**Biomechanics and Bionics: A Full Review of Exoskeleton Development**

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Abstract

Innovative researchers and engineers are taking advantage of novel research findings in the areas of bionics and biomechanics to craft new methods and ideas regarding exoskeleton design and development. Although the exoskeleton term may have its origins within biology, it is now being used for referencing contemporary biomechanical technology. Extensive exoskeleton pioneering work can be attributed to Miomir Vukobratovic and his fellow researchers. Exoskeletons can be designed specifically for either augmentation, rehabilitation or assistance. The exoskeleton systems created currently are designed in accordance with novel biomechanical research results. The most useful information for furthering exoskeleton development stems from biomechanical analysis of human limbs and the utilization of a human-exoskeleton system modeling approach. By coupling musculoskeletal models with exoskeleton models, simulations can be created that feature the response of the human body to the external torques and forces generated and exerted by the device. With the human-exoskeleton models available, biomechanical analysis can be performed in order to simulate both healthy and pathological gait as well. Novel exoskeleton designs are having a drastic impact on the areas of augmentation, rehabilitation and assistance when considering locomotion. The efficacy of exoskeletons is perhaps most evident when considering the effect of these devices on cardiovascular health, bone health and energy expenditure. Within the field of biomechanics, there are numerous sources of evidence supporting the fact that the development of exoskeletons is truly revolutionizing the way humans live.

**KEYWORDS**. Biomechanics, exoskeletons, musculoskeletal, paraplegia, spinal cord injury, bone density, efficacy.

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1. **Introduction**
   1. ***Overview***

The current age of mankind is best described as the age of the *enabled,* where the advancements in biomedical engineering are now making what was once impossible, possible. This is especially true concerning the crossroads of two key areas in the biomedical field: Biomechanical research and bionics. Innovative engineers are taking advantage of novel research findings in the areas of bionics and biomechanics to craft new models, methods and ideas regarding exoskeleton design and development. Although a true exoskeleton definition is hard to establish, an exoskeleton is considered by many to be an assistive device that people can wear on their bodies. More specifically, an exoskeleton is considered to be an active, anthropomorphic device that can be worn by a person as an assistive mechanism [1]. New knowledge and development concerning both biomechanics and bionics has proven to be crucial in combating the struggles in locomotion faced by victims of bone fractures, brain injuries, spinal cord injuries, and even paraplegia. Additionally, exoskeletons have been utilized to maintain proper human health and reduce the risk of injuries. To fully understand the profound effects that biomechanics has had on the development of exoskeletons and the crucial impact of these devices on the capabilities and health of users, it is important to first acknowledge the history, development and biomechanical modeling of exoskeletons.

* 1. ***Exoskeleton Definition***

In biology, the term exoskeleton refers to the external covering on an animal that serves to support and protect the creature [2]. An exoskeleton of this type also serves as a surface for muscle attachment, and most importantly, as a sensory interface with the environment [2]. Although the exoskeleton term may have its origins within biology, engineers and researchers are now using this term to describe novel bionic technology. Exoskeleton-system technology serves many functions and has numerous applications. Some of the key functions include support, such as providing walking assistance for a physically disabled patient, enhancement, in terms of strengthening the human user, sensing and fusing data by acting as an interface between the human operator and the environment, and of course, protection [2]. Many of these functionalities are achieved by the specific design of exoskeletons as they aid in the areas of augmentation, rehabilitation or assistance [3]. Exoskeletons designed for augmentation aim to greatly enhance and optimize many aspects of human locomotion, such as strength, endurance and even metabolic cost [3]. Performance enhancing exoskeletons are of particular interest to the military who strive to develop these systems to aid soldiers on the battlefield, especially for when they are carrying loads [3]. Rehabilitation exoskeletons are specifically designed to help provide the therapy needed to restore normal gait. These systems aid in the restoration of motion and are used to improve gait patterns of patients affected by numerous types of disabilities and illnesses, including strokes and spinal cord injuries [3]. Although exoskeletons may be seen as assistive across all types, purely assistive exoskeletons are designed to compensate for physical disabilities that may be caused by any type of trauma, injury or weakness in the user. With this in mind, it is important that these exoskeleton systems only support the impaired joints and keep the other joints unaffected [3].

* 1. ***The Origins of Exoskeletons***

Exoskeleton development can be traced back to the late 1800s, even though much of this early work was in the form of concept studies in which designs were drawn up but not actually built or even tested [1]. One of the earliest patented devices that resembled an exoskeleton was Yagn’s running aid [1]. This simple running aid, which was patented in 1890, was intended to enhance running and jumping. The device consisted of a leaf spring or bow that operated parallel to the users legs on both sides of the body [4]. Quite a few years after this, exoskeleton design and development was becoming much more alluring and the research being conducted was producing much more complicated devices. In fact, in 1960, Cornell University participated in research (funded by the U.S. Office of Naval Research) with General Electric that aimed at designing a prototype of a full-body powered exoskeleton. The prototype constructed was described as being able to drastically boost the strength of the arms and legs of the user and was quite massive, weighing 680 kg and allowing 30 degrees of freedom [1].

