DESIGN AND FABRICATION OF AN ADVANCED EXOSKELETON FOR GAIT RESTORATION

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Submitted in partial fulfillment of the requirements

For the degree of Master of Science

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May, 2012

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DESIGN AND FABRICATION OF AN ADVANCED EXOSKELETON

FOR GAIT RESTORATION RESEARCH

MARK J. NANDOR

Abstract

This thesis details the design and fabrication of an advanced, hydraulically actuated exoskeleton, with the intention of decreasing weight and increasing performance over a previous proof of concept device. The initial device was invented to provide a method of gait restoration to individuals with paraplegia. It combines two different ideas – functional electrical stimulation of the user's muscles, and an external, hydraulically actuated exoskeleton. By incorporating the user's own muscles, this method is theoretically more energy efficient than other alternatives while providing additional health benefits. However, in order to fully realize these advantages, the device must be made smaller and lighter, in order to decrease the overhead energy requirements placed on the user's own muscular system.

To accomplish this, a new exoskeleton was designed, that utilizes all off the advanced manufacturing and fabrication resources of the department. Part count has decreased at the cost of manufacturing complexity, and the use of aluminum and carbon fiber composite material is now prevalent in the device. Neither the hydraulic system nor the controller was modified in any way during this process.

The end result of this work is a substantial decrease in overall unit weight (30%), and an estimated decrease in user energy requirements of approximately 15.2%. This was accomplished while maintaining all previous benchmarks in range of motion. It is expected that this will have a positive influence on the operation of the device, particularly in planned future endeavors in stair climbing.

Future work in this area to further increase device performance can take place in integration and redesign of all hydraulic components – replacing the existing brass pieces with lightweight, high operating pressure, potentially seal free pieces made from high strength, aerospace grade 7000 series aluminum.

History and HNP Overview

History

The Hybrid Neuroprosthetic project (HNP) aims to restore gait to individuals with paraplegia by combining Functional Neural Stimulation (FNS) with an advanced exoskeleton featuring hydraulically actuated joints. This combination of different mechanisms combines the best features of both the FNS only and orthotic device only approaches, while the unique and novel hydraulic mechanisms of the exoskeleton solve the problems inherent in fixed constraint orthotic devices.

FNS is a method which applies electrical pulses generated by an external device to the peripheral nerve, eliciting muscle contraction. Coordinated pulse patterns to select muscles can produce a gait pattern, restoring gait to individuals with SCI [1-3]. FNS systems are typically available in two varieties - surface and implanted stimulators. Surface stimulation does exactly as the name implies, provides stimulation of the nerves via electrodes attached to the skin of the user. However, given that the electrodes must be removed and reattached, repeatability is an issue with this system. Additionally, the skin surface mounted electrodes lack the ability to trigger deep muscles, and thus the maximum torque produced by the joint via surface stimulation is severely limited compared to other alternatives [4, 5].

The other FNS option is to implant the electrodes below the surface of the skin [6]. These implanted electrodes deliver selective and repeatable muscle stimulation to the muscle groups they are applied to. Combined with an external stimulator delivering coordinated stimulation pulses, ambulatory functions have successfully been enabled in subjects with paraplegia. However, the FNS enabled gait is neither efficient nor very fast. Experimental results with an eight channel percutaneous FNS system yielded an average gait speed of .24 m/s

(18% of normal) with an energy expenditure 11 times normal [7]. The average maximum walking distance was 150 m[8].

From these results, it is clear that FNS applications have their limitations. The coordination of the joints is a difficult task to manage without the benefit of any sort of feedback. Additionally, fatigue and range are a hurdle that must be overcome before FNS can be accepted as a viable gait replacement option for SCI subjects.

Lower extremity exoskeletons and bracing are another alternative to restoring ambulatory function to SCI subjects. These are typically passive devices that constrain and reduce the number of degrees of freedom of the user's lower extremities. Occasionally a reciprocating gait orthoesies (RGO) is prescribed. The RGO both limits motion and establishes some constraints to aid in gait. The knees are locked in extension, and ankles are held in a neutral position with ankle-foot ortheses. The AFOs are typically thermoset plastic pieces, custom molded to each individual user. Additionally, each leg of the orthosis is constrained to move strictly in the sagittal plane. The reciprocating portion of the name comes from the final constraint that the device places on the user – it couples hip extension to contralateral hip flexion. This can be accomplished with a variety of mechanisms, from cable operation to a solid pivoting tie rod design. This coupling provides stability by eliminating the possibility of bilateral hip flexion or extension, while supposedly reducing the metabolic cost of forward ambulation.

