Considerations for the Use of an Exoskeleton for Extremity Control and Assistance when Learning to Walk with Cerebral Palsy

By

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Abstract

Cerebral palsy is an occurrence in which the nerves and muscles if the body may function properly, but there is damage to the brain that causes it to transmit incorrect electrical impulses to the muscles including both too many and too few signals. Without the correct cohesive electrical impulses to balance the opposing muscles of a joint, normal everyday tasks that most of us take for granted become very difficult to learn and perform. As exoskeletons become more advanced and practical, their applications have a lot of room for growth. Cerebral Palsy is one portion of the medical field that can benefit from the development of exoskeletons. As demonstrated with modern rehabilitation techniques, the application of an exoskeleton has the possibility of making the learning process and performance of many tasks easier and faster for both the patient as well as the doctor working with them. However, in order to appropriately apply the technology to the need, many changes in both the controls and the actual physical design of current devices need to be addressed.

An exoskeleton for the purpose of helping cerebral palsy patients learn to walk is not limited to one specific form depending on the complexity of the tasks it is desired to assist with. However, there are a couple needs of this type of exoskeleton that are absolutely necessary. The size of the exoskeleton must be designed around the size of a child and not an adult. If the individual is learning to walk from the very beginning, the controls of the device will need to initially be able to take complete control over the individual's limbs to exercise the motions of walking. With the nature of an exoskeleton controlling the limbs of a person instead of simply assisting with current movements, the physical attachments of the exoskeleton must be improved from current designs in order to make movements of the exoskeleton and the body more parallel. Other features such as different muscle sensing techniques may also improve performance, but are not required. An exoskeleton that can help cerebral palsy patients learn to walk can also be applied to many other rehabilitation needs.

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Acronyms

ATP	Advanced Technology Program
BLEEX	Berkeley Lower Extremity Exoskeleton
COM	Center of Mass
CP	Cerebral Palsy
DARPA	Defense Advanced Research Project Agency
DARwin	Dynamic Anthropomorphic Robot with Intelligence
EMG	Electromyography
HAL™	Hybrid Assistive Limb
HULC™	Human Universal Load Carrier
NIST	National Institute of Standards and Technology
PT	Physical Therapy

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Chapter 1. Introduction

As exoskeletons become more advanced and practical, their applications have a lot of room for growth. We have seen the first exoskeletons hit the market very recently as proof of concept, design, and production, and focus is beginning to change to varied purposes. One very important and large field of interest is medical application of these devices. Cerebral Palsy (CP) is only one small portion of the medical field that can benefit from the development of exoskeletons. This disorder affects the motor functions of many people all over the world. The damage to the brain of individuals living with CP not only makes many mundane physical tasks difficult to perform, it makes those skills much more difficult to learn. This learning process may take much longer than it would for someone without CP, and it can even make some actions unachievable. With the application of an exoskeleton, this learning process can be made easier and faster for both the patient as well as the doctor working with them. However, in order to appropriately apply the technology to the need, many changes in both the controls and the actual physical design of current devices need to be addressed. This paper will focus on the specific physical integration of one exoskeleton for the needs of learning to walk with CP, but the concepts may be applied to any exoskeleton in the interest of similar physical therapy and aid. As the target use of an exoskeleton varies, so must the physical design to fit that need. For example, an exoskeleton designed to help soldiers carry extremely heavy loads on their backs may not be the most effective to help another run exceedingly fast. At this point in time, we must still rely on the idea that function dictates form. The levels of technology that would be required for an exoskeleton to be integrated so well with the human body as to improve all aspects of motor function are not even on the horizon yet. This paper will provide

- A comprehensive background of the nature of CP
- The current level of technology of exoskeletons
- What is needed for an exoskeleton to aid in learning to walk with CP
- How to accomplish the specific needs of CP
- Projected benefits of the device

The background on CP will include typical symptoms and some therapies that are in use today to give a better understanding of what issues need to be addressed with the patients.

The discussion of modern exoskeletons will present a look at what they are capable of at this point in time. This will show how others have taken the first steps towards of combining robotics and the human body. These two topics will be combined to study what will be needed in order for an exoskeleton to successfully help CP patients learn to walk. This will be followed by how these needs can be met, and finally, the projected benefits of the device will hypothesize the projected benefits for CP patients as well as others based on previous research. It is important to remember that this analysis can be applied to many other situations and needs. A particular invention may not be nearly important as discovering or realizing the applications that can greatly benefit others from it. For example, a Segway can make life slightly more convenient and easy for a typical person. However, the same technology applied to a wheel chair in the form of the iBOT™ can dramatically improve the mobility and quality of life for those requiring the use of a wheelchair, including climbing stairs and curbs as well as reaching high shelves that a fully able person can reach. Fortunately, in this case the wheel chair application was the initial intent [Segway, Inc. (2008)].

1.1 Types of CP

There are over 600 muscles in the human body working in opposition at each joint of the body. Because muscles can only exert force through contraction, there must be opposing muscles functioning simultaneously to smoothly control the extension and retraction of every joint. The brain controls the muscle functions of the body through electrical impulses delivered through the nervous system. Cerebral Palsy is an affliction of the brain that affects about 2 out of every 1000 children born in industrialized countries, with the rate being higher in underdeveloped countries. It is an occurrence in which the nerves and muscles if the body may function properly, but there is damage to the brain that causes it to transmit incorrect electrical impulses including both too many and too few signals. Without the correct cohesive electrical impulses to balance the opposing muscles of a joint, normal everyday tasks that most of us take for granted become very difficult.

CP can be broken down into three primary types, characterized by the way muscle functionality is affected and the part of the brain that is damaged. The most common

form is Spastic CP. It is a result of damage to the cerebral cortex portion of the brain seen at the top of Figure 1.1 and Figure 1.2, and accounts for about 70-80% of all cases. This part of the brain is commonly known for the purpose of the left portion controlling the right side of the body and the right portion controlling the left side of the body. The resulting electrical signals from a brain with this form of damage commands the certain muscles to remain contracted the majority of the time. The contraction of opposing muscles at a joint cause it to behave in a stiff and jerky manner in which the individual is fighting against their own muscles to alter the angle. Smooth operation requires the relaxation of one of the sets of muscles as the other contracts. This can be imagined as similar to attempting to curl the right arm towards the chest while pushing it away with the left arm. These affected muscles are typically very lean from continuous exercise from contraction. This type of CP is often characterized by legs that are turned inwards with the knees slightly buckled and straightened fingers. This type of CP is also often difficult to assist with, because it is important not to force movement when the resistance is too great. The act of forcing any movement may result in painful damage to the muscle.
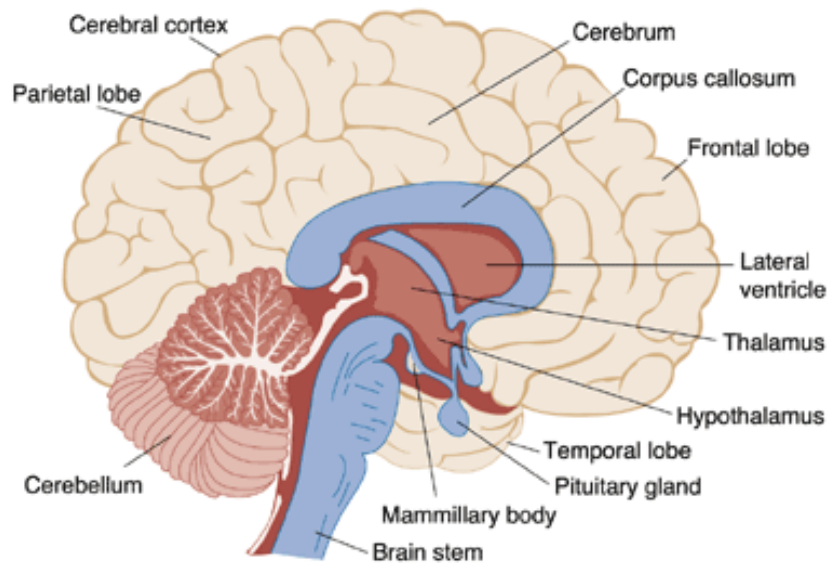

Figure 1.1 An image of the human brain. Special attention, for our purposes, should be paid to the location of the cortex and cerebellum. [Tapert et al. (2008)]

Ataxic CP is a condition resulting from damage to the cerebellum, located at the rear and bottom of the brain just behind the spinal cord, as seen in the lower left portion of Figure 1.1. This portion of the brain not only plays a role in motor control, working in combination with the cortex, but it is also an element of the brain that deals with sensory perception. This form of CP accounts for about 5-10% of all cases. The resulting muscle controlling electrical signals from a brain with ataxic CP command the affected muscles to be too relaxed the majority of the time. This can cause very weak movements or a lack of indented movement all together. With this part of the brain's multipurpose, the damage to the cerebellum also affects the balance and depth perception of the individual. These symptoms combine to cause the symptoms of unsteady walking, poor coordination, and tremors. The combination of poor balance with a lack of ability to control the muscles to correct that balance can be particularly difficult to function with. Not only is this form of CP affecting the control of the movements, but also the feedback required to improve these movements.

Athetoid CP is the third and final classification of CP resulting from damage to the basal ganglia, which are a group of central nervous system components located in the center of the brain that connect to the cortex and the brainstem as seen in Figure 1.2. These components are associated with a number of different functions such as cognition and learning, but most directly importantly for our interests, motor control. This form of CP accounts for about 10-20% of all cases. The electrical signals from a brain with damage characterizing athetoid CP can cause muscles to be too tight at some times while too loose at other times. This change in muscle state can occur randomly from relaxed to contracted and vise versa. This can make it difficult for an individual to hold a steady position, it can cause involuntary movements such as spasms or twitches, and it can make it difficult to hold objects in the hand. Also, precise movements, often with the hands and arms, may require increased concentration.
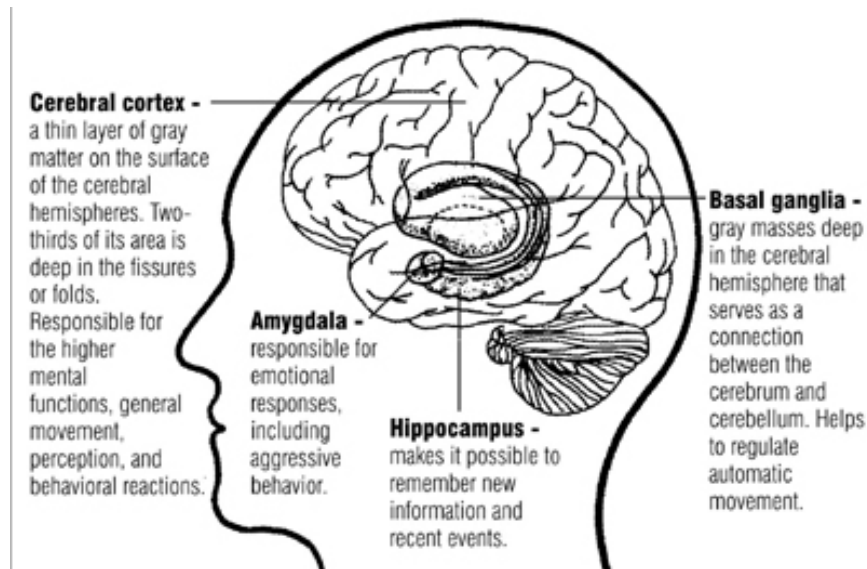
Figure 1.2 An image of the brain with general descriptions of certain parts. Special attention should be paid to the cerebral cortex and the basal ganglia. [National Institute of Mental Health (2008)]

Since these three types of CP are caused by damage to three different parts of the brain, it is possible for an individual to be diagnosed with mixed CP. If multiple parts of the brain are damaged, these individuals can display a combination of symptoms from any two or all three types of CP. This is the reason it is often difficult to firmly make a decision as to what percentage of CP patients fall under each of the three types previously discussed, and why the previously stated percentages may not add up to exactly 100%. In general, Figure 1.3 shows an approximate breakdown of the percentages of the different types of CP, however, 25% of all patients also display symptoms of this mixed CP affliction. Some muscle groups may remain too tight, others may be too loose, while others may fluctuate back and forth randomly. The combination possibilities are essentially infinite, with the level of affliction of each symptom being taken into consideration.

