# Design Considerations of Anthropomorphic Exoskeleton

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**Abstract: *The review examines the design considerations and challenges of anthropomorphic exoskeletons. There is an increasing demand for the design of exoskeletons for various purposes including rehabilitation training, human performance augmentation. There are several factors to be considered before actually manufacturing an orthotic device and it depends highly on the application of the device and requirement. This paper contributes to a comparative study of different methods of actuation, the effectiveness of the light-weight design, methods of force production, human-machine interface, and how application influences a design. It can be observed that exoskeletons are recently evolved to a stage of exosuits to provide comfort to the user, but there are situations where user comfort is sacrificed for other advantages. This study will help in better understanding the various design challenges and consideration to the design of a new exoskeleton. Five different designs are compared in this paper to better understand the validity of each design consideration.***

**Keywords:** Exosuit, Exoskeleton, Anthropomorphic design, Orthotic robot

## 1. Introduction

Exoskeletons are designed for specific purposes and mostly they either help with a human defect or enhance a particular functionality in humans [1]~[5].

As discussed in [2] stroke impairments can be partially treated by intensive training and the current methods are inefficient and they have developed a soft glove and a control system, which is used for training patients with activities of daily living(ADL) [6],[7]. Such types of soft exoskeletons (commonly known as exosuits) have become increasingly used and researched for many purposes. A similar type of material is used in [1], where a soft wearable exoskeleton is used to support in heavy feet walking situations like hiking; a comparative study of the gait patterns and metabolic cost of 5 human subjects has been made, interestingly found that there is a 6.4% reduction in metabolic effort. Soft methods have many advantages over traditional rigid suits [8]~[10]. Metallic suits can be heavy, consume more power from the battery to actuate the links, and offer high inertia.

One of the earliest attempts to develop exoskeletons for human performance enhancement was done under Exoskeletons for Human Performance Augmentation (EHPA) organized by DARPA,[11]. In the beginning, exoskeleton systems were powered by hydraulic cylinders, relied on the power from combustion engines, and also used turbines and rotors for locomotion, some of the devices were known as a “Lift”.

But now it has changed to more advanced battery-powered lightweight devices capable of assisting in chores and activities of soldiers, patients, industry workers, and healthy individuals. The scope of exoskeletons and orthotic robots has straightened with the availability of soft materials, as these materials do not affect the kinematics and dynamics of the wearer significantly[12]~[15].

This paper examines the different factors of an anthropomorphic design for exoskeletons. Various factors are compared and analyzed using the previous and ongoing research in the field. All the different designs have certain factors that are better than the other and the focus of each research is different, which makes all the designs to be equally considered for better quality designs in the future. Some designs try to enhance comfort by consuming lightweight design [16], [17].

## 2. Background

The development of exoskeleton was first attempted by General Electric, USA in the late 1960s and the prototype was named as ‘Hardiman’ [18]. Around the same time, the first preprogrammed exoskeleton for walking assistance was developed by Mihajlo Pupin Institute, Serbia [19]. And many attempts were failed to develop a prototype due to underdeveloped technology and lack of knowledge pushed it to a few more years. ‘Lokomat’ was the first commercially released product for uses in hospitals and rehabilitation centers worldwide [20]. Development has progressed rapidly in the past with an advantage from interdisciplinary approach and collaboration among engineers from different fields, military and medicine.

Exoskeletons are designed to perfectly fit the human body and should not hinder the kinematics and dynamics of the wearer. The design has changed drastically over the past 50 years. At the beginning, exoskeletons were designed using metallic alloys and steel structures powered by hydraulic drive systems. There were even devices which were powered using combustion engines [21] in the late 20th and early 21st century. Throughout the 21st century design of exoskeleton adapted to light weight materials powered by pneumatic, hydraulic systems or electric motors. Recently bio-inspired methods have been adopted and renamed as ‘exosuits’. These are low profile, light weight orthotic devices for various applications including walking assistance, rehabilitations e.t.c..

Actuation systems have many variants and soft materials are used for actuation. Soft actuator materials are useful in light weight actuator designs, they can change their shape and or size as a response to stimuli like magnetic field, electric field, pH, temperature e.t.c, [22].

In this review, different considerations of design are studied to analyse how these factors affect anthropomorphic design of exoskeletons and what are the challenges in each.

## 3. Actuator Design

Actuators are designed based on their application, torque/force requirement, and desired weight and compactness of the overall system, [1]~[5].

Electric actuators with geared motors can be used for applications that require large force/torque and compact design. For instance, in [1], two actuator units, each controlling one leg are placed proximally in a backpack worn by the user to retract Bowden cables using a pulley of 3.5 cm radius. Here a suitable textile material is used to increase human-suit series stiffness. In this setup, a cantilevered load cell, with an idler pulley on its end, is used to measure the force on top of the Bowden cable.