In studies conducted with RGO assisted gait in SCI subjects, the resulting ambulation required 5 times the normal human energy expenditure [9] for gait speed 16% of nominal able bodied gait [10-12]. Fatigue typically limited walking distances to 100 m. This difficulty arises from the RGO constraints that, while necessary, make ambulation difficult. By holding the knee in extension and the ankle in its neutral position, it is necessary for the users to raise themselves upward and lean to the side in order to obtain the necessary toe clearance height.

Consequently, upper extremity forces during use are very high [13]. So while the RGO may be a simple device in its concept and construction, that very simplicity is also what makes it difficult to use, and has discouraged its widespread use.

The Hybrid Neuroprosthesis (HNP) is a device that was developed with the goal of restoring gait to individuals with paraplegia from spinal cord injury (SCI). The HNP is a semi-active exoskeleton that offers the support of a traditional RGO while maintaining the range of motion and ease of movement comparable to walking without the exoskeleton.

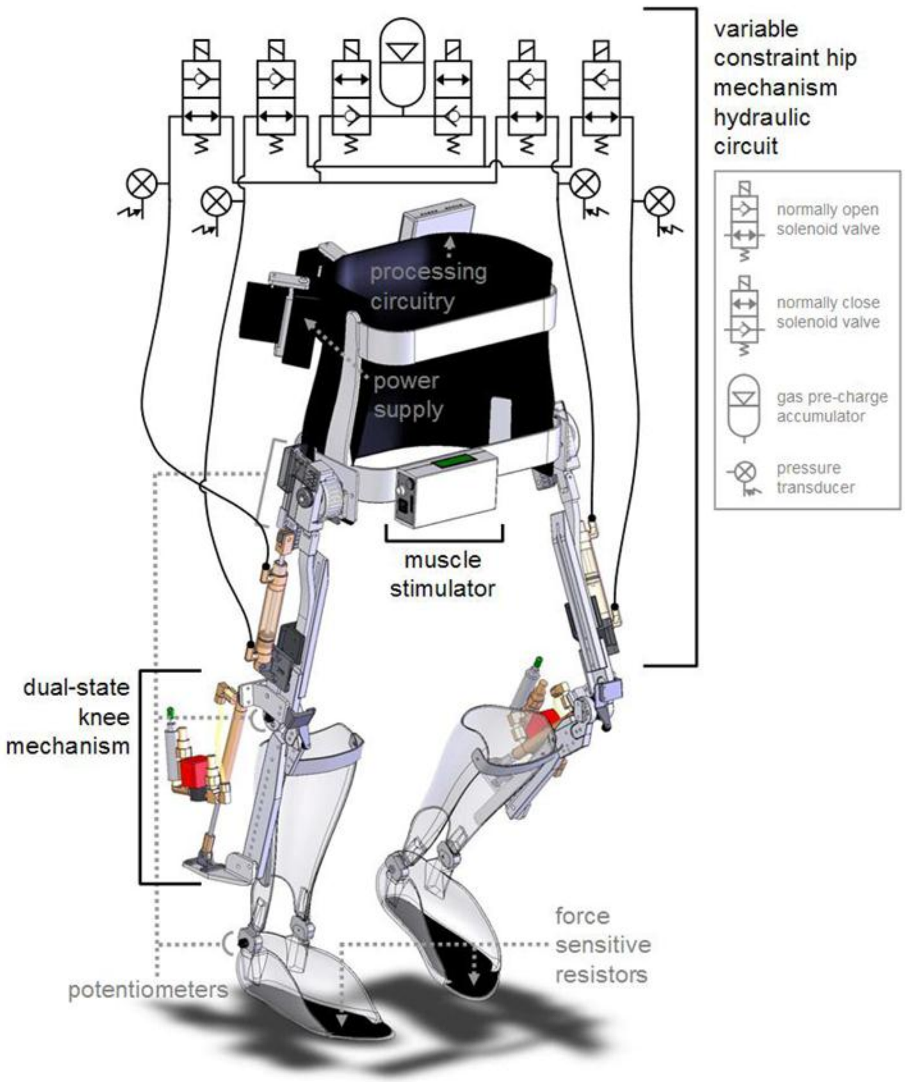

Figure 1 – A display of major systems and components for the Hybrid Nueroprosthetic (HNP).