70-80%

Spastic
Ataxic
Athetoid

10-20%   **5-10%**

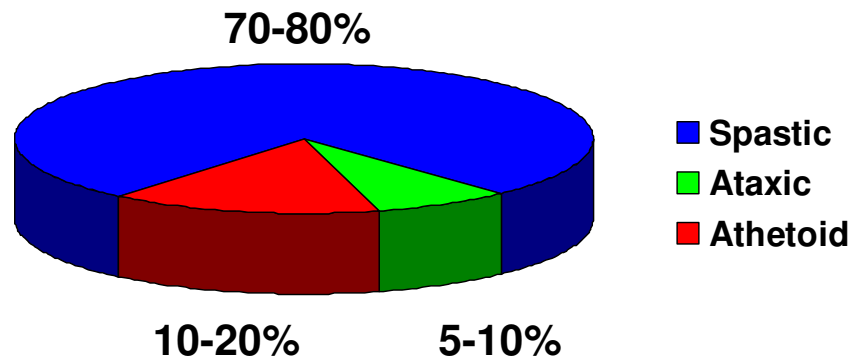**Figure 1.3** Overall relative percentages of cerebral palsy types among patients. Percentages overlap, because some patients show signs of multiple types.

The affected areas of the body can also be used to further break down different classifications of CP into three more types as seen in Figure 1.4. Quadriplegia is a case where all four limbs are affected by CP. However, each limb does not necessarily have to display the same symptoms as the rest. An individual's face and torso may also be affected by the brain damage similar to their extremities. Individuals with quadriplegia may require a wheelchair for any mobility, because of the complete affect of the disorder. This is the highest level of CP that can be diagnosed. Hemiplegia is a case when half of the body, left or right, is affected by CP. These individuals may be able to walk or even run, but their movements are often corrupted by a limp or other extraneous movement. Cooperation between the affected side and the fully functional side may produce cleverly alternative ways to perform some tasks. Diplegia is a case where only the lower body, primarily the legs, is typically affected. It is possible for only the upper body to be affected, but this case is rare. This unlikely case usually affects only the arms, but can also involve the torso, neck, and head in some cases. This level of affliction may require the use of crutches, a walker, or even a wheel chair for improved or any mobility.
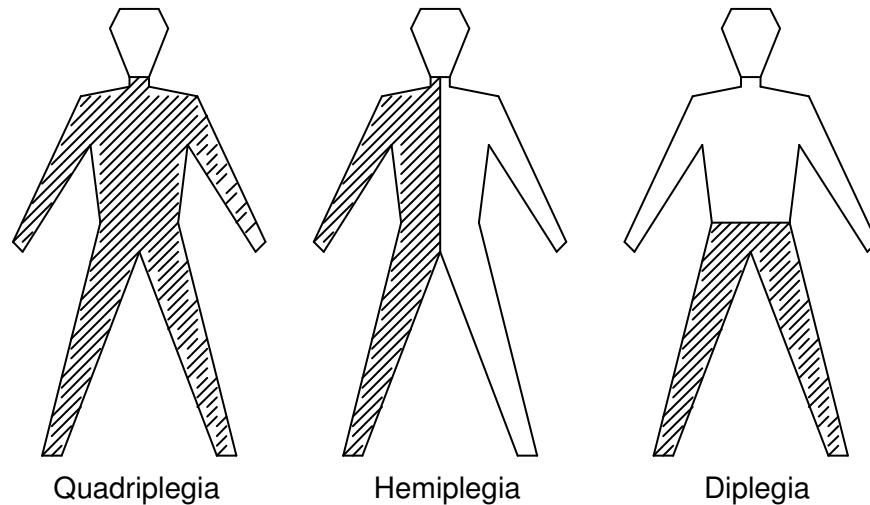
Figure 1.4 Common areas of cerebral palsy affliction. However, it is important to note that cerebral palsy can affect more than the highlighted regions. Hemiplegia can affect either side of the body. Diplegia can affect just the upper body, but it is rare. The face, neck, and head can also be affected by cerebral palsy.

1.2 Causes of CP

In the past, there were many speculations, but no concrete findings on what can cause CP. Today, it is known that there are many different causes for CP, and that the majority of individuals with the affliction are born with it. The time that a child is developing in the womb is a sensitive time when circumstances can affect an individual for the rest of their life. These complications can often be difficult to detect as well as prevent. For example, restricted blood supply to the developing brain can cause damage to tissues in a number of different areas. Maternal infection and fever can damage the white matter of the brain of a developing fetus. Damage to the white matter of the brain, which is part of the cortex, can cause interferences with electrical signal transmissions to the muscles from the brain. Brain damage can also simply be caused by genetic abnormalities possibly passed on from the mother or father. A fetal injury from a traumatic incident such as a fall or car accident can be severe enough to damage to a developing child as well.

If a child is not born with CP, it can still develop it after birth. If a child does in fact develop CP after birth, it is most commonly within the first couple of months out of the womb. This is because the child's body is still undergoing intense development. The

body has not developed the full protective or repair methods to prevent permanent damage. A transition incident that has been known to cause damage by restricting oxygen to the brain can occur during birth. If the child gets "stuck" on the way out or if the child does not start breathing soon after emergence, the brain is deprived of oxygen. A lack of oxygen can destroy tissue in the cerebral motor cortex and other areas. A brain infection such as bacterial meningitis (an inflammation of the membranes protecting the central nervous system) or viral encephalitis (an inflammation of the brain that can be caused by bacterial meningitis among other things) can also inflict sufficient damage to the brain to cause CP. The human body naturally produces bilirubin, which can protect tissues from oxidative damage, but when these levels are too high it is known as Jaundice. In newborn children this excess of bilirubin can penetrate the underdeveloped tissue protecting the brain and damage the basal ganglia, responsible for athetoid CP. This particular cause of brain damage is known as kernicterus.   Infant strokes can cause bleeding in the brain, and this has also been known to cause enough damage to result in CP. As with traumatic incidents while still in the womb, severe head injury from an incident such as a car crash within the first couple months of life can cause damage similar to that of fetal injury. Unfortunately, there are also cases in which the cause of CP is unknown. Whether a child is born with CP or develops it after birth, most symptoms will appear by age three. For example, one sign of improper muscle control in newborn babies is a "drooping" effect. When held face down by the torso, a healthy newborn baby's arms and legs should remain bent with some movement. The limbs of a child with CP may hang limp below the child will little or no motion.

There are also a number of situations that may not necessarily cause CP, but they increase the chances of suffering the damage that causes it. Premature births, multiple births, a fetus being small for its gestation period, being born in breach position, and complications in labor or delivery all increase the chances of CP. The mother can also increase the chances that her child has CP. Increased risk situations involving the mother include ones that have a different blood type than their child, thyroid abnormalities, mental retardation, and mothers who have seizures. Individuals with CP are also more likely to have other disorders. About half of all individuals who have CP also have other mental disabilities such as seizure disorders, and about two thirds have a form of mental

retardation. Those diagnosed with CP are also more likely to have vision impairments or hearing loss. Despite these increased risks of other afflictions, CP may be the only disability an individual has. It is absolutely possible to be a very intelligent and mentally stable individual who simply lacks proper muscular control. This can be one of the most frustrating situations for the individual.

1.3 Therapy for CP

There is no cure for CP, because the cause is damage to physical tissue, but there are many therapies that can improve the quality of life for those living with it. With any human action, practice and repetition can improve control and precision. Despite the damage to the brain and improper electrical signals to the muscles, the same is applicable to those with CP to improve motor function. Practice and repetition can improve the communication between the brain and the muscles, but it may take more time and effort for those with CP. However, some of the physical limitations of CP may prohibit the performance of some motor skills with proper or traditional techniques. If this is the case, the desired function may still be achievable with an altered technique that works around these limitations. Learning alternate techniques for certain functions may be necessary for motor skills and mobility. For any individual who is learning the basic motor skills of life, with or without CP, learning them in natural progression can increase the learning rate as well as proficiency. However, for individuals with CP, this may mean that many skills usually learned at a very young age, are learned at a later point in life. This process of learning a certain progression of skills, no matter what the age of the patient, is known as patterning physical therapy (PT). The PTs for individuals with CP are not only beneficial with basic motor function, but can also be utilized for occupational and recreational purposes. Occupational PT is simply focusing on motor skills that will assist with the patient's proficiency and diversity in their occupation. Recreational PT, on the other hand, is not necessarily focused on making the individual better at "playing," but to make the task of PT more enjoyable. Many of the motor skills used in recreational activities are also used in everyday life and work. If a demanding task such as PT can be made fun, the patient is more likely to put more effort into it, especially if the patient is a child. For some complex actions with danger of injury while

learning, such as walking, doctors often reduce these risks in a number of ways. One simple method is to perform therapeutic exercises in water with flotation devices. The buoyancy can help with balance, and the movement resistance of the water can increase the development of some muscles. More complex methods involve intricate setups of elastic bands to aid in support of body weight, balance, and stability. One such PT has been named "Spider Therapy," after the elastic bands that resemble of a spider's web. However, sometimes the limitations of CP are inhibiting to the point that mechanical aids are needed. Braces can be used to improve joint mobility as well as stability. At a higher level of need, rolling walkers or even wheel chairs may be needed to achieve mobility and the quality of life.

For some individuals, more invasive actions are needed for desired results. Drug administration can be used to control seizures, relax muscle spasms, and alleviate pain. Surgery, though invasive, can be used to loosen over tightened muscles as well as correct some anatomical abnormalities. Selective dorsal rhizotomy is a procedure in which problematic nerves are severed in the spinal cord. This is an extreme measure, but it can relax muscles and reduce pain in patients with spastic CP. Therapeutic electrical stimulation can also be utilized to improve some muscle function. As it is sometimes done with stoke victims, artificial muscle stimulation can increase muscle strength as well as control. It can exercise the targeted muscles when a patient can't stimulate them naturally, allowing them to maintain the muscle. In some situations, when the brain damage of a CP patient is caused by a lack of oxygen flow to the brain, such as from complications during birth, hyperbaric oxygen therapy can actually reverse some of the damage. This is a process where the individual is exposed to a pressurized and oxygen rich environment to make up for lost development. However, this must be done soon after the brain is starved of oxygen, and it is unlikely that it will repair all damage that has been done.

Chapter 2. Exoskeletons

Traditionally an artificial exoskeleton was simply armor that covered the body, similar to the exoskeleton of an insect, an exterior bone structure. Today, the definition of an exoskeleton has evolved, and is commonly known as any mechanical aid that is used to improve human abilities to levels often above normal standards. These can cover the entire body, or simply aid one specific portion. Exoskeletons have been prevalent in science fiction for years with a wide variety of uses. They are commonly known to make people run faster, jump higher, and lift more weight. In most depictions they are used by soldiers or for aggressive purposes. However, if an exoskeleton is capable of improving a typical person's strength and agility above normal, then it could also have the benefit of raising a person with below normal abilities to a normal or above normal standards. The benefits can not only give super human abilities, they can simply improve the standard of life for those living with a disability. The beginnings of the modern exoskeleton were found in the forms of orthotics (devices applied to the outside of the body to assist the muscular, neural, or skeletal systems) and prosthetics (devices designed to replace missing body parts). Myoelectric prosthetics are some of the most advanced devices in development today, and are very closely related to exoskeletons. A myoelectric prosthetic device uses electromyography (EMG), a process of detecting the electrical signals within the muscles with an electrode when they contract, to control the motor movement of the mechanical device. You can see how closely related these are to exoskeletons, because of the fact that they take their input from the movement of the user, and are designed to improve the wearer's abilities. Some of these devices have gone so far as to be able to provide some feedback from the device to the person, restoring the sensation of touch or pressure. For example, a powered mechanical hand can communicate the force with which it is grasping an object to its user. However, unlike exoskeletons, these devices are typically designed to create function when there is none rather than aiding and improving function that already exists.