To measure the true force delivered to the wearer, a second load cell is placed at the ankle. In figure1 the positions of each pulley at hip, knee, and ankle are marked. When the actuator placed in the backpack retracts the Bowden cable, necessary actions were created in the pulleys.

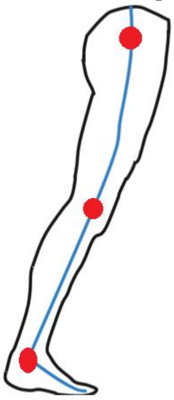

**Figure 1:** The points red-marked are the biological joints of leg

Hand has the most number of degrees of freedom (DOF) in the human body, which makes it harder to actuate all the 13 motions with conventional actuators. In [2], all fingers except the little finger is bi-directionally actuated. Here a tendon-driven actuator, similar to human anatomy is considered; the system is actuated using a combination of DC servo motors, elastic, and transmission design. Independent mobility of joints makes the device adaptable to any desired shape. A stationary cage with inlets is used to ensure that the tendons cannot derail and the dual pulley mounted can wind one of the tendons and unwind the other one, which is depicted in figure2. Bowden cables act as anchoring support and avoid the distal placement of the actuation unit. A control unit with four servo motors and a battery is placed intentionally on the upper arm to reduce the overall inertia of the wearer. 4 servo motors are utilized to control the bi-directional actuation of four fingers excluding the little finger. There is no independent movement given to the little finger, but it can be actuated together with the ring finger, but this movement has no visible advantage in the experiment. This design is a contradiction to traditional robotics hands, which could either flex or extend, probably controlled by a single motor. Tricodur Rhizo Forte [23], an orthosis, is integrated into the glove for a better grip on the tendons.

The actuation mechanisms used in [1],[2], and [5] are similar even though all the three used different actuators, which are: geared motors, DC servo motors, and Pneumatic muscles. The modeling of this type of mechanism is given later in this section (figure 3).

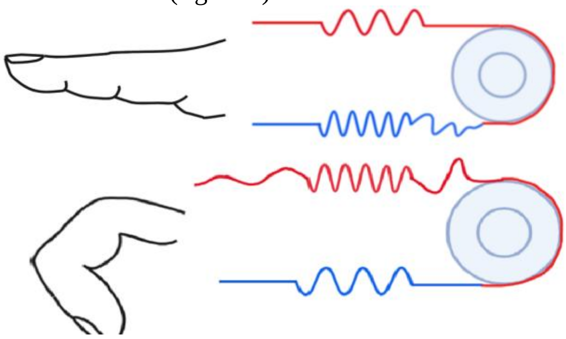

**Figure 2:** Behavior of tendons. First picture depicts extension and the second is flexion

Endorsement of higher DOF to a design, allows it to allocate to various applications. The design constructed in [3] is based on an analysis of 19 ADL of human subjects using the arm including general reaching tasks, functional tasks, eating and drinking, and hygiene-related tasks [24]. The Motor-pulley system is operated using cables that transmit assistive force for the desired motion in this design.

BLEEX uses double-acting linear hydraulic actuators of 2 cm bore diameter and rely on the pressure of 6.9 MPa[4]. Another customary actuator, Pneumatic Muscle Actuator (PMA) is a bio-inspired actuator design that utilizes pressurization to cause antagonistic tension-contraction, has an analogy to biological muscles. PMA provides clean, safe, and low-cost actuation. A special arrangement is made in the design of PMA to withstand pressure up to 700 KPa, although the operating pressure of the device is found to be only 600KPa. An elaborated design and construction of PMA can be found in [25].

Antagonistic action of two pneumatic muscles creates rotations to double groove pulleys of each joint, and it is discovered that most joints require a rotation excess of 90°. Each muscle of PMA, in this design, has a diameter of 2 cm and variable length between 15 cm to 45 depending on the maximum executable torque and range of motion required for a particular joint.

For the antagonistic action as described in [1]~[3],[5] it takes two muscles, both being either pneumatic or tendon driven pulled by an actuator, operating in opposite directions. This can be best explained by mathematically modeling the PMA as two antagonistic springs connected to a pulley.

In figure 3, the angle between OA and $OX_R$ is $\theta_1$ and the angle between OA and $OX_L$ is $\theta_2$. The force on the pulley, when the pulley rotates counter clockwise is

$$F_1 = K_1(x_1 + r\,\theta_1) \quad (1)$$

$$F_2 = K_2(x_1 - r\,\theta_2) \quad (2)$$

Here r is the radius of pulley and $K_1$ and $K_2$ are the spring constants for each spring and $x_1$ and $x_2$ are the extensions of each spring.