It accomplishes that feat by placing a hydraulic cylinder at each degree of freedom – one at each knee and one at each hip. The cylinders offer a low amount of passive resistance, allowing the joint to rotate freely under user supplied muscle power. However, when the cylinders are locked by closing the appropriate valves, it effectively locks the joint in question and prevents movement.

The system is shown in Figure 1, and it consists of a corset, two uprights running down the outside of the user's legs, and two molded Ankle Foot Orthoses (AFO). The corset supports the user's trunk, while also carrying many hydraulic and electric components vital to the operation of the system. This includes a majority of the hip hydraulic components (valves, accumulator, etc.) and data acquisition and signal conditioning boards (including optical coupling of all signals for safety).

The uprights travel down the outside of the user's legs, and are both the main structural elements of the HNP, and contain the hydraulic cylinders that constrain the motion of the exoskeleton. They terminate in a pair of thermoset plastic Ankle Foot Orthoses, pieces of molded plastic custom fitted to each individual user. In its current iteration, the HNP does not actuate the ankle joints at all – they are simply locked in place at a 90 degree angle [14].

Knee Joint

The Dual State Knee Mechanism (DKSM) is the device that controls and manages knee motion in the exoskeleton system. Theoretically, this would allow for FNS stimulation to be turned off during stance, conserving energy and delaying the onset of fatigue [14]. The intent behind the design and operation of the mechanism is to support the user's knee joint during the stance phases of gait while allowing free motion during the swing phases. This device is shown in detail in Figure 2.

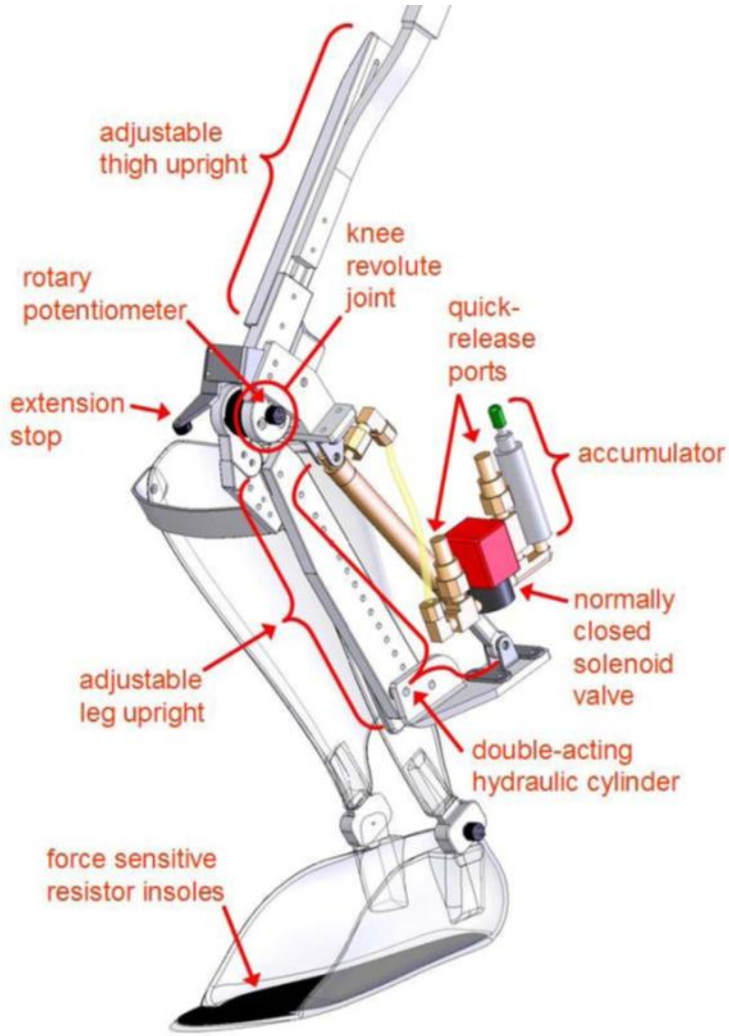

Figure 2 – Component view of the Dual State Knee Mechanism (DKSM).