2.1 Rehabilitation Exoskeletons

It is common practice in PT to move a patient's limbs and joints through natural motions in order to improve function. This includes moving the legs through the motions of walking in order to assist in regaining, teaching, or improving the ability to walk. Traditionally, if a physical therapist wanted to exercise the legs by moving them through the motions of walking, they would have to physically manipulate the patient's legs by hand. The patient's body weight is at least partially suspended over a treadmill while the therapist moves their legs with the moving belt. Despite the fact that the patient's weight is partially or fully supported by en external device, this method is physically strenuous for the physician. This therefore limits the productivity and versatility of the therapy [Ferris et al. (2005)][Hornby et al. (2005)]. However, this method has been validated by the findings that task specific training, such as walking, enables repair and reorganization of processes in the central nervous system [Winstein (1991)]. With CP patients, it is not possible to repair the damage to the brain and the nerves and muscles throughout the body may function properly. However, the reorganization of processes refers to the development of the brain to find alternate ways of sending improved electrical signals. It is possible for the brain to transfer function responsibility to another portion of the brain. One that is undamaged or damaged less than the portion initially responsible for the communication. It has also been found that strength training in children with CP can increase strength as well as result in a higher gait velocity [Damiano & Abel (1998)][Dodd et al. (2003)]. Similar to strength training, treadmill training with partial body weight support, as discussed before, can improve walking speed and endurance of children with CP who can already walk [Dodd (2007)]. Furthermore, it has been found that, in some cases, treadmill training with partial body weight support can achieve completely independent mobility for previously nonambulatory children with CP [Schindl et al. (2000)].

Because it has been shown that treadmill training with partial body weight support has proven benefits, but the task is difficult for physical therapists, there are now powered exoskeletons integrated with treadmills that are already being used today to help patients with their walking therapy. These devices utilize a harness to achieve the partial body weight support, but instead of a physician moving the patient's legs, the robotic

attachments move the patient's legs through the motions of a typical human gait. These devices have made therapy easier on physicians and more productive for the patients, because they can now conduct longer sessions of continuous movement. Unfortunately, these devices are very large and they require the patient to be stationary while conducting the therapy. The Lokomat®, produced by Hocoma and seen in Figure 2.1, and the AutoAmulator, produced by HealthSouth, are two therapeutic robotic partial body weight supporting treadmill based systems being used to improve patient walking abilities [Hocoma (2008)]. Due to their automatic nature, both of the rehabilitation devices allow for a wide range of speeds during training as well as longer and more intense therapy sessions. This greatly increases the rate at which a patient can progress though their therapy goals. However, they are only designed to move an individual's legs through a typical gate when used in coordination with the treadmill. The versatility of these devices is limited to only walking straight forward. This is very beneficial, but there are many more motions that a person performs in everyday life that could be improved upon with the same proficiency as walking with these devices.

Figure 2.1 The pediatric Lokomat. It is shown moving a child's legs through the motions of walking on the treadmill below foot. The pediatric version is similar to the Lokomat for adults, but contains a smaller harness, cuffs, and extremity attachments to fit a child. The programmed gait motions are also altered for a child's movements. ©Hocoma AG, Switzerland, www.hocoma.com [Hocoma (2008)]

2.2 Dynamic Exoskeletons

Despite the fact that their concept has been around for many years, the technology behind exoskeletons is just now reaching a level to make their production viable. The following is a look at three projects in the field of developing exoskeletons primarily focused on the lower limbs. Yobotics, Inc. is a small company that was formed from the MIT Leg Laboratory in 2000, and has been working on a powered lower limb orthotic device named RoboWalker. The project has focused primarily on the knee, with a sub-device called RoboKnee. The RoboKnee is a powered orthotic device designed to assist muscles of the thigh (quadriceps, hamstring, etc.) that can be seen in Figure 2.2. This orthotic mechanically assists in the extension and contraction of the lower leg, allowing above average performance in the tasks of walking, climbing steps, and deep knee bends. However, they have also developed an orthotic device focused around the ankle joint. This device is designed to supplement the calf and shin muscles in the pointing and flexing of the foot. This portion of the device has the possibility of playing a large role in the assistance of balance of individuals using the RoboWalker, because this is the primary point of balance while standing. These orthotic devices rely on electric series-elastic actuators to provide the controlled force to the system. These are essentially linear actuators with coiled linear springs residing between the input and the output of the actuator arms. There are no current plans to put this device into commercial production, but the developmental research associated with it could be utilized for the development of other products for a commercial end [Yobotics, Inc. (2008)].
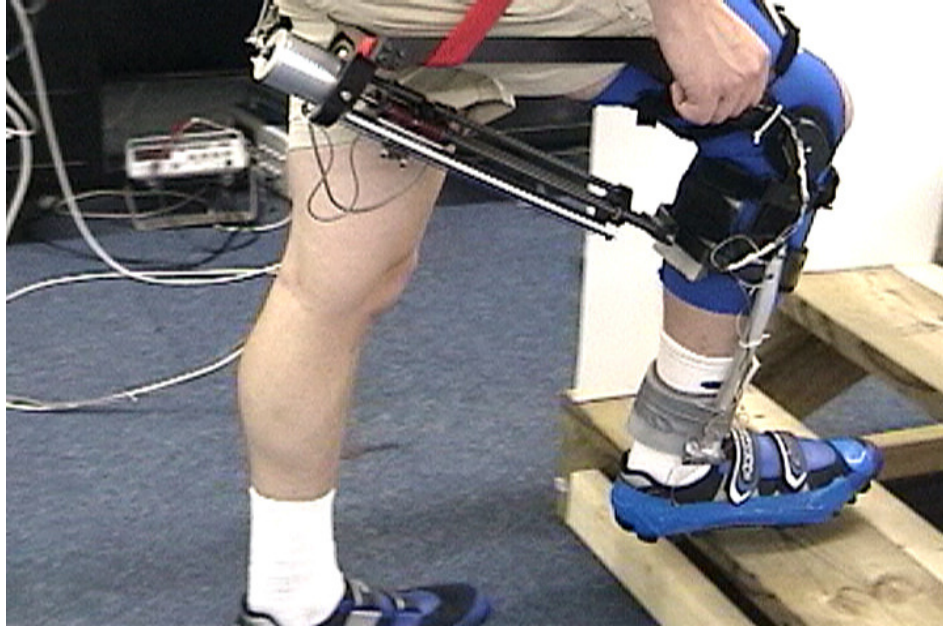
Figure 2.2 The RoboKnee in action, assisting in walking up steps. The powered elastic actuator can clearly be seen extending from below the hip joint to below the knee joint. ©Yobotics, Inc. [Yobotics, Inc. (2008)]

The Berkley Lower Extremity Exoskeleton (BLEEX) is an exoskeleton project that was funded by the Defense Advanced Research Project Agency (DARPA) at the University of California, Berkley, beginning in the year 2000. Unlike the RoboWalker, this exoskeleton was not specifically designed for those functioning below normal standards, but to increase the abilities of the wearer to above normal standards in both strength and endurance. It has been designed for the specific task of allowing the wearer to bear a large load on their back. The device is broken down into three parts, the two powered robotic legs, the power and computing unit, and a backpack frame. The power unit includes an engine that powers the hydraulics of the robotic legs as well as electrical power for the computer. Both the powered legs and the backpack are similar in their versatility in the fact that the backpack can be removed to allow for less inhibited movement, and the legs can be removed if the backpack needs to be used alone. The control scheme designed with the device is uniquely based solely on measurements from the exoskeleton, rather than from sensors monitoring the wearer. This has been done, because the exoskeleton is designed to primarily support the weight of the pack, not the user, and only attaches rigidly to the wearer at the sole of the foot and at the backpack.

Due to the design objectives of carrying large payloads on the back of the wearer and its ability to navigate complicated terrain, BLEEX has projected uses with soldiers, disaster relief workers, wild land firefighters, and other emergency personnel [Berkeley Robotics (2008)]. A company called Berkley Bionics was founded by scientists that were associated with the BLEEX project, and has developed several exoskeletons founded on the original project. The ExoHiker™ seen in Figure 2.3, the ExoClimber™, and the Human Universal Load Carrier (HULC™) all have significantly reduced the size and weight from the original BLEEX, and boast higher load capabilities. All of these exoskeletons are based around the task of carrying heavy loads on the wearer's back rather than the medical of improving the mobility of the disabled. However, in late 2007, Berkley Bionics won a National Institute of Standards and Technology (NIST) and Advanced Technology Program (ATP) contract to begin work on orthotic exoskeletons to benefit those living with mobility disabilities [Berkeley Bionics (2008)].

Figure 2.3 The ExoHiker™ attached to an individual. It is designed to carry a heavy load in the backpack portion of the exoskeleton. This is a good example of how small and sleek exoskeletons have become. [Berkeley Bionics (2008)]

Similar to the BLEEX project and the Berkeley Bionics exoskeletons, Sarcos (recently purchased by Raytheon) has developed an exoskeleton also based on hydraulics. However, their exoskeleton, the XOS, has been designed to encompass the entire body as seen in Figure 2.4. It also utilizes both linear and rotational hydraulic actuators to accomplish the desired assisting actions. This recently publicized exoskeleton began development in 2000 with funding from DARPA, and is probably the most physically capable exoskeleton to date, combining strength as well as agility. The device can lift heavy loads with minimal effort exerted by the wearer, while maintaining the dexterity to allow the motions of continuously punching a boxing speed bag. This exoskeleton also relies on monitoring and measuring the actions of the wearer to process and derive its own assistive actions. However, this system is not without its drawbacks. As it can be seen in Figure 2.4, the exoskeleton does not hug the human form as closely as some other exoskeletons. The arm control handles remove any functionality of the hands, forcing the wearer to rely on attachments to the ends of the arms to manipulate objects. However, the largest drawback to this device is its lack of a mobile power source. At this stage of development, it relies on a separate power source that it is tethered to with cables. This is a very large issue when trying to implement a freestanding exoskeleton, and will require much development achieve independence in its activities. However, the company has planned to design a capable exoskeleton first, and then design the mobile power source to accommodate its specific predetermined needs.

Figure 2.4 The full body XOS exoskeleton. This recently publicized hydraulic powered exoskeleton is probably the most capable exoskeleton to date. However, it is currently tethered for power reasons. [© Raytheon (2008)]

Utilizing electrical motors instead of linear actuators, the Japanese company Cyberdyne™ has developed a commercially available exoskeleton named the Hybrid Assistive Limb (HAL™), seen if Figure 2.5. Also unlike the other two projects, this exoskeleton relies on electrical signals within the muscles of the wearer to control the activation of the joint motors [Cyberdyne, Inc. (2008)]. As discussed before, the brain sends electrical signals through the central nervous system to the muscles controlling their contractions. The electrical signals causing these contractions can be monitored through EMG. The HAL™ exoskeleton utilizes surface EMG with electrodes that are attached to the skin with an adhesive, because it is easy to implement and non-invasive (some other types of EMG will be discussed later in the paper). Despite the resistance of the tissue between the muscle and the surface of the skin and materials on the surface such as sweat, surface electrodes can detect the electrical impulses when muscles are contracting. These biological signals are then amplified and processed by the computer

to determine the wearer's movement intentions. The computer then commands the motors in the joints of the mechanical limbs to match and assist in these movements. Due to the natural delays of the human body, the exoskeleton motors can actually respond slightly before the muscles contract. The system also utilizes stored functions to assist with common movements such as standing up from a chair. These are learned and stored by the computer during the users 'orientation' with the device, and are recalled during use to reduce the required computational power during these activities. In order to improve these autonomous actions, the system also updates the stored information each time an action is performed. HAL-5 is the current model produced by Cyberdyne, and provides mechanical assistance to the arms as well as the legs. This not only helps the wearer to stand, walk, and climb stairs, but also lift and hold loads in their arms. This project has been largely designed for medical uses such as support of disabled persons, rehabilitation, and physical therapy, but also for hospital workers lifting patients, laborers, emergency services, and entertainment uses [Cyberdyne, Inc. (2008)].