The torque developed at any joint is given by

$$T = (F_2 - F_1).r \quad (3)$$

The stiffness depends on two parameters, which is explained here with reference to PMA as described in [5]. One is a constant, elasticity of rubber and another is a function of air pressure.

Here the analogy between human muscle and PMA is clearer, where pneumatic muscle clones the function of muscle in the body, pulley has the same function of joints with only one DOF and the rope connecting these two act as tendons.

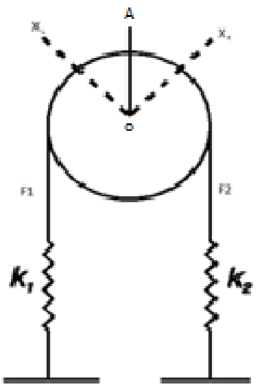


**Figure 3:** Antagonistic actuation scheme

All different actuation methods have its own advantages and disadvantages, selection of an actuator scheme should depend on the application and requirement.

**Table 1:** Comparison of actuator designs [1]~[5]

| Exoskeleton design | Actuator | Features |
|---|---|---|
| Bio-inspired Soft Exosuit for walking assistance [1] | Electric geared motor- cable-pulley system | 1.High series stiffness<br>2. Three DOF, parallel to human joints<br>3.Proximally placed actuators<br>4.Light weight suit |
| Anthropomorphic Soft Exosuit for hand rehabilitation [2] | DC Servo motors, tendon operated system | 1.High compliance<br>2.Automatic shape matching<br>3.Light weight motor(21 g)<br>4.Continuous grasping for almost one hour(54 minutes) |
| The cable-actuated dexterous exoskeleton for neurorehabilitation (CADEN)-7 [3] | Electric motor-cable-pulley-system | 1.Anthropomorphic design with all the 7DOF<br>2.Proximally placed actuators and distally placed pulley reductions. |
| Biomechanical Design of the Berkeley Lower Extremity Exoskeleton (BLEEX)[4] | Hydraulic actuator | 1.Double acting linear hydraulic actuators<br>2.Compact size<br>3.Low-weight<br>4.High Force |
| 7 DOF Pneumatic muscle actuator powered exoskeleton [5] | Pneumatic muscle actuator | 1.High power/weight ratio<br>2.Inherent compliance |

Table 1 represents the features of five exoskeleton designs. Exosuits need lighter, efficient, and compliant actuators that have a better frequency. CADEN-7 has a heavy mechanism where all the heavy actuators are stationary and forces are transmitted through pulley reductions to the desired human joint. This design is best suited for training purposes for patients but not suitable for ADL.

To obtain a complete anthropomorphic design, the actuation scheme can use antagonistic muscle action, where two muscles work in opposite ways as agonist and antagonist. But there are many options of actuators to choose from for this operation; in fact, all the actuators can be used for this motion by designing an apt mechanism. Muscle actuation in exoskeletons has its benefit of being compact design and inherent compliance [26].

## 4. Force production

One of the key features of each design [1]~[5] is the method in which force is produced in these exoskeletons. [1]

Explains two ways of force production in the exosuit: when the actuator retracts the Bowden cable and when the wearer moves. Here stiffness is considered as a lumped parameter, $K_{total}$., the series combination of $K_{cable}$, $K_{suit}$, $K_{body}$.

$$K_{total}^{-1} = K_{cable}^{-1} + K_{suit}^{-1} + K_{body}^{-1} \quad (4)$$

$K_{total}$ is suit-human series stiffness. If the wearer is stationary and the actuator retracts the Bowden cable, a force is generated due to suit-human series stiffness. In the experiments, the non-linearity of $K_{total}$ is observed. Due to the suit's specific architecture, a force can also be induced if the wearer moves, thanks to the ability of the suit to passively generate tension. And the suit can also be made completely transparent to the wearer at any point in the gait cycle by lengthening the cable, marked as the "slack" phase. In [2], the force transmission is similar to the anatomical structure of human fingers. Wires along both sides (tendons) of a finger act as flexor or extensor as shown in figure 2. And the action is controlled by rotating the servo motor. Although force sensors at fingertips inhibit the sense of touch, this gives data to control the amount of force between 5N and 15N; in certain situations, force as high as 15N can be undesirable, wherein in some situations it is required. Equations 1 and 2 represent the force equation of the tendons. If F1>F2, the pulley rotates counterclockwise and converse if F2>F1(figure 3). This gives the two behaviors in figure 2.