Mechanically, the device is a 4-bar linkage, with a hydraulic cylinder serving as one of the links. The actual knee joint is a simple revolute joint with a fixed instant center. The geometry is optimized to maximize holding torque at small flexion angles (such as when the user is standing straight up during stance). The graph of moment arm vs. flexion moment can be seen in Figure 3 [14].

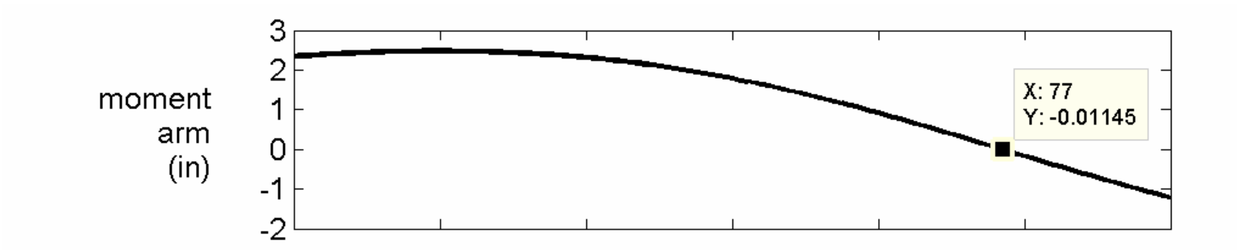

Figure 3 - Moment Arm profile for DKSM.

The graph shows the disadvantage of a 4-link setup as compared to a rack and pinion setup as found in the hip joint – there exists a point of zero moment arm, and thus zero holding torque. That singularity is unavoidable, no matter how the geometry is adjusted. The best than can be done is placing the singularity at the most inconvenient place possible – an angle not typically seen in normal gait patterns. In this case it is placed at 72 degrees of knee flexion, far beyond the typical range of motion found in gait.

The hydraulic circuit for the DKSM is relatively simple, consisting of a single hydraulic cylinder, a single hydraulic solenoid valve, and a single hydraulic accumulator. The cylinder is a 9/16" bore, 3" stroke unit from Clippard Minimatics. It is nominally a pneumatic cylinder that can also function with a liquid working fluid. It is rated up to 1000 psi, however the mechanism itself is designed for a maximum operating pressure of 800 psi for a small factor of safety.

The valve is a two way solenoid valve from Allenair. It is a standard, off the shelf unit selected for its small profile, low cracking pressure, and low power consumption. The initial design of the DKSM did not contain an accumulator. Initial testing of said design revealed an excessive amount of compliance in the system due to air bubbles occupying the volume difference in the rod and blind side of the cylinders. A redesign added an accumulator precharged to a low pressure simply to take up that volume difference. The accumulator itself is a spring loaded design – a ¾” bore, 1” stroke unit that requires 3 lbs. of force (7psi) to force open [14].

Final testing shows a minimum of compliance in the system, achieved by the addition of the accumulator. Despite the singularity, this arrangement provides the necessary holding torque through the range of motion typically seen in normal gait. However, it is also a bulky arrangement that sticks out a fair distance from the upright. In addition, the lower upright that connects the knee joint to the AFO and provides the hardware for mounting of the hydraulic cylinder is bulky and unnecessarily complicated. These issues can be rectified by utilizing more advanced material selection and manufacturing capability.

Control of the DKSM is fairly straightforward. Force sensitive resistors in the soles of the shoes can detect when each limb is in stance and carrying weight. When it is in a stance phase of gait, the joint is locked, allowing for the stimulation to be turned off. Conversely, the joint is free to move during the swing phases of gait. This allows the entire limb length to shorten, providing the necessary toe clearance for normal gait. That limb shortening action means that the massive upper extremity forces present in RGO use are also not necessary, increasing endurance and delaying the onset of fatigue [14].