Figure 2.5 The HAL-5 exoskeleton. The connection points, motor, power, and computing component locations are labeled. Special attention should be paid tot the physical connections on the torso, upper legs, lower legs, and the feet. [Cyberdyne, Inc. (2008), Prof. Sankai, University of Tsukuba]

Chapter 3. Improving HAL™ Integration

The RoboWalker is limited to only the knee and ankle joints, designed for individual use for those lacking the functionality of one or both of those joints. It has not been designed to form a compete exoskeleton, but components to improve injuries or disabilities. BLEEX and the Berkley Bionics exoskeletons were all designed around primarily supporting a large load in the form of a backpack. This limited their direct interaction with the human body, which prevents them from being the best option for the CP use. The XOS exoskeleton is a very physically capable device, but it may inhibit some actions in certain environments with its size and it lacks a mobile power source all together. This lack of true mobility reduces it to the equivalent of the rehabilitative robotics such as the Lokomat. The HAL™ exoskeleton is the most complete exoskeleton that has been developed with one of its target uses being rehabilitation and physical therapy. It is one of the most closely integrated with the human body. However, there are many improvements that need to be addressed in order to help CP patients learn to walk. These include specific size, physical connections, powered control, software, and communication needs. The exoskeleton will need to be redesigned around the size of a child in order to provide the necessary aid early in life. The links that make up the lower body of the exoskeleton will need to be redesigned to allow for the inclusion of additional motors, and the electric motors may need to be replaced with hydraulics all together to be able to perform with new and additional software requirements. These new software requirements will also need an alternate method of receiving commands from the body of the wearer.

3.1 CP Exoskeleton Needs

In order to use an exoskeleton for the purpose of helping an individual with CP learn to walk, the are a couple of specialized needs that will need to be addressed. The first and most basic difference between existing exoskeletons and one that could be used for CP patients learning to walk is sizing. The current exoskeletons are all designed around an adult stature. They have some ability to adjust to fit a small range of users, but not enough to accommodate an individual very far outside the range of an average adult.

The Center for Disease Control (CDC) keeps records on statistical growth measurements, including average child height and weight information [National Center for Health Statistics (2008)]. The human height and weight information that will need to be considered for control aspects of the smaller exoskeletons can be seen in Figure 3.1 and Figure 3.2 [National Center for Health Statistics (2008)]. More specific for the physical design of child exoskeletons, the difference in femur and tibia lengths between adults and children is very important. These do not level off until around age 14 for females and 16 for males, and can be seen in Figure 3.3 and Figure 3.4 [Anderson & Green (1964)]. This is what will determine the length of the appendages of the exoskeleton. However, the reduced size of the exoskeleton and user could make the design of the device slightly easier. One of the difficulties in designing the system is finding motors or actuators strong enough to support the weight of the exoskeleton as well as at least a portion of the wearer. A smaller exoskeleton and wearer would not require motors or actuators as strong as those being used in adult exoskeletons today. However, the smaller exoskeleton size would also dictate that the motors or actuators be slightly smaller for ease and versatility of operation. Fortunately, the size of the motor or actuators would not need to be significantly smaller to still be applicable.

Figure 3.1 Boys stature-for-age and weight-for-age percentiles. Notice the significant difference between the stature of adults and those under the age of 10. [National Center for Health Statistics (2008)]
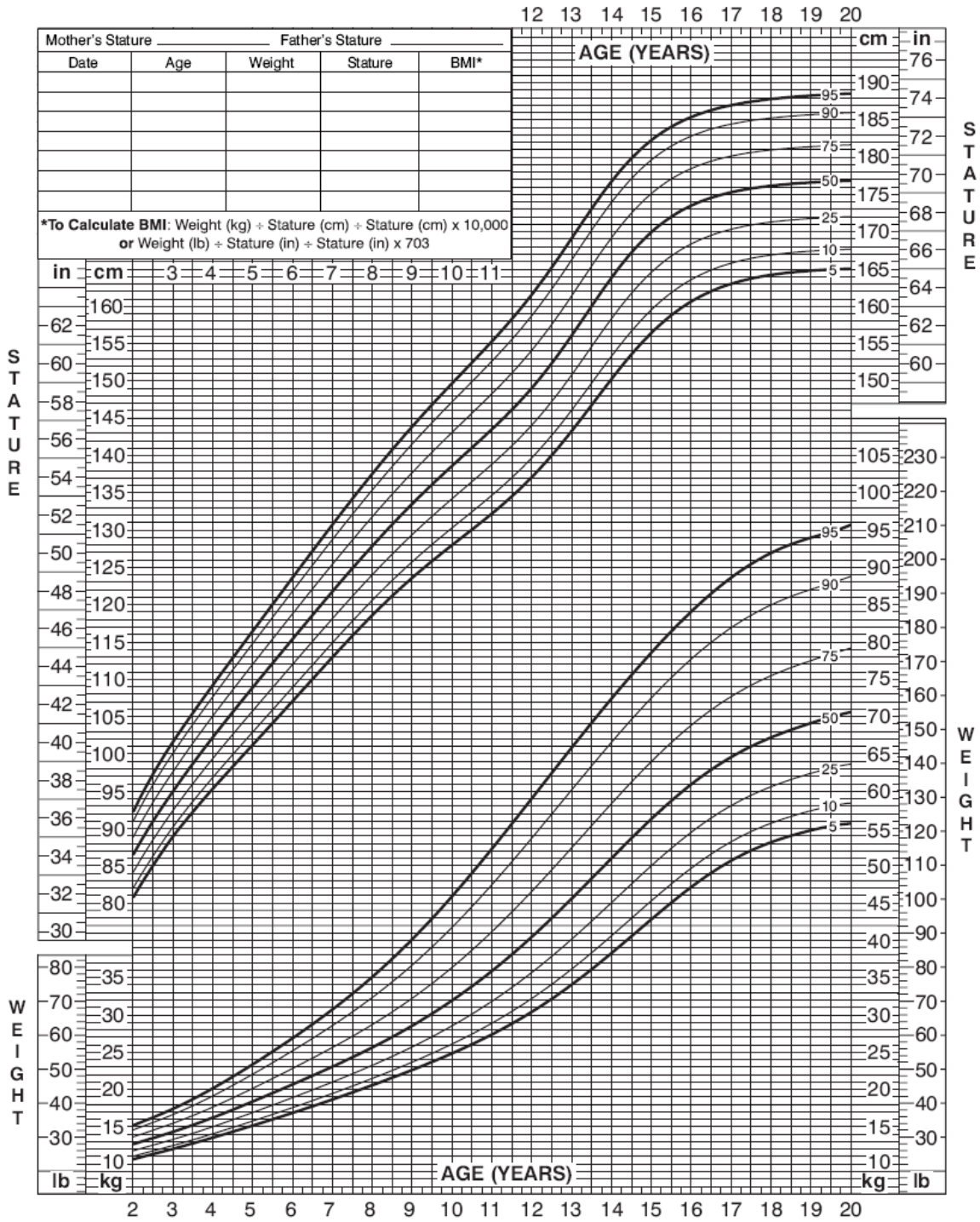
Figure 3.2 Girls stature-for-age and weight-for-age percentiles. Notice the significant difference between the stature of adults and those under the age of 10. [National Center for Health Statistics (2008)]
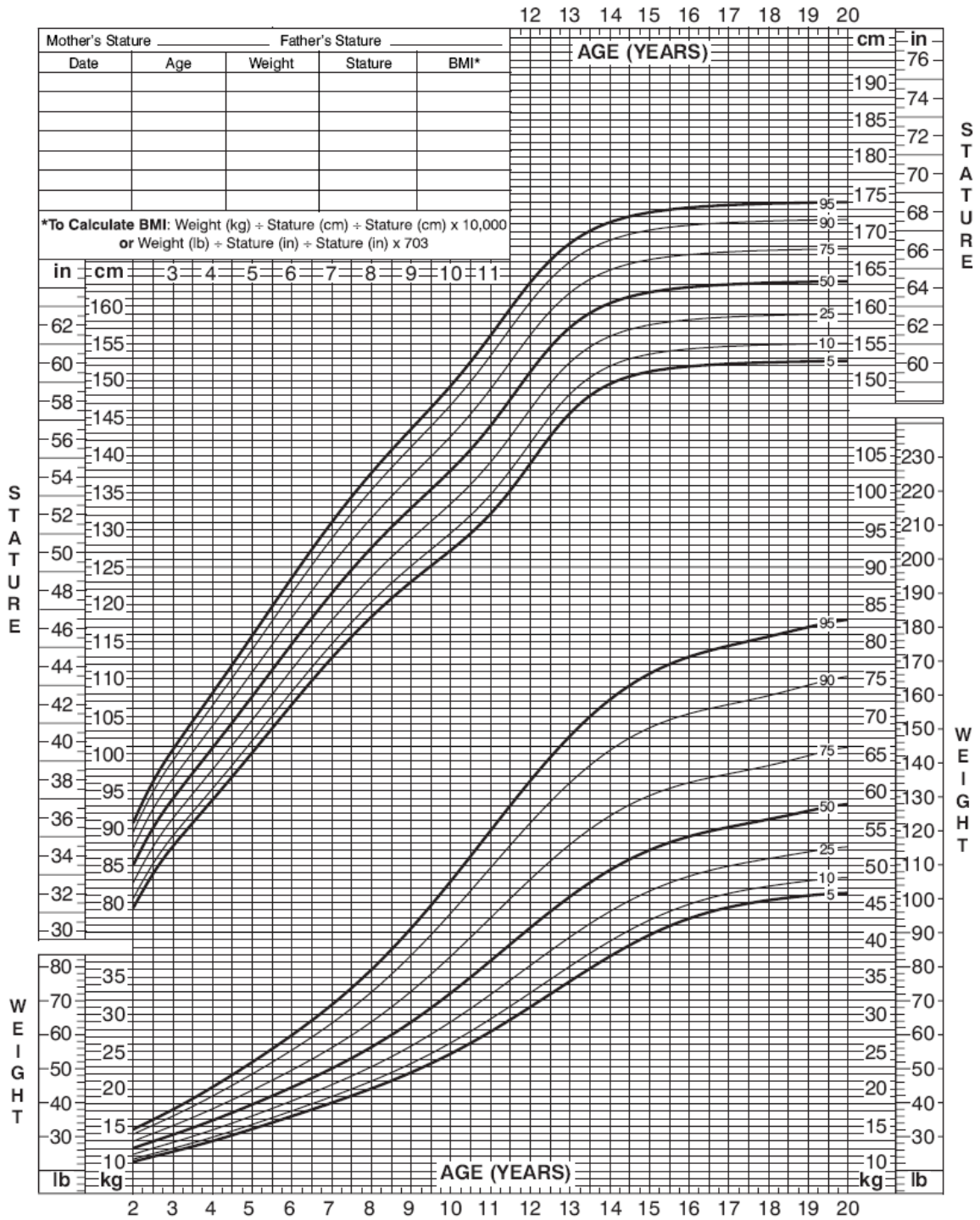
24

Femur

Figure 3.3 Child femur length percentiles. These lengths include the epiphyses. Notice the difference between the length of a femur that has stopped growing and the length of a child under the age of 10. [Anderson & Green (1964)]
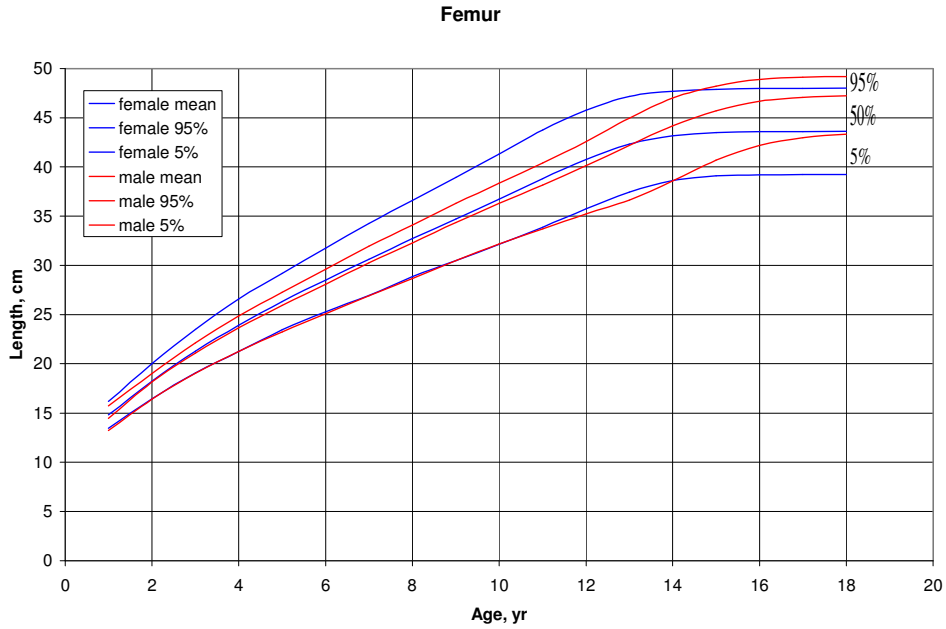
Tibia

