASs for the robot, which total only 10 kg. The hydraulic actuation mechanism for the exoskeleton now has a substantially higher weight and power density. Hydraulic actuators were formerly the only choice for highly dynamic-legged machines. The continual advancement of power-to-weight ratios in brushless electric motors, electronic controls, and batteries has made these options equally well-suited. Additionally, using electromechanical actuators rather than hydraulic ones enables significantly higher energy efficiency and reduced costs, especially at the human scale and below. Most robot bipeds currently do not exhibit this; however, the ones from Jonathan Hurst's lab do well, and the Cheetah quadruped from Sangbae Kim's team [11] is a fantastic example of what is feasible.

Pneumatic Actuators

Pneumatic actuators are devices that transform compressed air energy into mechanical motion. Through the stem, the actuator moves a control valve into place. The advantages of pneumatic actuators are their cost, improved power-to-weight ratio, cleanliness, and safety [17]. Long lifespan and resilience, ease of use, environmental friendliness, and reduced heat production under continual loading are additional features that add to the appeal [12]. Additionally, changing the air volume in two-cylinder chambers instead of using electric actuators makes it easier to obtain the actuator's compliance which is a necessary component for bipedal walking.

However, it has a few significant limitations that prevent it from being used in real applications: nonlinear dynamics, the requirement for compressed air, and PMA's hysteresis tendency [13]. A pneumatic actuator's pressure versus output force/distance/rotation curve is typically nonlinear. Operating its open loop is not repeatable enough, so an additional sensor is required to shut a feedback loop around the output. In general, servos carry out the instructions. Miller proposed soft pneumatic rotational actuators for wearable robots [14]. Even though its actuation speed is proportional to comparable devices, the current model can only maintain roughly 80 steps per minute instead of the 100 steps per minute needed for a moderate walking pace. Development work might comprise lowering the actuator volume and raising the volumetric flow rate to enhance the potential walking speed.

Due to their low power and challenging control, pneumatic robotics is not yet used extensively in rehabilitation. The portability of the power sources is the main problem with using pneumatic actuators in mobile robots [15]. The pneumatic muscle actuators (PMA) attached to steel wires power the upper-limb exoskeleton robot. To put the quasi-passive rehabilitative control in place. This actuation uses an active mechanical element to regulate the assistance given by a traditional passive element [16]. Only a rotational actuator capable of turning can move the exoskeleton's joints. A driving system must be integrated to convert the pneumatic cylinder [17] from a linear actuator to a rotating actuator. In this instance, pulley arrangements transform the standard pneumatic piston's linear motion into a rotating motion. Therefore, it isn't easy to move the exoskeleton precisely.

The pneumatic actuator can be used with the knee joint and upper body exoskeleton but not the hip joint. The utility of active upper extremity exoskeleton concepts is constrained by their difficulty in being lightweight, comfortable, and nonrestrictive movement. Additionally, most of the value systems demonstrated were made to support overhead work. There is inadequate proof that uses for load-holding and weight-carrying tasks, both at the local muscle level and the level of the body, reduces effort and fatigue [18]. It is still a work in progress to create a lightweight, powerful, and highly flexible device that can help with functional arm rehabilitation. Pneumatic actuators can help to solve this problem because of their high power-to-weight ratio, lightweight design, and flexibility similar to that of human muscles.

In contrast, the advantage of being controlled applies to electric actuators. This characteristic can be used to enable the exoskeleton's precise movements. So electric motors are frequently employed. Bowden cables, struts, ball screws, or belts are examples of how power can be transferred from an electric actuator. Furthermore, various electric motor types, including BLDCs, can be employed. However, an electric motor drive may occasionally require a gear system to increase power.

Electric Actuators

In this electromechanical device, electrical energy is converted into mechanical motion. The number of coils, their arrangement, the type of synchronization, and the current profile are the keyways that various electric motors vary (DC or AC). According to their first classification, electric motors can be divided into two types, linear and rotary. The great majority of exoskeletons primarily employ electrical actuation in various methods.

Due to the DC motors' simplicity in controlling speed and direction, they are currently the most widely utilized actuators in exoskeletons. They can operate at any speed, from maximum to zero, and with various loads. However, servomotor propulsion systems with permanent magnets are typically used [19] as drives in exoskeleton structures. DC motors can react quickly to changes in control signals because they have a high torque to inertia ratio. Without complicated power-switching hardware, a DC motor can be cleanly stopped at zero speed and quickly propelled in the opposite direction. The cost of permanent-magnet brushless DC motors is typically higher than that of brush types.

TABLE 2. Comparative Analysis of BLDC, BDC, and AC Actuator

Feature	Brush Less DC	Brushed DC	AC
Commutation	Electronic commutation	Brushed commutation	Not Required
Maintenance	Low, due to the absence of brushes	High, depends on the number of brushes	Low, due to the absence of brushes
Lifetime	High	Low	High
Efficiency	90%	80-90%	50-40%
Heat Dissipation	High, because the stator has winding	High Because heat is dissipated between the air gap	High Because the stator has winding
Rotor Inertia	Low, due to the presence of a permanent magnet	High Because the stator has winding	High, due to the presence of rotor winding
Speed Range	High	High	Moderate
Noise	Low, Because of no friction	Low	Low, Because of no friction
Control	Complex, the dedicated controller is required	Simple, controller is not required	Moderate control is required
Power to Weight ratio	High	Low	Low

However, by referring to Table 2, we may conclude that BLDC motors, which are essential in robotics, have several advantageous properties, including reduced power consumption, increased speed and torque characteristics, minimal maintenance, and increased efficiency. The ability to generate high torque when the motor shaft is stationary and outstanding torque to weight ratios are among the most crucial. Because standard DC motors require more maintenance and include brushes that produce friction, BLDC motors can operate more efficiently and fast. After all, brushes don't need to be changed frequently. The heat generated in the stator's coils can dissipate more quickly through the motor housing, making them more efficient. A BLDC motor with permanent magnets (PMSM) was employed to generate the drive torque necessary to support the strength of human muscles [20]. The mechanical components in the offered model were taken to be rigid due to the high dynamic of the permanent magnet servomotor operation.