* 1. ***Miomir Vukobratovic***

Around the same time period, being the 1960s and 1970s, extensive exoskeleton pioneering work was being done by Miomir Vukobratovic and his fellow researchers at the Mihailo Pupin Institute in Belgrade. Their first exoskeleton was coined the “kinematic walker” and consisted of a hydraulic actuator that drove the kinematically coupled hip and knee [1]. Following this device, another exoskeleton was created in 1970, called the “partial active exoskeleton”. At the time, this device was one of the most advanced exoskeletons ever created, utilizing pneumatic actuators for flexion and extension of the hip, knee and ankle in addition to an actuated abduction-adduction joint at the hip [1]. Eventually, the “partial active exoskeleton” concept became the “complete exoskeleton” design after certain modifications led to better results. Amazingly, when over 100 clinical trials were conducted with the complete exoskeleton developed by Vukobratovic, quite a large number of patients with certain degrees of paralysis were able to master walking by using the exoskeleton with crutches for enhanced support [1]. Soon after the work of Vukobratovic and his associates surfaced in the fields of bionics and bioengineering, there was a deep interest that began to evolve concerning research in the newly established exoskeleton field. In fact, there was an exoskeleton systems research boom in the late 20th century when numerous designs for these devices were developed by researchers from Germany, the United States and also Japan [2]. Going along with this deep interest, the United States began funding the Defense Advanced Research Projects Agency (DARPA) heavily in order to start performing extensive research related to exoskeletons. Perhaps some of the most recent breakthroughs in exoskeleton design and development came from DARPA in the early 2000s, which include the following devices: BLEEX, Sarcos and MIT Exoskeleton [1].

* 1. ***Success of Exoskeletons***

It is clear that exoskeleton designs started off very basic, but extensive research has uncovered the versatility of these devices and has transformed exoskeletons not only into a concept, but an entire field that relies on human biomechanics. The efficacy of exoskeletons has been so powerful that these mechanical devices are improving cardiovascular health, increasing energy expenditure in those who suffer from disabilities, maintaining body composition and bone health, and overall, improving quality of life. However, designing exoskeletons is very challenging and complex due to the fact that the human factor plays a major role in device development and success [5]. More specifically, successful design of an exoskeleton depends almost entirely on a strong understanding of the biomechanics and sensory mechanisms of the human body, since these two areas affect human-exoskeleton interaction the greatest [5]. By realizing how biomechanical analysis is conducted and how such extensive modeling is formulated, we can begin to understand how these revolutionary devices are being produced to effectively overcome immobility and alleviate the associated detrimental effects on the human body.

1. **Biomechanical Analysis**
   1. ***Anthropomorphism of Exoskeletons***

The exoskeleton systems being invented today are designed in accordance with the biomechanical results that are published from extensive research. In fact, the research results from the field of biomechanics - and associated biomechanical designs - are perhaps the most influential in determining novel exoskeleton prototypes. Exoskeletons should be anthropomorphic in shape and function, and there have been countless proposals over the years for certain exoskeleton designs and structures to achieve this, but it has been extremely difficult to imitate the natural motion of humans [2]. This is why biomechanical investigation is so critical in the development of these devices and essential in critiquing the shape, function and degrees of freedom in new exoskeleton structures. The desired anthropomorphic and ergonomic nature of exoskeletons can be described broadly with two main concepts. The first is that the exoskeleton should be analogous to the human limbs and torso in reference to joint positions and distribution of degrees of freedom [2]. From this, it is clear why we need to investigate and explore what contributes to the mobility of the limbs and trunk during locomotion. As we know now, the main contributions to motion in the human body come from muscle the synovial joints, of which there are six types. These six fundamental joints, which are categorized in accordance with their forms of motion, can be described as follows: Planar, hinge, pivot, condyloid, saddle and ball-and-socket joints [6]. The second main concept is that the actuations in exoskeletons should be allocated in the appropriate positions within the device to best represent and simulate the function of muscles in human limbs and the torso [2]. For example, it is common knowledge that hip motion is created by the extension and flexion of the rectus femoris and the gluteus maximus, while the extension and flexion of the knee is produced by the extension and flexion of the biceps femoris and the vastus maximus. Therefore, to effectively simulate walking by including the activity of muscles in the design of an anthropomorphic leg, actuators, which are components of a device that are responsible for moving and controlling a mechanism in a system, should be positioned in appropriate locations on the leg device to emulate the function of the rectus femoris and biceps femoris [2].