Figure 3.4 Child tibia length percentiles. These lengths include the epiphyses. Notice the difference between the length of a femur that has stopped growing and the length of a child under the age of 10. [Anderson & Green (1964)]
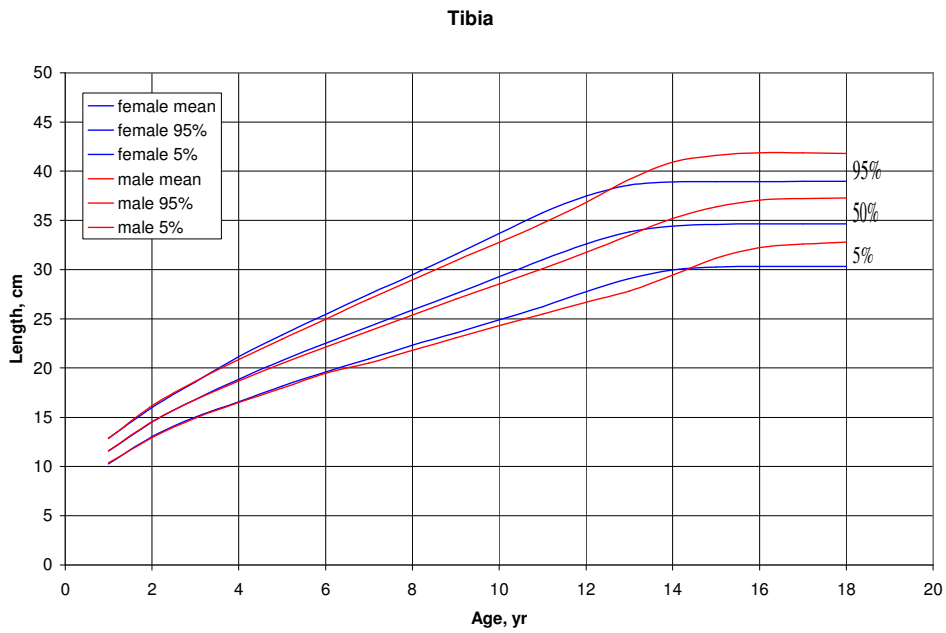
With the wearer and exoskeleton being shorter and lighter, the joint motors should be able to supplement the user's strength at a greater extent. For the purpose of helping children with CP learn to walk, the exoskeleton may initially need to support and control 100% of the individual's lower body actions. The process would begin with the exoskeleton supporting all of the person's weight and controlling all of the walking. In this situation, the exoskeleton will essentially be acting as a modern humanoid robot such as the Dynamic Anthropomorphic Robot with Intelligence (DARwin), as seen in Figure 3.5. This project, overseen by Dr. Dennis Hong at Virginia Tech, is a bipedal, soccer playing, humanoid robot capable of complex movements. In order to stand, walk, and turn, this robot has six degrees of freedom in each leg for a total of 12 degrees of freedom in its entire lower body. The hip joint has three degrees of freedom, with all axes of rotation intersecting at a single point, creating a kinematically spherical joint similar to the ball and socket joint of the human hip. The knee joint has one degree of freedom, as does the human knee joint. However, unlike the human ankle joint, DARwin only has two degrees of freedom in its joint. Since this robot is capable of basic human movement and balance, the design of an exoskeleton of these capabilities can be modeled after this design. As the user's legs gain strength and dexterity, the gains of the control scheme would be reduced so that the user does more of the work and balance. Ideally, the individual wearing the exoskeleton would eventually support all of their own weight and control all of the actions of walking. At this point the exoskeleton would no longer be needed for mobility. For some individuals, their CP may be too severe to reach a dexterity that would allow for unassisted walking. In this case the person would still be able to get around with the assistance of the exoskeleton. If not utilized for everyday use, the exoskeleton could still be used for physical therapy with the benefits as previously discussed with rehabilitation exoskeletons. However, a wearable and mobile exoskeleton would take up less space and allow for many more diverse activities to be included in therapy.
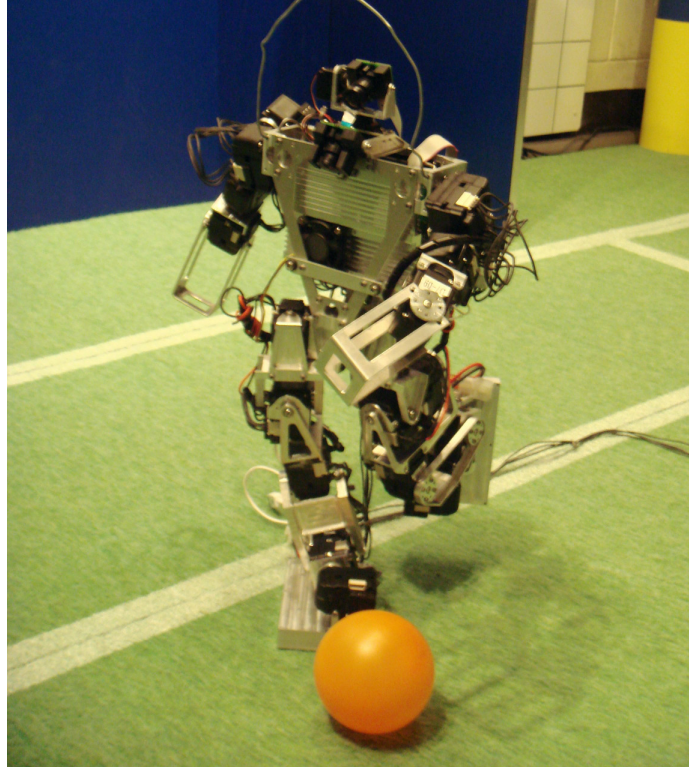
Figure 3.5 DARwin the soccer playing robot. This robot has three degrees of freedom at the each hip, one degree of freedom at each knee, and two degrees of freedom at each ankle. These 12 degrees of freedom allow for complex movements and balance. ©Dr. Dennis Hong, RoMeLa, Virginia Tech [RoMeLa (2008)]

An exoskeleton needed to help individuals with CP learning to walk could be designed with different levels of complexity. At a minimum, for the assistance in straight forward unobstructed walking with external balance assistance, the exoskeleton could function with one rotational degree of freedom at the hip, one rotational degree of freedom at the knee, and one rotational degree of freedom at the ankle. However, this level of complexity could only be used in closely monitored therapy with a physician, with the balance assistance coming from hand rails on either side or a harness suspended from above able to move with the patient. The complexity could be raised to a maximum with three degrees of rotational freedom at the hip, one degree of rotational freedom at the knee, and three degrees of rotational freedom at the ankle. With more degrees of freedom, come the possibility for more complex movements and more stability. An exoskeleton of this complexity could balance itself and allow for more freedom in therapy. However, the computing needed for motion with more degrees of freedom

increases significantly, especially for the situation of total control. If the exoskeleton was designed at the most complex mechanical level, it could always be limited by the software, but an exoskeleton designed at the least complex mechanical level can never gain more. Also, since we are focusing entirely on controlling the lower extremities of the human body, the operation of the device should never be used without at least supervision. No control system is perfect, and falls may occur. Getting up off the ground may require the assistance of someone else. For a future study, the upper body portion of the exoskeleton may also be integrated into rehabilitation. This may allow wearers to stand up from the ground by themselves, but at least some supervision over therapeutic activities is always a good idea.

        With total control of the lower body of the individual wearing the device, instead of simply assisting in actions that are already happening, the exoskeleton will need to attach more securely to the wearer's extremities. This will allow for more precise control during movements. At least one version of BLEEX only attached to the user at the sole of the foot and at the backpack [Berkeley Robotics (2008)]. This would provide very little control over the individual's legs. The next generation exoskeletons derived from BLEEX by Berkley Bionics similarly attach at the sole of the foot and around the waist and shoulders at the backpack, but they also have a strap connection around the middle of the thigh [Berkley Bionics (2008)]. This provides a little more control, but it is still not enough to exert precise control over the lower limbs. The HAL-5 exoskeleton attaches most securely to the wearer with a secure connection at the foot, with straps around the middle of the upper and lower legs, and at the torso with connections around the waist and over the shoulders [Cyberdyne, Inc. (2008)]. This provides the best physical integration out of these exoskeletons, but it is still lacking for the level of control that is needed to control the functions of walking. An improved model of connection points can be seen in Figure 3.6. The slight differences between these connection points and those already existing on the HAL-5 exoskeleton will be discussed in depth in the following sections.

Figure 3.6 Diagram of the lower extremities. The desired exoskeleton connection points are shown in red. The locations of these connection points will improve the exoskeleton control over the limbs in the initial stages of learning to walk.

The controls programming of the exoskeletons will also need to be tailored for the increased complexity of the exoskeleton as well as each individual patient, because the effects of CP vary so widely. Spastic PC may be the most difficult type of CP to work with, especially with the exoskeleton exerting complete control over the limbs. Individuals with spastic CP often have feet that are pointed all the time. This will make it difficult or impossible for the foot to rest flat on the ground during therapy. The constant tension in opposing muscles of the joints will also make it more difficult for the motors to manipulate the joints. It will also be necessary to limit the force that the motors exert, because forcing the joints to move with too much force can cause damage to the muscles or the joint. Unfortunately, spastic CP is the most common type of CP. Individuals with ataxic CP may be the easiest patients to work with, especially while the exoskeleton is exerting complete control over the limbs. The symptoms of muscles that are too loose will allow the exoskeleton to move the legs through the proper motions easily with little

resistance. Individuals with athetoid CP may allow easy or difficult control. For this type of CP, it will be important for the exoskeleton to suppress sudden movements such as muscle spasms as well as sudden relaxations. With any form of CP it may also be necessary to change the way the computer interprets muscle signals when the patient begins controlling some of their own walking and balance. For example, the muscles are continuously tight with spastic CP, so the computer may need to monitor changes in the electrical signals of muscles instead of just the presence of them. At any particular joint, the system may need to base its actions on the relaxation of certain muscles instead of the contractions of others.