Power is transmitted through a cable-driven system in [3]. The transmission system and placement of actuation were designed not to compensate in weight for structural rigidity and stiffness. Motors for the first four joints are placed proximally and mounted on a stationary base, this helps in reducing the weight of moving parts by 60%. The other three motors are mounted on the forearm because these joints demand less torque. Shoulder and elbow joints are driven by a high torque (6.2 Nm), low power/weight (2.2 Nm/Kg) motor, whereas the wrist is driven by a low torque (1 Nm) and high power/weight (4.2 Nm/Kg) motor. Joints 1 to 4 have a two-stage pulley reduction and 3 joints at the wrist have a single stage pulley reduction and a planetary gear reduction. This helps in maintaining a low torque and high angular velocity at the motor, whereas at the joint, torque is high and angular velocity is low.

Cable drives (wire rope is used for cable) can transmit loads over a long distance without backlash and friction of gears. This cable drive system is the same as its biomimetic counterparts, tendon drives, as utilized in [1], [2], [5].

Mechanical equivalent power consumed by an average human for walking is around 165W, whereas the hydraulic power consumption of BLEEX [4] is 1143 W. Its leg has a stiff heel to transfer the load to the ground and flexible toe for comfort. Here hydraulic power is directly utilized for the mechanical rotation of joints. Kinematics of BLEEX is a bit different from that of humans, which is discussed in section 10.4.

Even though [5] uses the same antagonistic action as [1] and [2], it uses 2 pneumatic actuators to control agonist and antagonist. Here the actuators are controlled independently of each other.

4 out of 5 designs in this review have an antagonistic actuation scheme, also known as tendon driven actuation, despite they all use different actuators for force production. Since it closely resembles human muscle it is a better method to use in anthropomorphic exoskeletons.

## 5. Weight of the system

The research study conducted in [4] shows that when joints are placed directly above the hip of the wearer, it causes trouble due to the high mass of the torso and payload. This problem was rectified by making the rotation of both hip joints to a single axis of rotation, behind the body and under the torso. This indicates the significance of lightweight and strong materials for the lower limb exoskeleton to support the weight of the system and load on the wearer's back as well.

Processes like walking, running, and even standing or sitting are metabolically costly processes. It takes energy and effort to stand in a normal position due to the effects of gravity. Muscles especially at the leg do the work against gravitational force [27].

Weight and its distribution affect the inertia of the wearer and design with heavyweight can affect the functioning of human operators and there are chances for muscle fatigue, imposing negative effects.

[1] was aimed to produce a lightweight design, which still is if only the proximal loads at two legs are considered alone, the weight on each leg is 2Kg, but the actuator unit and backpack frame make it too heavy(more than 30Kg).

The paper [2] substantiates that 435g is considerably low weight for hand rehabilitation and has a setup to reduce overall inertia.

The mechanical structure described in [3] is heavy as it appears, the target value for the design was to make it weigh around 6.8 Kg with a payload of 2.5 Kg in hand, but in practice, it has a weight of 3.5 Kg for link1 and 6.3 Kg for the links 2 to 7.

BLEEX was designed to support a 75 kg of payload with a walking speed of 1.3 m/s. The hydraulic actuation has been adopted for the design due to its weight benefits; nevertheless, the use of abundant electronics components for the particular control architecture makes it heavy [4].

The design in [5] has a lightweight design; the entire setup weighs less than 2Kg and relies on pneumatic muscle actuators. These actuators have a considerably higher power/weight ratio.

Weight is a principal factor that affects the stability of a system and the comfort of the user. Also, it is evident from the above observation is that weight is completely dependent on the application; for example, the weight of an exoskeleton designed for the lower limb is not comparable with the one made for the hand. Bio-inspired models in [1], [2] have a comparatively low weight due to the material used, but it has many limitations. One such limitation is the weight of the payload is not transferred to the ground. As a result, these devices cannot be applied in applications such as to help with heavy loads.

## 6. Degrees of Freedom

Compliance and safety can be achieved by designing exoskeletons that have the same DOF as humans [28]. The human body has a total of 57 degrees of freedom which is demonstrated in Table 2. Each Shoulder, Elbow, and wrist has 3, 1, 3 DOF respectively and a total of seven for the upper limb excluding hand. The design [3], [5] has seven degrees of freedom. The human hand has 13 DOF for each; the soft exosuit design in [2] is made as simple by making all the three joints of each finger under-actuated and all fingers except the little finger are bi-directionally actuated, but the combined actuation of the ring and little finger is possible. Thumb in humans has 5 degrees of freedom from three joints and in this design range of motion of the same is limited to simplify the motion.