* 1. ***Human-Exoskeleton System Models***

One might ask how such biomechanical investigation could be conducted to yield effective and significant results to be applied towards exoskeleton development. Some of the best information for furthering exoskeleton research is rooted in biomechanics analysis of human limbs and the utilization of a human-exoskeleton system modeling approach. With the continuing advancements of gait analysis equipment, the study of limb kinematics and dynamics has become very precise. Modern biomechanical analysis and research, with respect to limbs, tends to follow a general procedure for optimal results. The procedure starts with motion capture of the motion of interest, such as walking, with a gait analysis program [7]. Then, a mathematical model is used to describe the motion being analyzed in which, for instance, the torque dynamics of each joint can be studied through the analysis software. In addition, muscle forces contributing to the motion under analysis are calculated by inverse dynamics when inputting the experimental data collected by the motion capture system into a muscle biomechanics simulation software [7]. In general, the research process is divided into two parts, one of which is the motion capture system component of the analysis and the other is the biomechanical muscle simulation. The motion capture system of lower limb analysis, for example, consists of three main components. Firstly, multiple high speed cameras are positioned around the test area [7]. Secondly, multiple force plates are positioned on the ground where the human under study will be performing the motion. Thirdly, a series of marked points are positioned on the body of the human being studied so that computer recognition of point coordinates can be used for the dynamics calculations of each joint [7]. The marked points are positioned in accordance with accepted methodologies that have proven to be effective in joint dynamics calculations. Once this system is set up, the experimental human can begin performing the desired motion as the coordinate trajectories of the points are mapped to three-dimensions (from the 2D cameras) to determine the real positions of the markers in space. From this model, the torque at each analyzed joint during gait phases can be calculated and the data collected is analyzed by constructing kinematic models and dynamics models based on multi-rigid body kinematics and Newton-Euler mechanics, respectively [7]. The complex distribution of muscles in tissues makes it difficult to measure muscle forces directly, hence the importance of simulation approaches. In this case, since external forces and boundary conditions are defined for the specific environment under study and there is recorded motion data, a biomechanical muscle simulation can be created by feeding this information into a modeling system, such as the AnyBody Modeling System (ABMS). The system not only runs a simulation of the experiment, but will calculate the individual muscle forces, metabolism, joint forces and moments, and even elastic energy in tendons [7]. Therefore, we can see that quality research in biomechanics, especially when considering the activities of relevant muscles, is a key driving factor in the creation of innovative exoskeleton designs.

* 1. ***Musculoskeletal Models and Model Optimization***

Cutting-edge technology also allows researchers and engineers to design optimal exoskeletons by investigating efficient coupling of the device with the user. With optimization in mind, the human body is considered a centered subject, and this approach is known as human-centered design optimization [5]. This approach, like many others, starts with a particular problem of interest, such as a problem of physical assistance (i.e. patient suffering from paralyzed muscles due to injury). With the problem in mind, different types of exoskeleton designs are considered, but the overall structure of the design should be similar. The key differences here lie in the physical attributes, or design parameters, of the components, such as values for spring constants in an exoskeletal device containing springs. Not only can various device blueprints be created in computer aided engineering software tools, but musculoskeletal models of the human body can be created as well to conduct biomechanical analysis, including analysis of arm motions and muscle activations [5]. By coupling the musculoskeletal model with the exoskeleton model, it is desired to simulate the response of the human body to the external torques and forces generated and exerted by the device [5]. The coupling between the two systems is analyzed through prescribed motions, such as drinking out of a cup, and optimization is investigated by evaluating muscle efforts in each iteration of the simulation. If it was spring stiffness being analyzed, then the parameter iteration requiring the least muscle effort can be determined as the optimal design for an exoskeleton serving this particular function [5].

* 1. ***Full-Body Musculoskeletal Models and Misalignment Compensation***

The most recent developments in biomechanical analysis have resulted in full-body musculoskeletal models for detailed muscle-driven simulations [8]. With these models, biomechanical analysis can be performed in order to model both healthy and pathological gait, where a variety of injuries can be simulated by sending different signal profiles to muscle-tendon segments [8]. Forces and torques can be computed for muscles and joints at the same time too, so not only can complete biomechanical analysis be performed for medical purposes, but it can also be performed for the exoskeleton controller design and the dimensioning of the actuators featured in the device [8]. Musculoskeletal models are truly rich sources of information that are utilized to develop exoskeletons aiming to restore normal gait. In fact, these models helped bring about the concept of misalignment-compensation as a key element of newly developed exoskeletons. More specifically, for exoskeletons designed to help reduce the metabolic cost of motion for the user (i.e. performance augmenting and assistance devices), the inclusion of relevant human degrees of freedom and essentially perfect alignment of the rotation axes is critical to make the device metabolically beneficial [9]. Since perfect alignment is certainly impossible, many devices now have a misalignment compensation mechanism built in that handles misalignment effects during locomotion. Validation of this technology was successfully demonstrated in a novel bilateral hip exoskeleton [9].