3.2 Hip Joint Connection

The human hip joint naturally has three degrees of freedom, as seen in Figure 3.7, and needs to utilize all three for completely independent walking. These three degrees of freedom also aid in the safety of this joint, allowing for some rotational forces in all directions to prevent damage to the joint. This joint is responsible for control of the angle between the lower torso and the upper leg (femur). In order to secure the joint of the exoskeleton in parallel with the human joint, the torso and upper leg must be secured to the exoskeleton. HAL™ currently attaches to the torso firmly with restraints around the waist as well as restraints over the shoulders. These connections connection could be made rigid and seem firm and close enough to properly restrain the upper branch of the hip angle, the torso. The current control of the upper leg is a wide strap that loops around the mid thigh attaching to the exoskeleton on the outside of the leg. Moving this attachment point further down the leg towards the knee would limit the amount of movement in the exoskeleton before the human component is moved. As seen if Figure 3.8, it is basic geometry that if there is a given amount of compression under the strap, extending the length of the arm to that connection will reduce the angle of cushion before desired movement. This control connection would also control the angle of the torso for balance purposes in walking and standing.
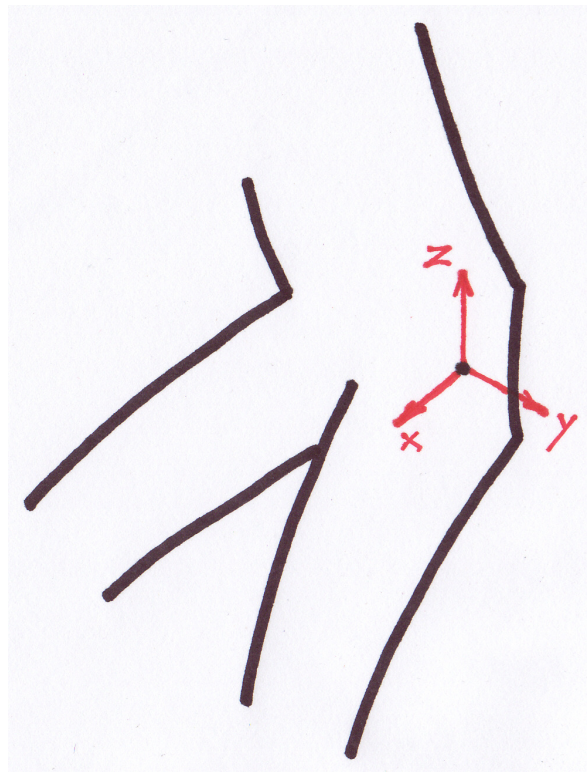
Figure 3.7 A diagram of the midsection focused around the pelvis. The origin of the axes shown represents the hip joint. Those with natural biological rotational freedoms around them are displayed in red. An exoskeleton will need all three rotational degrees of freedom to perform the task of walking and balancing for a person.
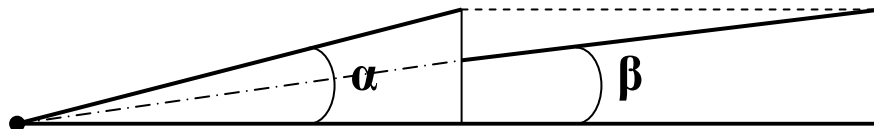
Figure 3.8 A comparison of arm length and angle. A longer base length of travel with equal vertical rise will produce a smaller angle between the two lines ($\alpha > \beta$). If the vertical rise represents the compression of tissue beneath an exoskeleton connection, then having a longer arm will reduce the motor rotation before limb rotation. This also explains why, for instance, the force from the knee motor will be primarily applied at the waist and ankle connections instead of the ones directly above and below it.

3.3 Ankle Joint Connection

The ankle joint of an exoskeleton is a necessary control point for the complete control of the human body in the activity of complete and proper walking. However, the HAL™ exoskeleton does not currently have any control motors at the ankle. The human foot naturally has three degrees of freedom, which will generically be called the ankle joint. This joint is shown in Figure 3.9 at a point for simplicity, but in reality the rotation of the foot is achieved through a series of hinge joints. For the purpose of simply walking, only two rotational degrees of freedom are needed. As it can be seen in Figure 3.9, rotation about the x-axis and y-axis are the necessary requirements for basic forward human walking and balance, as long as the hip joint maintains a rotational degree of freedom around the z-axis for turning. Similar to the hip, these three degrees of freedom also aid in the safety of this joint, allowing for some rotational forces in all directions to prevent damage to the joint. This joint is responsible for control of the angle between the lower leg (tibia) and the foot. In order to secure the joint of the exoskeleton in parallel with the human joint, the foot and lower leg must be secured to the exoskeleton. HAL™ currently attaches to the lower leg with a wide strap that loops around the mid shin attaching to the exoskeleton on the outside of the leg. Moving this attachment point further up the leg towards the knee would limit the amount of movement of the exoskeleton before human movement, as discussed before and shown in Figure 3.8. The current control of the foot is a secure connection to the user's shoe. This is a wide and somewhat rigid attachment, making this connection satisfactory for the proposed use. This being the case, no modifications to the foot attachment would be needed.
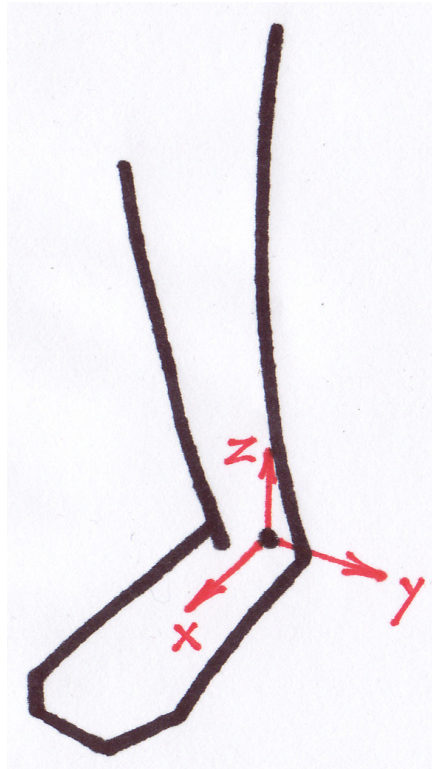
Figure 3.9 A diagram of the lower leg and foot focused around the ankle. The origin of the axes shown represents the generic ankle joint when in reality the rotations are achieved by a series on hinge joints and not a single point ball joint. Those axes with natural biological rotational freedoms around them are displayed in red. For the most basic functions of walking and balancing, only rotation around the x-axis and y-axis are needed.

3.4 Knee Joint Connection

The human knee joint naturally has only one degree of freedom, but this has both beneficial and disadvantageous effects on the joint. As it can be seen in Figure 3.10, rotation about the y-axis is the only degree of freedom for the knee, and therefore the only required rotation for proper forward human walking. The beneficial effects of only one degree of freedom are simplicity of movement and increased stability. The disadvantageous effects of only one degree of freedom are that rotational forces in any direction other than around the y-axis can cause pain and damage to the joint. This joint is responsible for control of the angle between the upper leg (femur) and the lower leg (tibia). In order to secure the joint of the exoskeleton in parallel with the human joint, the upper and lower leg must be secured to the exoskeleton carefully. As discussed before,

HAL™ currently attaches to the upper leg with a wide strap that loops around the mid thigh. For control of the upper segment of the joint, this connection is not necessary. This would make the length of the control arm longer, decreasing the movement of the exoskeleton without human movement as previously discussed with Figure 3.8. HAL™ similarly attaches to the lower leg with a strap around the mid shin. Similar to the control for the upper segment of the joint, the strap at the middle of the shin is not needed for control of the lower segment of the joint. HAL™ connects securely to the foot, and this location maximizes the length of the effective arm of the motor as well as minimizes the movement of the exoskeleton without human movement. Connections closer to the knee are not needed for this joint, because with consistent compression at each connection, the closer connections would still be compressing while ones further away would be completely compressed and moving the portion of the body that they are attached to, as shown in Figure 3.8.
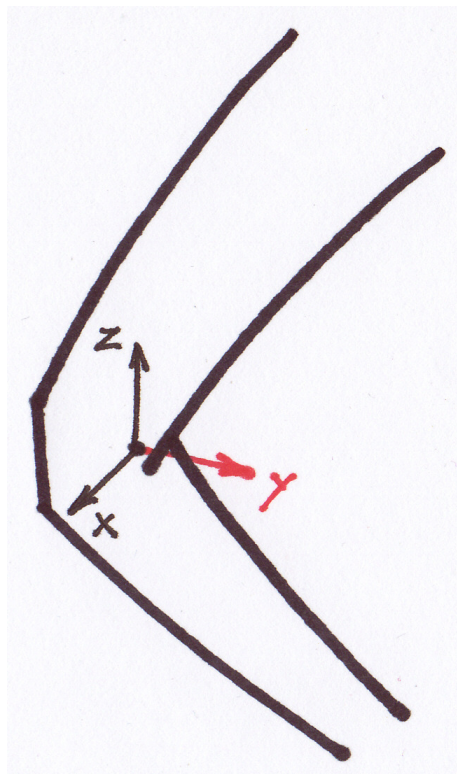

Figure 3.10 A diagram of the upper and lower leg focused around the knee. The origin of the axes shown represents the knee joint. Those with natural biological rotational freedoms around them are displayed in red.

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With only one degree of freedom, protection of the knee joint is a primary concern. This is especially important when exerting complete control over the individual's movements with forces at the joints. Current exoskeletons are not as concerned with this issue, because their movements are based off of the user's intended or current movements. The use of a functional knee brace, as seen in Figure 3.11, for the connections to the exoskeleton above and below the knee would serve a dual purpose. It would protect the knee from improper force exertion on the joint by transmitting these forces to the connection areas just above and below the joint. It would also serve as the secure connections to the human leg that is needed for control from the exoskeleton's hip and ankle motors. As previously discussed, this connection would not be for exertion of knee motor forces, because forces from the knee motor would be largely applied through the foot and waist connections. However, the knee brace must be implemented and aligned carefully. In the past, improperly designed and aligned knee braces have been the cause of damage to the knee in many situations [DeVita et al. (1996)][Styf (1999)][Yang et al. (2005)][Khan et al. 2007].

Figure 3.11 An example of a functional knee brace. These are used to increase stability and support at the knee joint. Different designs of this brace differ slightly, such as how far it extends from the joint, but all are designed to perform the same function. [Biomet, Inc. (2008)]

3.5 Powered Control Needs

All of the powered joint motors will need to be redesigned from HAL™ slightly for a child size exoskeleton, and a number of motors will need to be added. As discussed before, the mobility of the exoskeleton will be very closely related to that of the DARwin robot. Figure 3.12 shows the differences in the kinematics of the current exoskeleton design and the redesigned device. Beginning with the hip joint, two more powered degrees of rotational freedom will need to be added. As discussed earlier, controlled rotation around all three axes shown in Figure 3.7 is needed for full walking mobility and balance. Also, because the hip joint is a ball and socket joint, these three rotational axes must intersect at the wearer's natural hip joint and be normal to each other. This alignment is very important in the prevention of damage to the individual's joint. For this joint, three separate motors will be needed to power each degree of freedom as shown in Figure 3.13. Motor A will reside at the posterior of the wearer's hip, and will provide

control over the rotation around the x-axis. It will attach to the torso support for stability and restriction from misalignment. Motor B is in the form of a semicircle with its circular axis coinciding with the z-axis. This will control the rotation around the z-axis by extending and retracting the semicircular arm attached between motor A and motor C. This semicircular segment will need to extend a maximum of 45° in both directions around the individual. This amount must be limited by the patient's natural rotational ability of their biological joint, but it can be reduced limiting the turning ability of the exoskeleton. This will allow for necessary freedom of motion while walking, but will prevent the exoskeleton from interfering with large rotations of the hip around the x-axis and the y-axis. Motor C will be similar to the motor currently present on the HAL™ exoskeleton. This will control rotation around the y-axis of the joint. It must also be realized that the forces of motors A and B must be able to be applied through the arm containing motor C forcing them to exert more force.
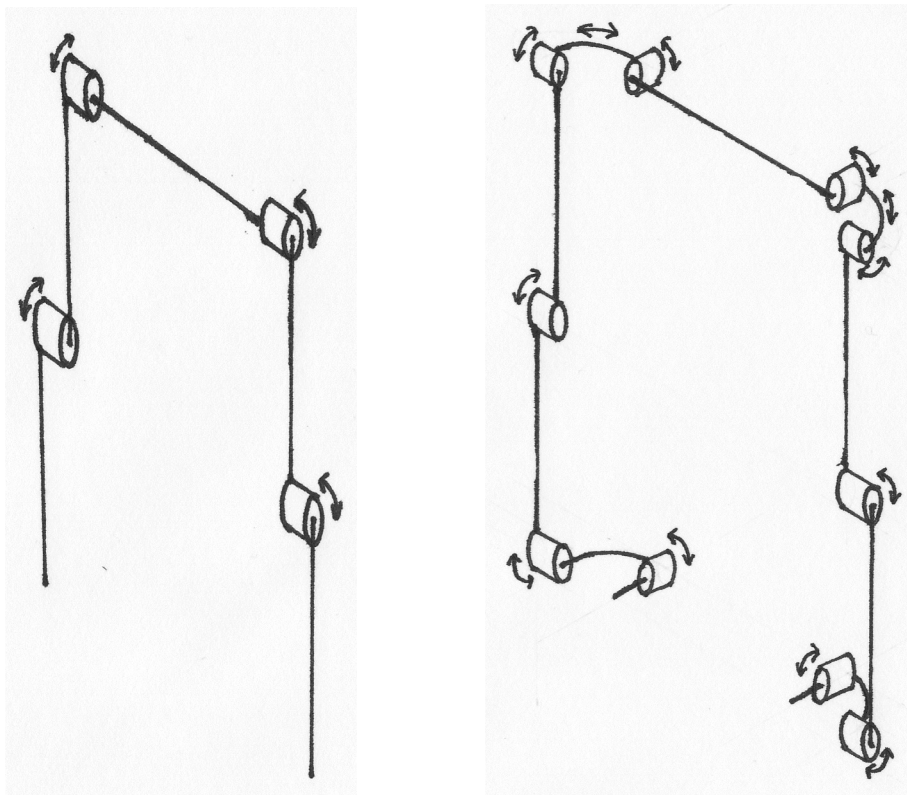