Although they have already been discussed in this context, linear hydraulic and pneumatic actuators have a high-power density but are typically large and have problems with internal leakage and friction [21]. SEAs have been employed in some rehabilitation equipment [22], although they have a typical limitation regarding the fixed elastic element's spring constant. It takes a complicated combination of factors to ensure that the patient and exoskeleton move harmoniously [23]. Electric motors reduce the amount of power used during stride, and DC motors offer a portable and compact design that meets wearable device power requirements. So, for this study, BLDC motors coupled to a planetary gearbox were used.

ACTUATOR SELECTION

Based on the average torque and power of each joint during a typical gait at the average speed, actuator design and selection were made. The mobility and specific power (the ratio of actuator power to actuator weight) are the most important considerations when choosing the actuation technology to drive human joints.

The hip, knee, and ankle joints are often supported by the lower extremities exoskeleton. As a result, the biomechanics of human lower limbs, including the kind of motion, range of motion (ROM), degree of freedom (DoF), and torque, should be considered when designing the mechanical components of the LLE. The lower extremity exoskeleton can support one joint, two joints, or the complete leg, depending on the design. Aspects of exoskeleton design primarily focus on the application goal and biomechanics of the biological limb.

Exoskeleton applications require actuators to deliver high moments while operating at high speeds. Larger and heavier actuators are needed for this. However, the available space around the joint is insufficient for attaching the actuators. To achieve the necessary moment-speed values for the required movements, it is crucial to select the most compact actuators possible. To choose actuators correctly, one must know the joints' velocity-moment properties for the targeted movements.

Using Eq. 1, the torque required for each is calculated and tabulated in Table 1. In this study, the exoskeleton supports normal walking and sit-to-stand activities for paraplegic patients. The selected actuator should meet the torque requirements for these activities. In this study, the BLDC motor is selected as a joint actuator because this actuator has more efficiency and less maintenance. and a longer lifetime than the other actuators. A comparative analysis of electric actuators is given in Table 2. Since the joint actuators of the exoskeleton demand more torques and the motor can't provide that much torques, speed reducers or gearboxes need to select to fulfill the torque requirements. Different types of gearboxes are available. In this study, a planetary gearbox is used for trading speed for more torque, as this gearbox offers more benefits and more significant speed reduction in the compact frame compared to the other speed reduces. Specifications of the selected actuator and gearbox are shown in Table 3 and Table 4.

TABLE 3. Specifications of the Selected Actuator

S.No.	Parameters	Values	Unit
1.	Supply voltage	48	V
2.	Input current	4.06	A
3.	No load speed	1960	rpm
4.	No load current	278	mA
5.	Rated torque	0.964	Nm
6.	Rated speed	5000	rpm
7.	Speed constant	41.3	RPM/V
8.	Speed/Torque Gradient	0.151	RPM/mNm
9.	Phase-to-phase resistance	0.6	Ω
10.	Insulation class	B	-
11.	No. of poles	11	-
12.	No. of phases	3	-
13.	weight	980	g

TABLE 4. Specifications of the Selected Gearbox

S.No.	Parameters	Parameters		Unit
		Hip	Knee	
1.	Gear ratio	65:1	30:1	-
2.	Rated torque	60	35	Nm
3.	Rated speed	30	65	rpm
4.	Output power	260	260	W
5.	Efficiency	81	81	%
6.	Weight	1.72	1.75	Kg

Our LLE focuses walking as its primary movement, and the clinical gait analysis is used to calculate the moment-velocity values of the joints (CGA). Throughout a gait cycle, CGA data monitors changes in joint angles and normalised joint moments. Joint velocities corresponding to the desired walking velocity can be computed from the joint angle fluctuations found by CGA. We took into account the other criteria when choosing an actuator in addition to the aforementioned specifications. The greatest speed permitted by the gearing mechanism and the no-load speed must be greater than the maximum speed necessary for the application. The gearbox's maximum average speed should be greater than the task's maximum average speed.

The mechanical strength of the motor, demagnetization of permanent magnets in the rotor, or magnetic saturation of the stator's laminations limit the maximum motor torque. Gearbox damage and motor overheating are associated with electrical motor torque limits. When the required motor torque is less than the motor's nominal value, motor overheating is fully prevented. When the torque is between the nominal and peak values, the thermal model must take into account motor overheating. The gearing mechanism determines the trade-off between internal and exterior forces. As a result of the higher rotor acceleration and speed caused by a high ratio, there are more inertial and frictional forces. When the ratio is low, the task torque is supported by a higher current. It follows that the ideal reduction ratio would balance these needs for internal and external forces and lead to selecting the task requiring the least amount of current.

CONCLUSION

This work suggested an approach for selecting the actuator that fits the task being performed the best. With this approach, exoskeleton design considerations that are often disregarded are considered, including requirements for multiple parallel stiffness improvements, internal actuator behavior, and motor heat interactions. The methodology is demonstrated using an exoskeleton for the lower limb targeted for paraplegic patients. To improve robustness to activity fluctuations, the approach explicitly suggested considering a lighter, more transparent, and more compact motor like the EC90 flat motor. We plan to incorporate it into the LLE prototype design for paraplegic patients in subsequent study.

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