1. **Exoskeleton Designs**

***3.1. Overview***

Novel exoskeleton designs are having a drastic impact within the areas of augmentation, rehabilitation and assistance with respect to locomotion. The most effective way to understand this drastic effect is by learning about many specific contemporary exoskeleton designs. In other words, to fully appreciate the efficacy of these devices, we must understand how accurate modeling of the human body, acknowledgement of human biomechanics, and the utilization of advanced actuators, sensors, computer processors and materials are all coming together to construct extremely efficient exoskeletons.

***3.2. Performance Augmentation***

Performance augmentation exoskeletons are of particular interest to the military due to their potential in decreasing fatigue experienced by soldiers during missions or in combat. The Berkeley Lower Extremity Exoskeleton (BLEEX), developed by researchers at U.C. Berkeley, was the first energetically autonomous lower extremity exoskeleton developed to successfully carry a cargo load [10]. BLEEX is best described as an anthropomorphically-based exoskeleton that has seven degrees of freedom per leg in order to provide the user the ability to carry, with minimal effort, substantial loads on their backs over any type of terrain [10]. The main components of this device include two anthropomorphic powered legs, a power supply and a frame to which heavy loads can be mounted. The ability to carry cargo like this stems from the fact that this exoskeleton is guided by human interaction. This means that instead of completely controlling or driving the locomotion, BLEEX shadows the user’s movement as they wear the device as essentially artificial legs [10]. Some of the most critical elements of the BLEEX design include the degrees of freedom at the hip, knee and ankle joints that closely mimic human kinematics. There are three degrees of freedom at the hip, one degree of freedom at the knee and three degrees of freedom at the ankle. These degrees of freedom coincide mostly with the degrees of freedom found naturally in the human body and allow flexion-extension, abduction-adduction and rotation at these various locations [10]. Another exoskeleton designed for performance augmentation is the device termed RoboKnee. RoboKnee is an exoskeleton worn around the knees of users and allows them to climb stairs and perform deep knee bends while carrying loads during locomotion [11]. This device allows the user to stay balanced and in control as they decide when and where to walk while also providing a significant amount of energy to work against gravity during the motion [11]. As the user bends their knee, torque is applied across the knee in order for the user’s quadriceps muscles to relax, since the knee joint angle and ground reaction forces are taken into account by the device. A key element of this design is the low impedance that is attained through Series Elastic Actuators that, in contrast to stiff load cells which are expensive and delicate, consist of compliant elastic elements that are inexpensive, robust and stable [11]. In Series Elastic Actuators, a spring is put between the load and the motor, allowing the sensor to measure the spring deflection that is proportional to the force of the load. Subsequently, the error between the calculated force and the desired force is sent to a control system which finally produces a current on the motor to then provide the appropriate motion [11].

***3.3. Rehabilitation***

Exoskeletons are becoming essential components of the rehabilitation industry and current rehabilitation exoskeletons are revolutionizing the ways of achieving mobility after experiencing disease or injury. For example, hand rehabilitation is being achieved through various exoskeletal designs. A cable-driven exoskeleton for hand rehabilitation, named DexoHand, has been developed for this particular function and allows patients who suffer from spasticity to manipulate their fingers effectively [12]. The key component of this design, being the driven cable, keeps the motor away from the device so that the exoskeleton’s weight is reduced on the patient’s hands. Amazingly, there is a one-to-one correspondence between the finger position and the motor position that enables precise joint angle control [12]. Additionally, tension sensors were designed to be placed on each of the cables that effectively drive the extension and flexion of the fingers so that the force generated by the actuators can be measured precisely [12]. This exoskeleton was studied with stroke patients experiencing various levels of spasticity during continuous passive motion (CPM) therapy and the results showed that DexoHand met clinical needs with excellent usability and tension force monitoring while providing satisfaction to the patients, thereby providing a practical and stable platform for exoskeleton hand rehabilitation [12]. Other exoskeletons have been developed for patient rehabilitation in regard to spinal cord injuries. The MAHI Exo-II exoskeleton is one particular example of these rehabilitative devices. MAHI Exo-II has been implemented to help in exoskeleton-assisted training for improving arm and hand functions in patients suffering from injuries to their spinal cords that induce disabilities such as tetraplegia [13]. In particular, it was hypothesized that intense active repetitive movement training with an exoskeletal device such as MAHI Exo-II could help improve arm and hand motor function in patients with chronic tetraplegia, while evaluation of this device’s therapeutic potential in mild to severe arm paralysis could be done as well during clinical trials [13]. The MAHI Exo-II exoskeleton is a haptic and electrically actuated upper limb device that allows five degrees of freedom. This device is perfect for its therapeutic applications because it allows therapy to be delivered to both arms of the patient which often have various levels of impairment [13]. This is because traumatic spinal cord injuries very often produce bilateral arm weakness which results in unbalanced impairment in voluntary movement control of both arms [13]. After a study was conducted using this device, it was found that there was a substantial change in muscle strength in elbow extension and little finger abduction, while grip and pinch force also demonstrated substantial improvement after the treatment itself and a six month follow-up [13]. A different novel exoskeleton design experiment conducted by Yun-Ping Sun and other researchers to combat lower-limb disabilities yielded promising results in aiding rehabilitation and function. The design involved pneumatic artificial muscles for human lower limb motion that, when worn by a human test subject, resulted in little effort to move the subject’s leg and displayed incredible human-robot collaboration [14].