Figure 3.12 Improved exoskeleton kinematics. The kinematic diagram on the left represents the current HAL-5 dynamics, and the diagram on the right represents the improved dynamics that will be needed to completely control and balance the motions of walking.
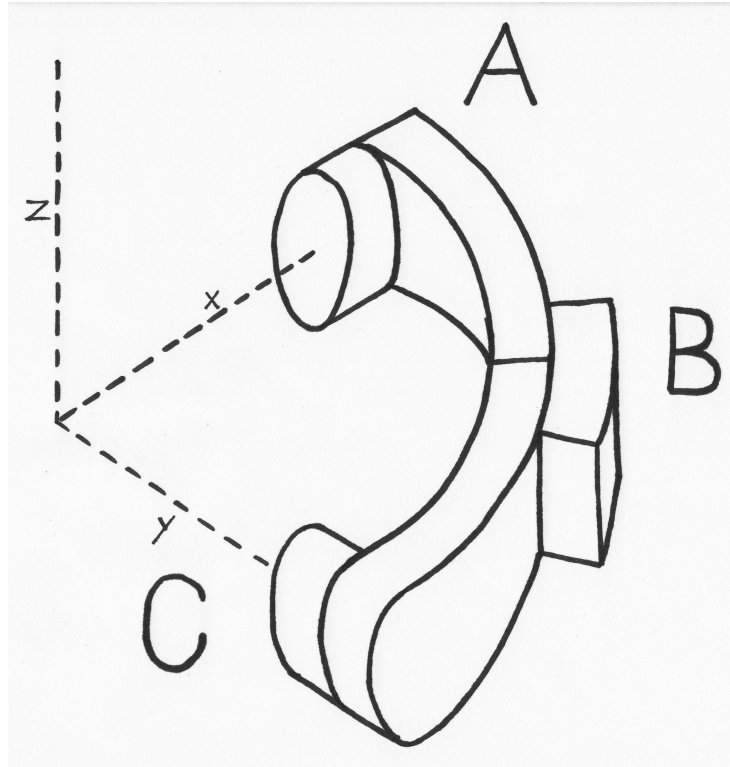
Figure 3.13 Powered hip joint with three degrees of freedom. Motor A controls rotation around the x-axis, motor B controls rotation around the z-axis, and motor C controls rotation around the y-axis. Motor A is attached to the torso support, and motor C attaches to the upper leg segment of the exoskeleton. It is very important that these three axes intersect at the center of the wearer's hip joint to prevent damage to the individual's biological joint.

The exoskeleton knee joint will contain a motor directly in line with the wearer's knee joint similar to the motor currently in place on HAL™. However, the segments of the exoskeleton above and below the will need to be attached to the functional knee brace to protect the biological knee. This will keep the individual's knee, the knee brace, and the motor aligned to prevent any damage. However, the knee brace may add some resistance in the bending of the joint that the motor will need to account for.

The ankle joint of the exoskeleton will need to have two motors to control the rotation around the x-axis and the y-axis. As seen in Figure 3.14, this joint of the exoskeleton will be similar to the hip joint, but there are a few differences. With only two degrees of freedom, the semicircle arm will be a solid link without the ability to provide rotation around the z-axis. Also, motors A and B will not be of equal height to each other, because the joints of the ankle reside with one on top of the other. Therefore,

the rotational axis of motor B will be slightly higher than motor A. As with the other joints, it is important that these axes of rotation coincide with the natural axes of rotation of the patient to prevent damage to the biological joint. The transmission of the forces from the motor through the link of the arm between motors A and B must also be considered when searching for the appropriate motors for the exoskeleton.
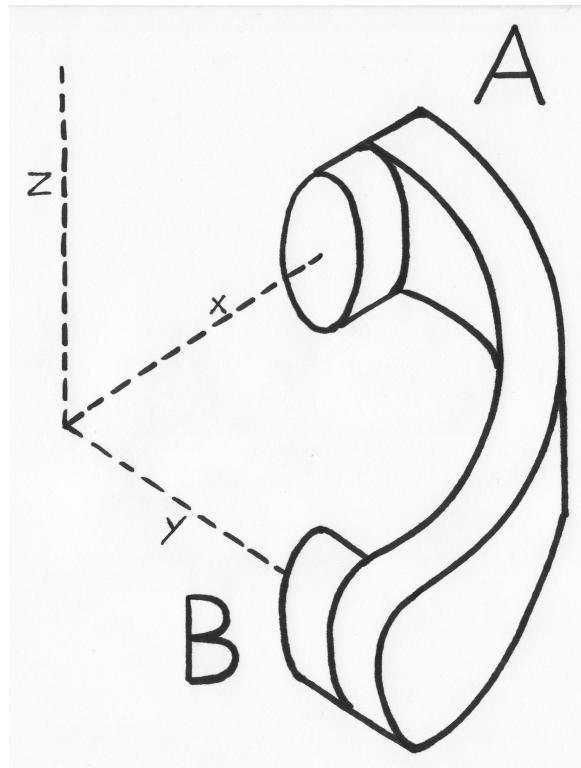
Figure 3.14 Powered ankle joint with two degrees of freedom. Motor A controls rotation around the x-axis and motor B controls rotation around the y-axis. Motor A attaches to the foot, and motor B attaches to the lower leg segment of the exoskeleton. It is very important that these axes coincide with the rotational axis of the wearer's ankle joints to prevent damage to the individual's biological joint.

With the addition of four motors to the lower extremities of the exoskeleton, the power source on HAL™ will need to be improved, even though the four motors of the upper body will not be utilized for this initial design. The lower body motors must exert higher forces more regularly than the upper body motors. However, the fact that the exoskeleton is designed for children will help to alleviate some of these force demands as compared to an adult. It is also important to remember that hydraulics similar to those

used with Roboknee and the BLEEX project with its descendants could also be used for some of the powered control of the degrees of freedom. In fact, it may be advisable to replace the electric motors with either linear or rotational hydraulics. Electric motors are often not as capable in producing high levels of torque when compared to hydraulics. Reasonably sized electric motors my not have the capability of providing enough torque to fully control the lower extremities when the exoskeleton is exerting 100% control. However, the introduction of hydraulics would require a complete redesign of the power system of the exoskeleton. As an example, the maximum torques around the y-axis at each joint for the most basic of actions for an average adult have been found to be about 73 Nm at the hip, 82 Nm at the knee, and 70 Nm at the ankle [Tian & He (1997)]. This gives you a general idea of the amount of torque each motor at the joints of the exoskeleton would have to output to perform the necessary actions of only a human, and these are going to be a little higher to account for the added weight of the exoskeleton.

3.6 Communication Options

One of the primary difference between the current model of HAL™ and one that could be used to help CP patients when first learning to walk, is the fact that the exoskeleton could exert total control over the lower body of the patient. This being the case, the electrical signals from the patient's leg muscles would provide no productive information to the exoskeleton. Without the electrical signals from the wearer, the individual will need a way to send commands to the exoskeleton. This can be accomplished simply with a joystick carried in the hand. If the individual's CP had too great of an affect on the hands, the joystick could be placed elsewhere on the body such as in proximity to the mouth, similar to some powered wheel chairs. The wearer would essentially be 'driving' the exoskeleton wherever they wanted to go. Also, if this joystick is limited to a circular boundary, commands of speed of motion and turning could be limited in relationship to each other. This could serve as a way to reduce a small portion of the computing power needed for the processing of actions.

Once the patient has gained some of the normal functions associated with walking, the muscle activity can begin to be used for exoskeleton control. Surface EMG electrodes are good options for situations where the user will be switching in and out of

the exoskeleton every now and then, such as physical therapy or use at a physicians office. Needle EMG is a process of injecting a needle through the skin directly into the muscle to detect electrical signals. However, this is not applicable for dynamic uses, because of the pain and interference with movement while the electrode is in place. Fine wire EMG is a process of using a needle to inject a thin wire into the muscle tissue to reduce discomfort during actions, but this method is unproven for dynamic actions. These two types of EMG are also not good options for common use, because they can not be left in place and must be inserted before every use of the exoskeleton. This would be very inconvenient for uses with exoskeletons, because they would need to monitor many different muscles of the wearer. However, for situations where the exoskeleton will be worn for many hours each day, implanted electrodes may be a better choice than surface electrodes. Implanted electrodes are sometimes used for muscle stimulation in individuals trying to regain muscle function after a stroke for instance. Those who choose to pursue this option often spend a lot of time in physical therapy, and implanted electrodes makes the process a little faster, easier, and more precise. Similarly, electrodes could be implanted for EMG purposes for use with an exoskeleton. Permanently implanted electrodes could reduce the time it takes to attach to and detach from the exoskeleton. They would also provide more accurate and detailed signals from the muscle activations than those collected at the surface of the skin. This could also give insight in to the strength of action of the muscles, improving the interpretation of intent and therefore the control of the exoskeleton. There have also been recent advancements in implant materials, making them more likely to be accepted into the body, merging with the correct type of cell while limiting merging with unintended cells. A Thomas J. Webster et al. study has shown that a coating of carbon nanofibers on a neural implant may slightly decrease neural adhesion, but significantly decreases the adhesion of astrocytes (glial cells) that can interfere and change the resistivity of the electrode [Webster et al. (2004)]. This can improve the performance of these electrodes.

3.7 Software Requirements

As discussed with the topic of the DARwin robot at Virginia Tech, in order to create stable walking conditions, the lower limb portion of the exoskeleton will need to exert control over six degrees of freedom with each leg for a total of 12 degrees of freedom. This will allow the exoskeleton to create a walking motion with turning abilities as well as maintain balance and correct for minor disturbances. In order to create stable walking motion, DARwin receives a command of what action needs to be performed or where it needs to go, and creates a stable path for the center of mass (COM) to follow. The exoskeleton can also utilize this method to create desired motions with a patient. Also similar to DARwin, inclinometers can be used to monitor pitch and roll of the individual and exoskeleton, and force sensors at the bottom of the foot can be used in combination with monitoring the motor torques at the foot to provide information about the stability of the exoskeleton and wearer. Measurements from all of these sensors can be used to determine and monitor the individual's zero moment point. The zero moment point is the point on the floor where the total inertial forces equal zero. This is very important to bipedal movement, and possibly more important than the monitoring of the COM, because a fall will occur if the zero moment point moves outside of the region of stability. Therefore, the motion of the leg segments must be set along a trajectory that will not only carry the body in the desired direction, but also keep the zero moment point within the region of stability. However, unlike DARwin, with the integration of human beings, the actions of the exoskeleton must be limited to prevent the exoskeleton form injuring the wearer. With any patient, the kinematics of the exoskeleton must be limited to the individual's natural flexibility and range of motion. Similarly, the kinetics of the system must also be limited. The motors must not be able to exert a torque on the user's joints that could potentially result in injury. These limitations are particularly important for patients with spastic CP. These individuals are characterized by joints that are often stiff and lack typical range of motion. The exoskeleton's control system must be limited to each patient's individual limitations. Therefore, before any therapy with the device can take place, a patient must be tested for range of motion and comfortable forces at each joint. This is paramount for the individual's comfort and safety. However, over time, the individual's range of motion and flexibility may improve, allowing for extended

control by the exoskeleton. The range of motion and comfortable forces at each joint should be evaluated regularly to allow the exoskeleton to provide optimal performance as the patient progresses through therapy. For example, it has been found that a generally comfortable range of motion for the hip an average adult rotating around the x-axis is between -110° and 10° with the normal to the rotation in the positive x direction. An average rotational range for the knee around the x-axis lies between 0° and 110° with the normal to the rotation in the positive x direction. Finally, an average rotational range for the ankle around the x-axis can be found between -30° and 20° with the normal to the rotation in the positive x direction [Tian & He (1997)]. However, these generalizations to range of motion are not always going to be true for each joint. It must also be taken into consideration that the range true range of motion of any joint is also dependent on the position of the components connected to it. For example, the average person can generally bring their knee closer to their chest if their knee is bent. If the leg is straightened out, the flexibility of the hip joint around the x-axis is typically significantly reduced [Riener & Edrich (1999)] [Silder et al. (2007)]. It is these limitations that will determine the range of activities that can be performed with an exoskeleton, and with increased physical abilities of the wearer will come an increased variety of activities that can be performed.