**Table 2:** Human joints and Degrees of Freedom (DOF)

| Joints | Movements | DOF | Pair |
|---|---|---|---|
| Neck | Up/Down, Left/Right, Rotation | 3 | No |
| Shoulder | Up/Down, Forward/Backward, Rotation | 3 | Yes |
| Elbow | Forward/Backward | 1 | Yes |
| Wrist | Up/Down, Left/Right, Rotation | 3 | Yes |
| Arm(Fingers) | Grasp | 13 | Yes |
| Hip | Rotation | 2 | No |
| Crotch or Groin | Up/Down, Forward/Backward, Rotation | 3 | Yes |
| Knee | Forward/Backward | 1 | Yes |
| Ankle | Forward/Backward, Left/Right | 2 | Yes |

The benefits of flexible joints are yet to be studied and there is not much data to understand how an under-actuated system can affect the kinematics of the wearer. The design in [1] has three articulated joints, each one at the hip, knee, and joint. Since the links are flexible and the suit is considered as an under-actuated mechanism, it is compliant with the human user. Moreover, during the “slack” phase human actuators can operate freely. BLEEX [4] has 7 DOF legs, of which 4 of them are actuated.

The design described in [5] demonstrates a 7DOF exoskeleton for application in simulating virtual effects like grasping. For a better anthropomorphic design, it is recommended to design each joint with DOF the same as the human joint where it is supported. But certain joints are hard to copy. For instance [4] has explained the difficulty in designing a joint with all the 3 axes of rotation passing through the human ball and socket joint of the hip; this can result in singularities at some of the human postures and has a limited range of motion. In the final design, necessary adjustments are made in BLEEX to overcome this problem. A better and efficient spherical joint mechanism could be a solution for this.

## 7. Human Machine Interface

Research is being carried out in the field of human-robot interaction to develop systems that meet the current needs. How the wearer is communicating with an exoskeleton or prosthesis has significantly changed in the past. Depending on the preference of the user or the purpose of the exoskeleton, different methods can be employed. The simplest of all is control using buttons for preprogrammed grasps and actions.

The research in [2] has currently utilized three different modes.

1) Mirroring the function of one hand using sensors that read bending angles from it and transmit to the controller, which in turn controls the actuation of the other hand on which the glove is worn. “Mirror therapy” is particularly useful when one side of a patient is affected such as stroke patients. In [2], this is achieved using two different sensors namely piezo-resistive bending elements and electroactive polymer-based sensors in two separate modes.
2) Control using buttons for independent training can be helpful for untrained personnel in helping patients and in ADL
3) Training program for automated is an EMG based intention recognition program, suggested for independent training and ADL.

BLEEX [4] has employed a method in which measurement from the exoskeleton is solely for the control, there is no direct force feedback from the wearer.

The technique of surface electromyogram ( sEMG) [29], is widely used in this area of research. The brain sends a signal to muscle fibers in the process of muscular contraction or relaxation. There is a time gap between the action potential reaching the muscle and contraction or relaxation starts and this is called the lag phase or latent phase. For muscular contraction, a contraction phase follows the lag phase. Action potential creates a contraction in muscle fibers that are associated with a particular neuron and this contraction is called a ‘muscle twitch’; a single twitch has 3 phases (figure 4).

The lag phase is a short delay (1-2 ms) from the time when the action potential reaches the muscle until the contraction occurs in the muscles. The length of the twitch varies between different muscle types and could be as short as 10 ms or as long as 100 ms. The action potential can be measured and monitored using sEMG.

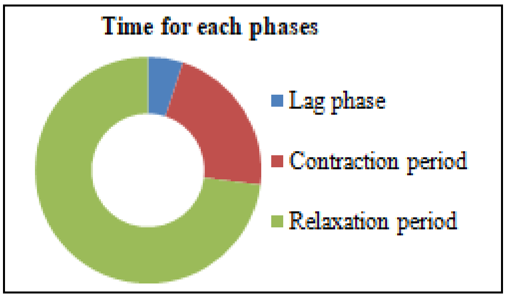


**Figure 4:** Periods of phases of muscle twitch

sEMG is a better method for several reasons, one of which is being non-invasive. It is easy to get signals by tapping an electrode to the nerve connecting a particular muscle fiber to the central nervous system. However, muscle fatigue and continuous and repetitive use may hinder the process. Force estimation using EMG is one human-machine interface that can provide independent and automatic control of exoskeletons. It is necessary to adjust the response time before the lag phase for patients who are partially or completely paralyzed because they might not be able to initialize the movement of joints. These designs must have a higher frequency to avoid injury from accidents.