Another novel gait rehabilitation device is the KNEXO knee exoskeleton. This exoskeleton was constructed such that it would be wall grounded instead of body grounded, consisting of a mechanical structure that demonstrates a serial linkage interconnected by a revolute joint that functions along with the human knee [15]. Additionally, the mimicked knee joint is powered by pleated pneumatic artificial muscles and this powered joint was designed to be capable of providing a joint torque, speed and range of motion that is closely related to natural knee joint performance [15]. This exoskeleton was tested in a pilot study to determine its effectiveness on gait rehabilitation in patients suffering from strokes and multiple sclerosis. After comparing walking analysis data of these patients with and without the device, it was found that the KNEXO exoskeleton significantly improved gait. More specifically, KNEXO provided a small flexion torque to prevent hyperextension of the knee during stance while also greatly reducing the variability of the joint angle [15]. Extension torques up to 10 newton-meters helped provide significantly more symmetric and smooth extension-flexion during the swing phase and resulted in a flexion angle that enabled a larger foot clearance in comparison to unassisted walking [15]. Overall, this device demonstrated impressive therapeutic potential for aiding in improved gait symmetry for patients dealing with impaired knee function.

***3.4. Assistive Exoskeletons***

Exoskeletons designed strictly for locomotive assistance purposes during everyday life have significantly impacted the capabilities of those fortunate enough to use them. Such exoskeletons, for example, have helped prevent over-extension injury and even improved firearm training. In order to strengthen a variety of muscle groups, numerous methods for upper limb muscle training using various exercise devices or machines have been proposed in recent history with the limitation that they isolate specific muscle groups from being trained when controlling the direction of resistance [16]. To eliminate this limitation, compact and cost-effective novel exoskeletons are being designed with a shoulder and elbow joint, with three degrees of freedom and one degree of freedom, respectively, that enables the user to train more muscle groups [16]. This is due to the fact that these exoskeletons allow the user to move their limb in various planes with increasing resistance by simply adjusting the spring length. The springs of the exoskeleton are specifically designed to equalize the joint torques, with respect to abduction-adduction and flexion-extension, for the elbow and the shoulder joints with the joint torques experienced during free-weight exercises [16]. Results of preliminary studies with healthy subjects show that this exoskeleton design had an equal effect on elbow and shoulder joint torques with respect to free-weight exercises with the advantage that the risk of overextension was eliminated [16]. A more specific assistive exoskeleton, termed the ARCTiC LawE, has been developed as an upper body exoskeleton for firearm training [17]. The full device name is the Armed Robotic Control for Training in Civilian Law Enforcement, and as the name implies, it is utilized to assist members of the military, civilians and even law enforcement personnel in practicing precise, accurate and reliable handgun techniques [17]. This training device consists of a laser-based handgun with dimensions and trigger pull mimicking handguns commonly used in the private and public security sectors. The great benefit of this exoskeleton is that it has a significant influence on sensory motor learning [17]. Moreover, the biomechanical implications have been successfully confirmed due to physiological and performance data taken from studies training subjects with and without the ARCTiC LawE in regard to accuracy, speed and precision [17]. Not only does this device increase the effectiveness of law enforcement and military drills, but it also acts as a great substitute training exercise for live-fire handgun drills that typically are expensive, dangerous, and require even more training time [17].