Managing the hip joint motion is the duty of the Variable Constraint Hip Mechanism (VCHM). Like the DSKM, the VCHM has a mechanism of selectively locking and unlocking the hip joint. However, the VCHM also has additional hydraulic circuitry that allows for a third mode of operation – in addition to the locked and unlocked states, the hip joints can also go into a coupled state, coupling hip flexion in one hip to hip extension in the other in a 1:1 ratio, as found in a typical RGO [14].

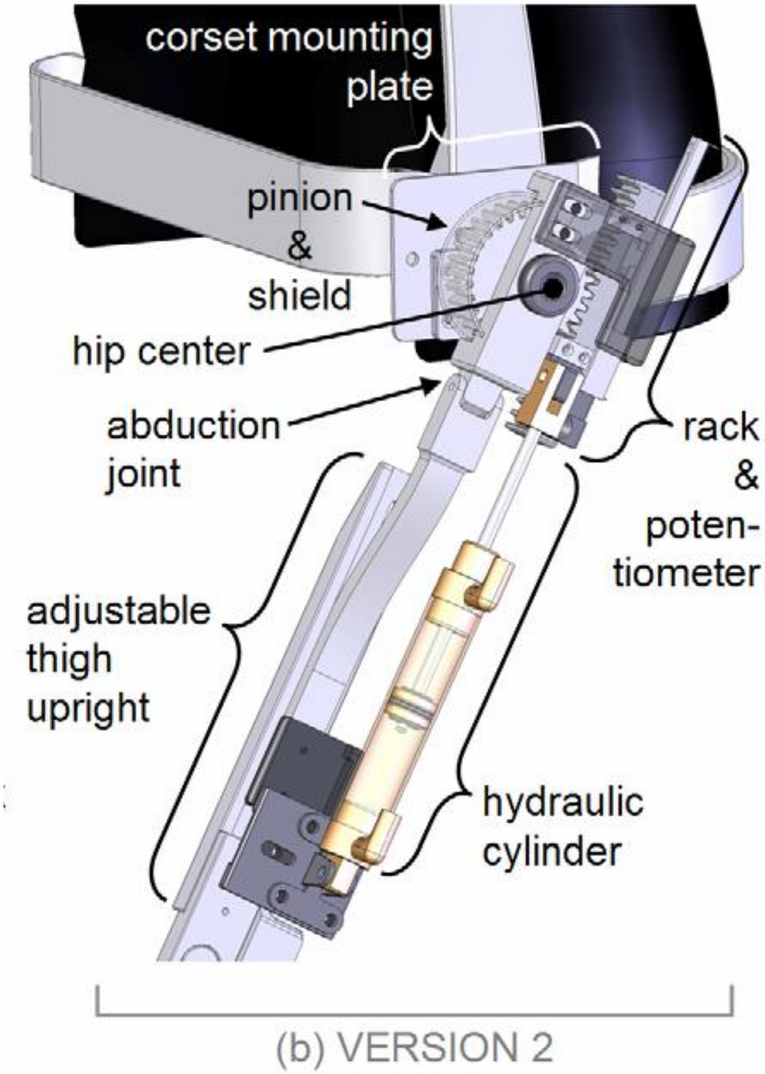

Figure 4 – Layout and component view of the Variable Constraint Hip Mechanism (VCHM).

The torque transmission capability is not accomplished by a four bar linkage arrangement, as found in the DSKM, but rather with a rack and pinion gear set. The gears were purchased from McMaster Carr, and are 1018 steel, 12 pitch, 0.75" wide gears. Additionally, the pinion is a 2.5" pitch diameter gear. These gears and their integration can be seen in the above Figure 3.

The pinion gear is fixed to the torso corset, held in place with three screws that maintain the orientation of the gear with respect to the torso. Except for three bolt holes, the gear is not modified in any way. The rack gear is affixed to the hydraulic cylinder by means of a spherical rod end [14].

This setup offers advantages and disadvantages compared to the 4 bar linkage as found in the knee joint. Most notable, the geared arrangement means that the moment arm that the hydraulic cylinder acts on is constant throughout its range of travel. This eliminates the singularity found in the knee joint, allowing for the complete range of motion to be utilized. However, this arrangement is also significantly heavier than the linkage arrangement, due to those large and cumbersome steel gears. This is clearly an area of concern for performance, but because the gears are located at the hip joint, they do not contribute to the moment of inertia of the upright, and thus do not add to the necessary torque at the joint to overcome the weight of the upright.