## 8. Problem Solving Approach and Challenges

Researchers are trying to develop low-cost, feasible, and anthropomorphic designs for various applications in collaboration with different disciplines including engineering, medicine, and physics [30].

In general, the problems that are faced by engineers to build an optimal orthosis are numerous as explained in the above sections. One such problem is the reduction of metabolic cost to assist in walking both healthy individuals and patients with partial impairments. Traditional rigid exoskeletons use heavy components that might have larger inertia associated with their mass and thus higher metabolic expenditure. In [1] an exosuit is designed to help abled individuals to help in walking. This Exosuit is made of textile material that is light-weight and low profile. The team is trying to build a portable soft wearable robot that is lightweight and low profile and that can reduce the net metabolic cost of walking, the current model has exhibited 6.4% metabolic reduction in the best-case scenario. The present challenge to this approach is that there is not enough data to decide whether the soft materials are capable of providing the required force to the desired locations of the body. The suit is designed to copy both the structure and the function of underlying tendons, muscles, and ligaments at the ankle and hip. The suit can apply moments to the ankle and hip from 20-65% in the gait cycle, and no forces at other times in the gait cycle. Maintaining a zero external force at other times, during the swing phase, prevents the disruption of dynamics of motion because swinging legs act like an inverted pendulum. The moments are applied at appropriate positions, at the back of the ankle to create a plantarflexion moment, at the front of the hip to create a flexion moment, and close to the center of the knee to create a minimal moment there.

There is a reason to place actuated cable across ankle the, first is that the ankle is the largest contributor to positive power during the walking cycle and second is by having the actuated region across the ankle joint, the ankle will receive the full force transmitted to the suit; the suit has slightly less tension across the hip due to friction with the skin along the leg. And finally, the ankle is narrower than the rest of the leg where the cable connects; this enables the cable to float above the skin at the ankle, preventing abrasion of the suit during actuation. The suit mimics biological muscles by passively absorbing power due to kinematic changes of the leg. Many approaches have been carried out to develop reliable exosuits for hand rehabilitation and training. In [2], the research focuses on developing a simple, cost-effective design of exosuits for hand rehabilitation and as part of the research, it is tested and used in ADL of verified subjects. Through the research, they have tried to rectify the grasping movement of the human hand that is mostly caused by a spinal cord injury or a stroke. The design is devised after a careful study of human anatomy and a similar tendon-driven actuation mechanism is employed using a dual pulley coupled to a DC Servo motor. They have also provided a perspective of using rigid links in series instead of the suit, it would have been efficient in force transmission and could be controlled easily. However, it would take a trained therapist to customize the joint alignments and it is time-consuming. Thus a soft and compliant mechanism is more favorable to adapt to the requirement of the current scenario, where human labors are expensive. All four fingers except the little finger are bi-directionally actuated and joints of each finger are underactuated, which makes it easier to grip any shape.
The above two designs have used soft materials and flexible links instead of rigid links, it can provide comfort and compliance but rigid links are better at transmitting force.

CADEN-7[3] has 7 degrees of freedom and has features like relatively low inertia when compared with other contemporary rigid designs, back-drivable actuation with negligible backlash, high stiffness, and physiological range of motion. The initial designs were proof of concept models with 3 or lesser degrees of freedom and design with non-anthropomorphic joint configurations. CADEN-7 has all seven anthropomorphic joints (Table 3). Another feature of the design is the human-machine interface and control algorithms designed to trigger motions of the joints. The initial data for the design was obtained from kinematics and dynamics from the ADL of the arm. This method has a limited range of applications since it is mounted on a stationary base, but the design is best suited for training purposes of the upper-limb.

BLEEX [4] is the first field-operational exoskeleton that can be worn by an operator and capable of carrying heavy loads over any terrain, where the human wearer can traverse. The research aimed to resolve the problem of transporting loads over difficult terrains, where wheeled vehicles are not accessible. The design initiated a method of incorporating the navigational intelligence of humans with the performance of machines. The device has features including compact and high power supply, better design architecture, and special communication protocols. BLEEX can eliminate complex mapping problems in these scenarios and potentially apply them into the field to help soldiers, disaster relief workers, and wild firefighters. The key feature that sets BLEEX apart is the force transfer to the ground using a footstep instead of directing to the wearer's body.

The design in [5] suggests a different actuator but it uses the same tendon driven actuation scheme. By using pneumatic muscles that are light-weight and with a feedback system, it guarantees high power and stable operation, low-cost manufacturing, flexibility, and portability. Each design has different challenges and desirable characteristics. It is evident from the past that the researchers are trying to utilize different properties and combine them to produce a suitable system. Using a better and efficient actuator in muscle actuation (tendon driven) is desirable, but the selection of actuator and materials depends on application and requirement.