1. **The Effect of Exoskeletons on The Human Body**

***4.1. Combatting Spinal Cord Injuries (SCI)***

The efficacy of exoskeletons is perhaps most evident when considering the effect of these devices on cardiovascular health, bone health, neural pathways, energy expenditure, body composition, level of physical activity and, especially, quality of life. The hybrid assistive limb (HAL) exoskeleton, for example, has been shown to normalize cortical excitability in the primary somatosensory complex and improve walking parameters in patients who experience SCI [18]. As a consequence of SCI, significant structural and functional reorganization of the primary somatosensory and primary motor cortices occurs and results in increased excitability in sensorimotor cortical areas in addition to enlarged cortical maps [18]. The HAL exoskeleton enables researchers to monitor muscle contractions through surface EMG electrodes placed at the extensor-flexor region of extremities. The design of this device allows voluntary machine-supported motion by utilizing minimal signals recorded at the flexors and extensors of limbs, such as the hip and knee [18]. In various studies, the HAL exoskeleton was coupled with body weight supported treadmill training (BWSTT) in order to analyze improved functional abilities in patients with SCI. It was found that this exoskeleton did in fact improve functional abilities for over-ground walking in multiple walking tests due to the device’s ability to form the foundation for a proprioceptive feedback loop in SCI patients with sensory pathway trauma [18]. Patients with SCI often struggle or fail to regain the ability to perform daily activities such as walking and sit-to-stand motion. Even after completing rehabilitation programs, more than half of such SCI patients remain with substantial disabilities, hindering ambulation and sit-to-stand motion [19]. Even though unpowered orthoses have been developed to help aid these patients in regaining proper locomotion abilities, these devices often require large input energy from the user and unfortunately present unnatural movement patterns [19]. However, wearable exoskeletons have been designed to specifically help retrain patients in standing, walking and sit-to-stand (STS) tasks. In particular, the initial inclination angle of the body’s center of mass, the rate of change of this angle (angular velocity) and center of mass momentum have all been analyzed in a study with various test combinations in order to optimize balance control and energetic consumption of the patient [19]. From the results of the study, it was found that the initial hip angle directly affected maximum lumbar efforts, and more specifically, it was concluded that a greater initial hip angle coupled with a smaller angular velocity was the best combination of the two variables in order to provide an appropriate compromise between balance of the body and momentum transfer [19]. It is important to note that increasing the angular velocity helped reduce the total required mechanical energy. Not only did this study show that lower limb exoskeletons can increase the quality of life of SCI patients, but it also provided data that will be beneficial in improving the design and clinical use of exoskeletons created to help users struggling with conditions like SCI [19].

***4.2. Adipose Tissue and Energy Expenditure***

Individuals with impaired locomotion, such as those with SCI, experience an increased percentage of body fat due to physical inactivity. Among the SCI population, one of the leading causes of death is cardiovascular disease and similar metabolic abnormalities due to the accumulation of excess fat in the visceral cavity [20]. However, those that suffer from SCI no longer have to be immobilized due to their condition. Instead, these individuals can utilize powered exoskeletons in order to exercise through rehabilitation and over ground ambulation, ultimately resulting in positive effects on cardiometabolic health and body composition [20]. In an observational study lead by Christopher Cirniglario, changes in total body fat mass, total body fat percent, subcutaneous adipose tissue percent and even visceral adipose tissue percent were analyzed after patients with chronic SCI underwent 100 sessions of powered exoskeleton training [20]. Upon completion of the study, not only did the exoskeleton serve as a mechanism for sufficient energy expenditure, but it reduced most of the measures of central adiposity including total body adiposity. As a result, there is a reduced risk of metabolic syndrome and cardiovascular disease in SCI patients who are able to utilize exoskeletons for exercise [20]. Along similar lines of the previous research, a clinical study investigated heart rate and oxygen demand within individuals suffering from paraplegia during powered exoskeleton-assisted walking [21]. As part of this study, eight paraplegics were trained to move with the ReWALK powered exoskeleton and practiced the motions associated with sitting, standing and walking while average oxygen uptake and heart rate was monitored [21]. As expected, the average values for oxygen uptake and heart rate were substantially larger during walking than in any of the other exercises, thereby demonstrating the ability of the ReWALK device to allow persons stricken with paraplegia to locomote effectively and efficiently [21]. Additionally, two of the key findings of the study were that the ReWALK exoskeleton enabled greater locomotive efficiency for walking in comparison to passive orthotic devices (i.e. RGO, ARGO, Parawalker) and that devices like ReWALK, if used routinely, can increase regular activity and possibly improve the health consequences of paralysis, including adiposity, insulin resistance and even carbohydrate tolerance [21].