In order to accomplish that third functional mode of coupled hip motion, the hydraulic circuits of each hip cannot exist on their own – they must be selectively linked together. To accomplish this, the joints are connected together in an arrangement of 6 solenoid valves and a single hydraulic accumulator, as seen in the below diagram. Again, the hydraulic accumulator is precharged to slightly above atmospheric pressure in an effort to eliminate air bubbles and compliance in the system [14].

This hydraulic circuitry allows the VCHM to operate in one of three states. The first mode of operation is free, where each hip is free to move without hindrance and independent of the motion of the other hip. The second is locked, which locks the hip to the trunk corset, and the third is coupled. The brace alternates between these modes in an effort to provide the benefits of both standalone FNS modulation (free, unconstructed range of motion) and external bracing (external support to decrease user exertion).

All of this hardware is carefully coordinated to work in conjunction with the user to augment his or her abilities. Onboard sensors feed information to a controller programmed with a state machine. This state machine is capable of identifying different phases of gait, and adjusting the hydraulics accordingly.

The end result is a product that offers the support of traditional bracing, while allowing for free movement similar to an FES only approach. It shows what can be accomplished by adding a small amount of smarts and power to a traditionally passive system.

Design and Fabrication of HNP 2.0

Available Facilities

The largest opportunity for improvement in the second generation prototype lies in the availability of a wider range of resources available to the Biorobotics Research Group at Case, compared to the facilities used to construct the first generation prototype. As such, the proposed design would make full use of all available resources.

These resources include a large number of machine and manufacturing tools, and specialized facilities for the construction of composite pieces. The Biorobotics manufacturing center includes a manual mill and lathe, a vertical bandsaw, various hand tools, and most importantly a Hurco 3 axis CNC mill. Additionally, the second generation prototype made use of the Reinberger CNC Plasma cutter. The composite material layup and baking was completed in the Case Aerostructures lab, which features the necessary oven and vacuum bag equipment to complete the process.

Software packages used include Solidworks 2010 for design and three dimensional modeling work, Mastercam for use of all necessary G-code, and Solidworks Analysis was utilized for all finite element approximations.

Geartrain Redesign

When looking at areas for available weight reduction, one area that stands out is the large rack and pinion gearset that were used to transmit power in the VCHM. Each hip joint of the first generation HNP prototype features 2.5” pitch diameter, 0.75” face width, 12 pitch pinion gear and a 12 pitch, .75” rack gear. Both gears are a low carbon 1018, non heat treated steel and were purchased from McMaster-Carr. The advantages of utilizing these gears are that they are easily sourced and cheap to acquire.

The disadvantage of this rack and pinion combination is that the 1018 steel alloy is not ideal for this application (possessing a low strength to weight ratio compared to other alloys or other metals), and that the gears were chosen for their geometry, rather than their power transmission capabilities. The large face width is necessary for the 1018 steel teeth to not break under the applied forces, but the pitch line velocities experienced by the gears in a typical gait pattern are much lower than the rating they carry. Consequently, the gears are vastly overbuilt for the intended purpose.

Purpose built gears, either of different geometry or material, would provide a large source of weight savings over the cumbersome pair initially utilized. These constraints consisted of the following:

1) Given the unavailability of any hydraulic with a higher operating pressure, it was decided that the 2.5” pitch diameter feature would be kept. Any attempt at significantly reducing that parameter would result in a high pressure seen by the cylinders, possibly in a range of operation that they are not qualified for.
2) Because of the limited range of motion provided by both the limitations of the human body and the limitations on cylinder stroke, all 360 degrees of teeth are not necessary – in fact, a minimum of 120 degrees of motion was decided upon, comparable to performance possible with the first generation prototype.

Given the design limitations outlined above, a large variety of materials and two different manufacturing processes were considered. Traditionally, gears are hobbed, or cut to specification on a particular machine designed to cut the involute curve required for gear teeth. However, this process is limited to making complete, full 360 degree gears. A secondary machining operation would be required to cut away the unneeded teeth and to fully realize the optimal result. Additionally, with this method of gear production, the option of helical gears is possible.