## 9. Applications

Most of the other considerations are dependent on the applications (Table 3), as it is explained in the above sections. The purpose should be the first consideration for the design of an exoskeleton or exosuit. Soft exosuit as in [1], [2] are applied for special purposes but they cannot be used for carrying heavy payloads; On the other hand, rigid exoskeletons are capable of carrying heavy payload (75 kg for BLEEX) but does not provide comfort or low profile design.

**Table 3:** Applications of exoskeletons

| *Exoskeleton design* | *Possible Applications* |
|---|---|
| Bio-inspired Soft Exosuit for walking assistance [1] | 1.Walking assistance for partially abled patients and healthy individuals<br>2.Study of physiological changes and metabolic cost of walking |
| Anthropomorphic Soft Exosuit for hand rehabilitation [2] | 1.Hand rehabilitation for diseases and injuries including stroke and spinal cord injury |
| The cable-actuated dexterous exoskeleton for neurorehabilitation (CADEN)-7 [3] | 1.Therapeutic diagnostic device for physiotherapy<br>2.Orthotic device for human power amplification<br>3.Haptic device<br>4.Teleoperation |
| Biomechanical Design of the Berkeley Lower Extremity Exoskeleton (BLEEX)[4] | 1.Assistive devices to soldiers<br>2.Help in disaster relief and rescue operation<br>3.Wildfire fighters |
| 7 DOF Pneumatic muscle actuator powered exoskeleton [5] | 1..Virtual Reality |

Categorically either healthy individuals or patients utilize the benefits. Healthy individuals use exoskeletons for enhancing their performance in carrying heavy weight over a distance, save metabolic energy while hiking, extra hand in lift loads, and much more. Exoskeletons are especially helpful in patients with spinal cord injuries, paraplegia, or accidents that force them to be confined to a wheelchair, bed, or even paralyzed in half. These difficulties are found to be less traumatic if the patient has found a coping mechanism [31]. Exoskeleton can help them overcome challenges in ADL and help in independent training and rehabilitation. The exoskeletons can also be employed to enhance the virtual reality experience [5].

## 10. Discussions

Since each exoskeleton designs [1]~[5] have specific applications, the result of performance of each design is limited to that particular field. For instance, [1] has attempted to reduce the metabolic cost of walking while providing maximum comfort with the suit.

### 10.1. Bio-inspired Soft Exosuit for walking assistance [1]

The suit was tested on 5 healthy individuals with no gait abnormalities. The subjects were allowed to walk on a treadmill at 1.25 m/s and a Vicon T Series 9-camera system [32] was used for motion tracking. The subjects are made to wear a portable pulmonary gas exchange measurement system [33] to measure the metabolic cost. Including the necessary apparatus and additional mass to simulate hiking conditions, a total mass of 34.6 Kg was carried by the subjects. The experiment was divided into sections to accurately measure the expenditure during the exercise.
Metabolic expenditure is evaluated by measuring the O2 and CO2 gas exchange between the subject and the environment. Brockway's standard equations [34] is used to estimate the normalized metabolic cost of walking

The knee and hip trajectories during the "active" conditions were found to be less than 2° different than those in the "slack" conditions and during the "active" conditions, the ankle trajectories were shifted towards plantarflexion throughout the gait cycle with differences of up to 3° with respect to the "slack" conditions at the peak dorsiflexion angle.

For all subjects, there is no significant difference in step width, step length, and stance time, which is measured by the force-sensing treadmill, in all the "active" conditions when compared to slack conditions. Biomechanical results (changes in kinematics and gait) suggests that the exosuit does not change the wearer's "active" gait in comparison with the "slack" gait. This denotes that suit does not affect the biomechanics of the wearer drastically.

The average metabolic reduction under best conditions is 6.4% ± 3.9% and this is equivalent to the metabolic reduction of 36W power (Power usage for slack is 575W and active is 539W).

### 10.2 Anthropomorphic Soft Exosuit for hand rehabilitation [2]

A lightweight, customizable design is suitable for rehabilitation training or support in ADL. The total weight of the system is 435g, of which only 130g needs to be worn on the arm. Wearers can pick up objects of various shapes and sizes. The precision grip of 27.4N peak force and 23N continuous force has been achieved. Due to less contribution to gripping force, the thumb was excluded from measurement. Grasp the cycle frequency of more than 4Hz is measured. It is estimated that with a 2200mAh battery an average of 1725 grasp movements or 54 minutes of continuous grasping is possible with a continuous power consumption of 2.23A at 7.4V.