***4.3. Bone Health***

Bone health is another crucial component of the human condition that exoskeletons have a tremendous impact on, especially in reference to space exploration being conducted by the National Aeronautics and Space Administration (NASA). The two main concerns that NASA has for crew health in space is muscle atrophy and bone density loss due to the lack of gravity and absence of natural compression loading on the body [22]. Although numerous hours have been spent by crew members on board the International Space Station (ISS) maintaining a specific workout regimen to counteract this lack of gravity, researchers at NASA are looking to utilize exoskeletons in order to develop new, innovative exercise technologies. By using these exercise technologies, crew health would be maintained effectively and efficiently as the lengths of missions could also increase, thereby encouraging deeper space exploration [22]. The X1 exoskeleton is the device that NASA has a particular interest in to help further their goals regarding new exercise technologies. The X1 exoskeleton was initially developed for aiding mobility on Earth but was soon recognized as having incredible potential for use in space and as a muscle strength measurement device [22]. This exoskeleton is designed for lower extremity use and, through the positioning of actuators at the knees and hips, can either assist or resist human movements. NASA is aiming to use the small and portable X1 device as a method of providing muscle resistance at the hips, knees and ankles in order to allow crew members to perform concentric and eccentric exercises [22]. Currently, this exoskeleton has four active degrees of freedom at the knees and hips while also having six passive degrees of freedom for internal and external rotation, abduction and adduction, and lastly, dorsiflexion and plantarflexion [22]. The X1 device is more beneficial than existing exercise devices aboard the ISS because of three key reasons. First, existing devices are usually massive and often require a large vibration isolation system to decrease the vibrations transmitted to the ISS during workouts. Instead, X1 is of small size and low profile, resulting in low cost and low storage requirements during space travel [22]. Additionally, the vibrations transmitted to the capsule are essentially eliminated due to the forces imparted in the device existing in a closed loop system. The second main reason is that the X1 exoskeleton allows substantially greater real-time feedback to physicians on Earth in comparison to current exercise devices aboard the ISS. More specifically, this exoskeleton allows resistances and automated movements to be regulated in real-time in addition to acting as a method for conducting specific muscle strength assessments that physicians and crew members can monitor easily [22]. Lastly, X1 is a desirable device to have on board the ISS since it does not restrict crew members to certain areas in the station for exercises. It is clear that this device, when tested and developed appropriately, will be able to help astronauts maintain bone density, muscle strength and their overall health during extensive space exploration missions.

1. **Conclusion**

Within the field of biomechanics, there is countless evidence supporting the fact that the development of exoskeletons is truly revolutionizing the way humans live. Not only has the effectiveness of these devices been shown throughout individual studies, but systematic reviews, such as the one published by Stefano Federici and affiliates, have highlighted the efficacy of these devices across the board while also addressing safety concerns [23]. Within Federici’s review, 27 studies published over the course of about 15 years starting from 2001 were analyzed, which involved over 140 participants from more than six countries. As a result of the review, it was concluded that exoskeletons provide a safe and practical method for neurorehabilitation, and such conclusions could certainly be extended to other applications of these devices as discussed prior [23]. Additionally, it was concluded that exoskeletons, while being easy to learn, require minimal demands on working memory and are not too physically exhaustive. These devices improve the functioning of limbs in mobility and significantly reduce the risk of subsequent injury by the re-establishment of more common gait patterns [23]. However, there do exist limitations in this discipline and market in regard to the availability of exoskeletons, the pricing of these devices, and also experimental methods for showing the relative efficacy of these devices in comparison to alternative technologies [23]. Unfortunately, these devices are not readily available to commercial businesses or consumers yet because of the development that still needs to be done. Additionally, these devices can reach somewhere around $77,000 individually, making them difficult to acquire [24]. The only way to make these devices more available at more affordable prices is by continuing research and testing. If this type of device was highly available to patients who suffer from related mobile and functional limitations, disability would not have to be experienced by these patients anymore as there would be a method to improve their limitations and make use of their deficient limbs.

Overall, the advancements in biomedical engineering in regard to biomechanics and bionics are dramatically transforming the way we currently live. At the crossroads of biomechanical research and bionics, researchers and engineers are taking advantage of novel exoskeleton designs to develop extraordinary devices that are capable of augmenting human performance, assisting those who struggle with locomotion in many respects, and serving as instruments for rehabilitation. Moreover, research has exposed the ability of exoskeletons to help in maintaining the well-being of humans, especially when considering cardiovascular health, bone density, adiposity and the overall composition of the body. The capabilities of such devices are rooted in extensive and elaborate biomechanical testing and simulations that heavily influence the final design and functionality of exoskeletons. Without a deep understanding of human biomechanics and the vast amount of resources available to model and build exoskeletons, the extent to which this field has developed would be minimal.

References

1. Ali, H. *Bionic exoskeleton: history, development and the future*. in *IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE), International Conference on Advances in Engineering & Technology*. 2014.

2. Yang, C., et al., *A review of exoskeleton-type systems and their key technologies.* Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 2008. **222**(8): p. 1599-1612.