The second, and preferred option, involves a Wire EDM cut gear. Such machines are capable of cutting both the two dimensional spur gear tooth profile (a three dimensional helical gear would not be possible), and the post machining necessary to carve away the unnecessary teeth and material. Also, this process is capable of being applied to any metal, be it a low carbon steel, hardened steel, titanium, or even aluminum. Ultimately, given the unusual requested geometry and the versatility of and EDM machine in both possible working mediums and cutting ability, this method of producing both the custom pinion and rack gears is preferred over the more traditional gear hobbing methodology.

The second question to be considered was one of material. The 1018 steel used in the original gears was selected primarily for its low cost, high availability, and ease of machining/cutting. However this is not the best material of choice for the task at hand.

Better suited materials do exist, in terms of higher yield strength and possible lower density, at the cost of a difficult (but not impossible) ease of manufacturing. Some candidates include different steel alloys (specifically the 4000 series, which responds very well to heat treatment) or titanium. Due to the slight but significant geometric changes brought on during heat treatment, it would be necessary to obtain pre-heat treated material, and then cut the parts out of it. The table below summarizes the characteristics of some candidate materials (all properties via matweb.com).

Material	Yield Strength (MPa)	Young's modulus (GPa)	Density (lb/in^3)
1018 Steel	370	205	0.284
7075 Aluminum	462	71.7	0.102
4340 Steel, heat treated	1145	205	0.284
Titanium, Grade 5	880	114	0.16

Table 1 - Material Properties for potential custom gear materials.

Unfortunately, all of this design work and criteria turned out to be a moot point, as the cost of getting prototype wire EDM pieces was prohibitive – approaching $1000 for a single gear, $2000 for an entire set. This was prohibitively high, and placed these possibilities beyond the reach of the current level of funding. Clearly a compromise needed to be made.

The major hurdle to obtaining custom gearsets was the fact that they required resources not at the disposal of the Mechanical Engineering Department, and needed to be done through an outside contractor in order to get finished. If the manufacturing process could be done in house, the cost becomes much more manageable. A compromise was developed that reduced the substantial mass of the gears, accomplished the design goals of maintaining geometry and eliminating unnecessary teeth, and was able to be produced in house to keep cost in check.

The final pinion gear design is simply a modification of the existing gears. Recall that the gears were chosen for their geometry, rather than their power transmission potential. Thus, much of the interior metal is not needed, and can be removed while still maintaining a safe minimum factor of safety. The specific amount of material to be machined away was calculated and verified using Finite Element Analysis (FEA), the final results of which can be seen in Figure 5. Specifically, material was removed to remove weight while maintaining a 2.2 minimum factor of safety under the maximum torque specified by the design parameters. Practically speaking, that design parameter resulted in fairly small thickness cross members, which could not realistically be reduced much further.