A company named AnyBody Technology has been developing software that analyzes the kinematics of the human skeleton to relate them to determine not only the contributing muscles of the action, but the amount that each one contributes. The introduction of this software could be very beneficial to the therapy of patients. By analyzing the specific motions of the exoskeleton, and the human body in turn, this software can extract what muscles should be working. These are the muscles that are going to be benefiting the most from the action. If an individual is utilizing a slightly irregular gait patter, this software can determine which muscles are being used and which ones aren't. This can then be compared to a typical human gait for analysis. Similarly, if a specific muscle needs to be targeted with the exoskeleton, the AnyBody software can be used to develop the kinematics of the motions to most effectively apply the exercise. In the case of the irregular gait, this can then be used to plan exercises to strengthen the

muscles that are causing the irregularities. The EMG portion of the HAL-5 exoskeleton can also potentially contribute to the integration of this specialized software.

The next step in the therapy progression is to give the patient more responsibility in the actions of walking. Assuming that the benefits achieved by the patient are similar to those that have been shown for current rehabilitation robotics such as the Locomat, the wearer will gain ability and proficiency in walking with the exoskeleton controlling all of the actions. As these abilities increase, the patient should be able to contribute more to the motions of walking. Therefore, the software of the exoskeleton needs to be able to decrease the influence of its control over the body. As the wearer becomes more capable, the exoskeleton needs to be able to take its commands from the individual's muscular electrical changes rather than from a joystick, as is done with complete control. Eventually, the control system should receive all of its commands from interpreting the wearer's actions, as the HAL-5 exoskeleton operates today. With continued reduction of assistance from this point, a patient may be able to achieve a level of proficiency that would allow them to walk for periods without the exoskeleton, and eventually never need the exoskeleton again. At this point, the controls of the exoskeleton would simply be acting to support the weight of the device and no longer the individual as well.

Chapter 4. Results & Conclusions

The many advancements in robotics over the years have brought us to a point in time where mechanical devices can be tailored for a specific needs of individuals. Exoskeletons have reached a production level, and humanoid robots are now playing soccer in tournaments. The medical field is continuously searching for devices to better the quality of life for patients, and cerebral palsy is no exception to this. The exoskeletons and control theories discussed in this document are simply one method of improving a small portion of this search. The increasing the mobility CP patients, with the applications being discussed, has the possibility of increasing the quality of life. These ideas can make the therapy and learning process easier for both patients and physicians with the independence and mobility of an exoskeleton. The combination of knowledge of CP characteristics, technology that is currently being used, the knowledge of fields that need further development, and redesign in the physical integration of the system can provide needed aid to CP patients as well as many other individuals with related afflictions.

4.1 Results

This project has the potential to help a lot of people throughout the world with CP as well as many other afflictions. With the existence of exoskeletons in their current state, we have advanced the physical technology to a level where meaningful specific applications can begin to be considered. Motors and hydraulics have developed the strength, response time, and size to create exoskeletons strong enough to support excess weight in addition to the individual wearing the device without inhibiting their freedom of movement. The materials available for the frames of current exoskeletons have become lighter, stronger, and less expensive than previous options. Finally, the power sources for current exoskeletons have been developed to provide high levels of power for long periods of time, while remaining small enough to be considered mobile while attached to the exoskeleton. Most recently, Berkeley Bionics has been working on the development of a power source that would recover a very small portion of its power from the interaction between the foot and the ground at every step, similar to the regenerative

braking in modern hybrid and electric cars [Berkeley Bionics (2008)]. All of these factors have been combined to create exoskeletons that contour the human form, allowing for uninhibited movement through everyday environments such as homes and workplaces. These advancements and characteristics make this specific project feasible in the near future if not this point in time. It has been proven that the human body can be assisted and even supported by these mechanical devices.

With the development of humanoid robots that can perform complicated and agile movements such as playing soccer, the control aspects of robotics have also progressed to a point to begin considering applications that could possibly benefit those in need. The movements required for walking and navigation have become fairly reliable and versatile. Also with the development of the humanoid robot, the ability to maintain balance though a variety of motions has come a long way. Even complicated motions such as standing up from the ground are now commonly seen among humanoid robot designs. However, the controls to maintain balance during incidents of increased outside interference may still need some development. Many humanoid robots are currently programmed with the acceptance that falls may occur on a regular basis, which is why the action of standing up from the ground has become more prevalent. Programming in which falls are not a very rare occurrence is not acceptable when working with human subjects. Therefore, the balance maintaining controls of any exoskeleton designed to command a person's movements must be very robust, as to prevent possible injury to the individual. The achievable motions may also need to be refined to closer reflect the natural gait of a typical person, but this is under constant development. There are many different techniques to walking, and therapy in a more typical method will create a more efficient walking technique for the patient.

There are also devices that are not powered that this type of therapy could benefit from. In the situation where a patient gains the motions of walking from therapy with an exoskeleton, but lacks the physical strength to conduct the actions independently, a gravity balancing leg orthotic device can be used to reduce or eliminate the effects of gravity on the legs. The University of Delaware has been developing these devices by utilizing springs and parallelograms [Agrawal & Fattah (2004)] [Banala et al. (2006)]. This will additionally help the patient by allowing them to continue to move their legs

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through the motions of walking while further strengthening their legs and reducing their reliance on an additional device. This may be more cost effective in these advanced cases.

4.2 Conclusions & Recommendations

The application of the HAL™ exoskeleton for the purpose of helping CP patients learn to walk will require some alterations from its current form. Most importantly, is to increase the number of controlled degrees of freedom of exoskeleton. The hip joint will require two additional motors as shown in Figure 3.13, and two motors will be required at the ankle joint as shown in Figure 3.14. One additionally difficult aspect of the motor design is the fact that two motors at the hip and the two motors at the ankle will have to apply their torques through a perpendicular arm. This means that these small arms will need to be strong enough to handle this torque. In the current HAL™ design, all of the motors in the lower limbs apply their torques between segments that neutrally rest at 180° from each other. In this case, the force between the two segments in their neutral position rests on the joint connection and not on a small arm between the two. This makes the application of force easier than between segments that will most commonly reside perpendicular to each other.

With the addition of these degrees of freedom, and the combination of humanoid robot motion planning, the exoskeleton has the possibility of providing the safe practice in motion to increase a CP patient's mobility. The two primary aspects that need to be focused on are the motor specifications and the controls. The hip and ankle powered joints previously discussed will need to be designed to support and manipulate a child's body. The average body size and weights provided earlier may be used for the controls aspect, while the average femur and tibia lengths can be used for the specific leg segment lengths of the physical device. It is also entirely possible that the electric motors will need to be changed to hydraulics, in which case the entire power scheme for the device will need to be redesigned. When testing of the device is to begin, it may be safest to conduct the desired tests with a mobile partial body weight support harness that can both increase stability as well as protect against falls. Working in cooperation with the Cyberdyne, Inc. may also be very advantageous for both parties. Their research

background can provide invaluable information for the development of this project, while our academic community can provide fresh ideas and often less expensive labor. However, even if a cooperative effort is not achieved, contacting the company to obtain an exoskeleton can also be very valuable. At the moment Cyberdyne, Inc. is only offering the use of their product within Japan, but they may be willing to consider releasing one in the United States for a cause such as this.

4.3 Projected Benefits

As discussed before, rehabilitation robotics that are being used today have beneficial results with CP patients. They can improve the communication between the brain and the muscles, improving coordination, dexterity, and strength. Despite the fact that the damage to the brain can not be repaired, the electrical signals sent to the muscles can be improved. This is all accomplished through simply moving the legs through the motions of traditionally correct walking gaits. The use of an exoskeleton to learn to walk would perform this same task, and therefore produce these same beneficial results. However, the freedom of mobility, due to the fact that it is worn by the wearer and not a large stand-alone device, allows for many advantages and comforts of using an exoskeleton over the current rehabilitation robotic devices. One very basic example of an action that is performed every day that traditional walking therapy does not cover is walking up steps. The freedom of an exoskeleton would allow patients to walk up a wide variety of steps with the balance and strength assistance needed to accomplish the task. This simple action therapy will be a large progression for more proficient and independent movement in everyday life. One very large benefit of physical therapy with an exoskeleton, especially with children, is the possibility of making therapy more "fun". The ability to perform therapy exercises outside of a physician's office allows for a wide variety of more entertaining environments. Using an exoskeleton, taking a walk through a park, going to the zoo, or even playing frisbee golf can be therapy. If therapy is fun for the patient, they are more willing to participate. As exoskeletons advance in both form and function, therapeutic exercises may even include more complex activities such as sports. The freedom of using an exoskeleton with the assistant of walking also creates more opportunities for performing therapeutic actions. Once the patient achieves a level

of mobility that allows them to walk without the supervision of a physician, they can perform the therapy under the supervision of a friend or family member or possibly by themselves. This can increase the rate that the individual progresses with their walking abilities, because they are more willing to participate and they have the freedom to do so more often. They may be able to schedule appointments with physicians to periodically monitor progression to adjust the exoskeleton gains, instead of performing each therapy session with the therapist. Depending on the individual's type and intensity of affliction, a patient's ultimate goal may be a proficiency of mobility that will not need the assistive exoskeleton. However, even if the patient never reaches this proficiency, the freedom of an exoskeleton may allow them to live a very mobile and free life with the assistance of the exoskeleton. This therapy should be beneficial for all types of CP, but the amount of improvement will depend on many things from the type of CP to the intensity of the affliction.

The therapeutic possibilities of an adjustable assistive exoskeleton go well beyond the application of CP patients. This technology could be applied to victims of stroke, spinal cord injury, traumatic brain injury, multiple sclerosis, and many more. Patients of all of these afflictions have benefited from therapeutic rehabilitative robotics in use today, and as with CP patients, the advancement of exoskeletons for therapeutic purposes will improve the diversity and possibilities of the therapy for these individuals. The cases most closely related to CP are traumatic brain injury, stroke victims, and multiple sclerosis. Traumatic brain injury is simply a severe incident that can damage the brain. Strokes are typically caused by a lack of blood flow to the brain or bleeding within the brain. Finally, multiple sclerosis is a condition where the immune system attacks the white matter of the brain. As it was discussed at the beginning of this paper, all of these are incidents that can cause CP at a very young age. However, an adult has more advanced regenerative abilities than a young child or a fetus. This being the case, older children or adults may very well produce faster and more significant results with this type of therapy than CP patients. Their brains may be more efficient at reorganizing the processes associated with the motor functions of walking. Spinal cord injury typically falls under the category of damaged nerves. However, it has been shown that moving and exercising deficient muscles in common motions can not only reorganize the

processes in the brain, but it can repair nerve cells. This will produce results very similar to those with CP and the previous afflictions. The benefits of an assistive exoskeleton can also be applied to the aging process. Many elderly people have difficulty getting around because of strength, balance issues, and even arthritis issues. An assistive exoskeleton could allow for much greater mobility for these individuals at possibly a greater percentage than CP patients. In the case of elderly with arthritis, exercise and joint motion can alleviate symptoms. This will not only give the individual increased mobility, but it can make them more comfortable with the use of less drugs. There are also many less intense injuries that could benefit from the development of this technology. Any injury that is improved by moving the limb or joint through basic actions could show faster improvement if the reliance on scheduling therapy sessions with a physician can be reduced.

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