3. Gálvez-Zúñiga, M.A. and A. Aceves-López, *A review on compliant joint mechanisms for lower limb exoskeletons.* Journal of Robotics, 2016. **2016**.

4. Yagn, N., *Apparatus for facilitating walking, running and jumping. 420,179.* US Patent, (1890).

5. Zhou, L., Y. Li, and S. Bai, *A human-centered design optimization approach for robotic exoskeletons through biomechanical simulation.* Robotics and Autonomous Systems, 2017. **91**: p. 337-347.

6. Premkumar, K., *The massage connection: anatomy and physiology*. 2004: Lippincott Williams & Wilkins.

7. Chen, J., X. Mu, and F. Du, *Biomechanics analysis of human lower limb during walking for exoskeleton design.* Journal of Vibroengineering, 2017. **19**(7): p. 5527-5539.

8. Cardona, M. and C.E.G. Cena, *Biomechanical Analysis of the Lower Limb: A Full-Body Musculoskeletal Model for Muscle-Driven Simulation.* IEEE Access, 2019. **7**: p. 92709-92723.

9. Junius, K., et al., *Bilateral, misalignment-compensating, full-DOF hip exoskeleton: design and kinematic validation.* Applied bionics and biomechanics, 2017. **2017**.

10. Zoss, A., H. Kazerooni, and A. Chu. *On the mechanical design of the Berkeley Lower Extremity Exoskeleton (BLEEX)*. in *2005 IEEE/RSJ international conference on intelligent robots and systems*. 2005. IEEE.

11. Pratt, J.E., et al. *The RoboKnee: an exoskeleton for enhancing strength and endurance during walking*. in *IEEE International Conference on Robotics and Automation, 2004. Proceedings. ICRA'04. 2004*. 2004. IEEE.

12. Tsai, Y.-L., et al., *Usability Assessment of a Cable-Driven Exoskeletal Robot for Hand Rehabilitation.* Frontiers in neurorobotics, 2019. **13**: p. 3.

13. Francisco, G.E., et al., *Robot-assisted training of arm and hand movement shows functional improvements for incomplete cervical spinal cord injury.* American journal of physical medicine & rehabilitation, 2017. **96**(10): p. S171-S177.

14. Sun, Y.-P., et al., *Design of a bionic-inspired exoskeleton robot for lower limb assist.* Journal of Vibroengineering, 2016. **18**(8): p. 5452-5461.

15. Beyl, P., *Design and control of a knee exoskeleton powered by pleated pneumatic artificial muscles for robot-assisted gait rehabilitation.* Mechanical Engineering, 2010.

16. Wu, T.-M., S.-Y. Wang, and D.-Z. Chen, *Design of an exoskeleton for strengthening the upper limb muscle for overextension injury prevention.* Mechanism and Machine Theory, 2011. **46**(12): p. 1825-1839.

17. Schnieders, T.M., et al., *ARCTiC LawE: An Upper-Body Exoskeleton for Firearm Training.* Augmented Human Research, 2017. **2**(1): p. 1.

18. Sczesny-Kaiser, M., et al., *HAL® exoskeleton training improves walking parameters and normalizes cortical excitability in primary somatosensory cortex in spinal cord injury patients.* Journal of neuroengineering and rehabilitation, 2015. **12**(1): p. 68.

19. Mao, H.-F., et al., *Balance Control and Energetics of Powered Exoskeleton-Assisted Sit-to-Stand Movement in Individuals With Paraplegic Spinal Cord Injury.* Archives of physical medicine and rehabilitation, 2018. **99**(10): p. 1982-1990.

20. Cirnigliaro, C.M., et al., *Decreased total and central adiposity after 100 exoskeletal-assisted walking sessions in persons with chronic spinal cord injury.* Journal of Clinical Densitometry, 2018. **21**(4): p. 1.

21. Asselin, P., et al., *Heart rate and oxygen demand of powered exoskeleton-assisted walking in persons with paraplegia.* Journal of rehabilitation research and development, 2015. **52**(2): p. 147.

22. Rea, R., et al. *X1: A robotic exoskeleton for in-space countermeasures and dynamometry*. in *AIAA space 2013 conference and exposition*. 2013.

23. Federici, S., et al., *The effectiveness of powered, active lower limb exoskeletons in neurorehabilitation: a systematic review.* NeuroRehabilitation, 2015. **37**(3): p. 321-340.

24. Eveleth, R. *Exoskeletons for the Disabled Let Cities off the Hook.* 2015; Available from: [www.theatlantic.com/technology/archive/2015/08/exoskeletons-disability-assistive-technology/400667/](file:///Users/Kyle/Downloads/www.theatlantic.com/technology/archive/2015/08/exoskeletons-disability-assistive-technology/400667).

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