It is estimated that an average of 222° of bending angle is required for each finger, which is divided among distal interphalangeal joint, proximal interphalangeal joint, and metacarpophalangeal joint. However, a mean bending angle of 132° is achieved in the prototype presented here. Due to the lesser mass at hand, the design was able to maintain a lower moment of inertia at the wrist and elbow. The force provided for power grip exceeds 20 N and for precision grip, it is 15N.

### 10.3 The cable-actuated dexterous exoskeleton for neurorehabilitation (CADEN)-7 [3]

n the final design, there are three joint configurations as a measure of the relative alignment of two adjoining joints when the joint is centered within its range of motion:1) 90° 2)180° and 3) axial. Joints 1 and 7 are modeled as 180° joints, 2,4 and 6 are 90° joints, and 3 and 5 are axial joints.
In this exoskeleton, the glenohumeral, joint at the shoulder, is designed as a spherical joint with three intersecting axes. The elbow is modeled as a single axis orthogonal to the third shoulder axis. A human-inspired joint is designed for prono-supination of the forearm. And two intersecting axes at 90° actuate the wrist.

### 10.4 Biomechanical Design of the Berkeley Lower Extremity Exoskeleton (BLEEX)[4]

BLEEX was designed to achieve kinematics and dynamics almost the same as humans. This was an initial assumption that made it easier to design the exoskeleton from CGA data. The torque data from BLEEX through experiments suggest that the device is capable of maintaining torque within the maximum limit of the actuator. However, there are noticeable differences in angle, torque data between the measured and CGA(Clinical Gait Analysis). This is due to the BLEEX knee always bending at 5°, the BLEEX torso has a center of gravity behind the human torso but weighs almost the same, and the absence of a perfect torque controller. This mismatch clearly shows that BLEEX kinematics and dynamics are not exact copies of that of humans. Besides, both hip and knee differ most from CGA and consume more energy than predicted whereas the ankle consumes less energy.

CGA data helped design the servo valves, actuator mounting points, and actuator sizes as well.

But still, BLEEX is the first “energetically autonomous lower extremity exoskeleton” capable of carrying a payload of 75Kg and a walking speed of 1.3 m/s.

**10.5 7DOF Pneumatic muscle actuator powered exoskeleton [5]**

The design in [5] is a full arm exoskeleton to introduce a force feedback system to enhance the capabilities of virtual reality simulations. This review is interested in the method of actuation and the design of the 7 DOF upper-limb exoskeleton. However, it is worth to mention that the system has features that can replicate virtual contact forces to the arm for training purposes.

**Table 4:** Torque data of human isometric strength and joint torque achieved by PMA

| Joint | Movement | Human isometric strength | Joint torque using PMA | Percentage accuracy of PMA |
|---|---|---|---|---|
| Shoulder | Flexion/ Extension | 110 Nm | 30Nm | 27.3% |
| | Adduction/ Abduction | 125 Nm | 27 Nm | 21.6% |
| | Rotation | | 6 Nm | |
| Elbow | Flexion/Extension | 72.5 Nm | 6 Nm | 8% |
| | Supination/ Pronation | 9.1 Nm | 5 Nm | 55% |
| Wrist | Flexion/ Extension | 19.8 Nm | 4 Nm | 20.2% |
| | Adduction/ Abduction | 20.8 Nm | 4 Nm | 19.2% |

Table4 suggests that the accuracy of PMA in achieving torque closer to human isometric strength. For supination/pronation, the actuator shows greater accuracy but still needs a better design to obtain an anthropomorphic joint actuation.

## 11. Conclusions

In this study, almost every characteristic of an exoskeleton is taken into account. It is identified that the design largely depends on the purpose of the system and specific requirements. Exosuits are in a stage of development to deliver lighter, low profile, and efficient designs. But their challenges are significant when it comes to certain applications. Hybrid of both rigid and soft materials could be a solution. Tendon driven antagonistic actuation scheme is particularly helpful in providing lighter and compliant motions. Another area of development is in the human-machine interface, where EMG based systems can lead to non-invasive force estimation and feedback control for exoskeletons. The use of soft materials instead of rigid links reduces the weight significantly, but these materials do not support payload or even the weight of the necessary equipment.

Incorporating features of rigid links and soft materials could optimize the necessary characteristics for a new exoskeleton. Hybrid materials should have all the desired properties for an anthropomorphic design. Combining soft actuator materials and rigid but lightweight links can enhance the performance of exoskeletons with desired properties such as lightweight design, low profile, higher frequency, compliance, and comfort for the user, repeatability, and energy efficiency. It is safe to project that in the future hybrid exoskeletons would be habitual and also indistinguishable from non-wearers..

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