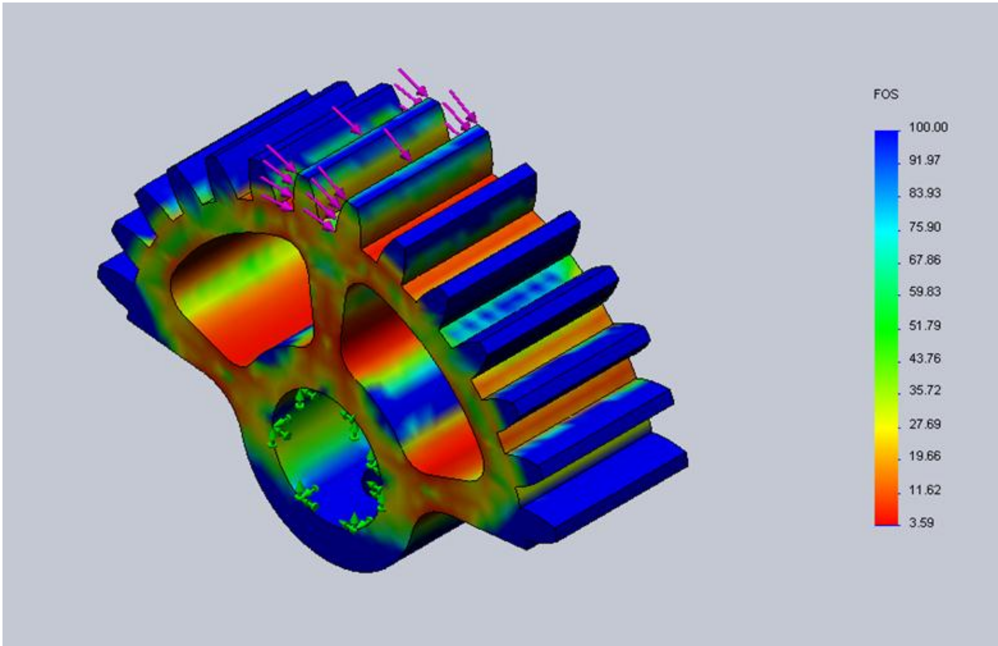

Figure 5 - FEA results of the customized pinion gear.

The actual machining was done on the Hurco VM-1 CNC mill housed in the manufacturing center of the Biorobots laboratory group. Generation of G-code was done in Mastercam. Fixturing of the gear was made possible by the fact that the gears come from McMaster Carr with a large cylindrical boss. Flats were milled into the boss to allow it to be secured in a vice without clamping down onto the teeth and potentially damaging them. This method of attachment means that the pinion was machined as a single sided part, with all of the material removal pockets going completely through the piece.

The rack gear was similarly modified from its stock appearance, although the modifications were nowhere near as drastic as those found in the pinion gear. Given the linear geometry of the rack the gear, the modifications consisted of a simple slot through the base of the gear. Again, a minimum factor of safety of 2.2 was maintained. Additionally, the rack could be machined as a two sided part, allowing for a thin (0.05") web to be left in the middle, increasing the strength of the part for a minimum amount of added material. The final pieces can be seen in Figure 6 below.

The end result of these modifications is reduction of transmission weight from 4 lbs to .75 lbs. This weight reduction does not contribute to the rotating mass of the upright, but still reduces the overall energy requirement of both level ground walking and stair walking, by virtue of reducing the potential energy change of the center of mass. This is discussed further in the results.

Figure 6 – A manufactured modified rack and pinion gearset.

In order to transmit torque between the upright and the torso corset in the current configuration, the pinion gear must be fixed to the torso. It is attached through a shaft welded onto the corset mounting plate, which in turn is bolted onto a steel adapter plate, which is bolted onto the corset. The actual torque transmission is accomplished by a single ¼"-20 bolt that passes through the pinion gear and threads into the shaft. This arrangement is simpler and requires less parts than the previous design, at the cost of ease of assembly and disassembly.

That same design philosophy is applied to the rack and pinion carrier pieces. Utilizing the advanced manufacturing capabilities (namely the Hurco 3 axis CNC mill), the number of parts has been reduced, at the expense of more complex geometry, multiple setup parts. The 3 piece housing consists of two outer, mirrored housings, with a small spacer in between. All of the carrier pieces are machined out of 6061-T6 Aluminum, a lightweight yet strong aluminum alloy. All faces that move are protected by a bearing surface to ensure low friction and passive resistance. The outer carrier pieces contain nylon bearings on the interface with the steel rotational shaft, and the carrier has a small needle roller bearing on a shoulder bolt that rides on a track machined into the rack gear. This ensures that the rack can move freely throughout its entire range of motion, and the bearing also contains the radial forces generation by the gear mesh. The completed assembly can be seen in Figure 7 below.

Figure 7 – A completed and assembled VCHM gear assembly.

For simplicity of manufacturing, all three pieces are .5” thick in order to be machined out of a single piece of stock. The middle spacer required only the initial setup to be produced, but the two outer carrier pieces required an additional setup and jig to machine the radius onto them. The radius was done with an endmill specifically shaped to do cut an external, .25” radiused corner, rather than cutting a 3D contour with a ball endmill. This produces a smoother result with no scallop height, and can accomplish it in a single pass, a fraction of the time that would be required for a 3D contour cut. The radiused edge is again both a functional requirement of reducing the possibility of injury to the user, and also serve to reduce stress concentrations found on the corner. The CAD for the modified VCHM is shown below in Figure 8.

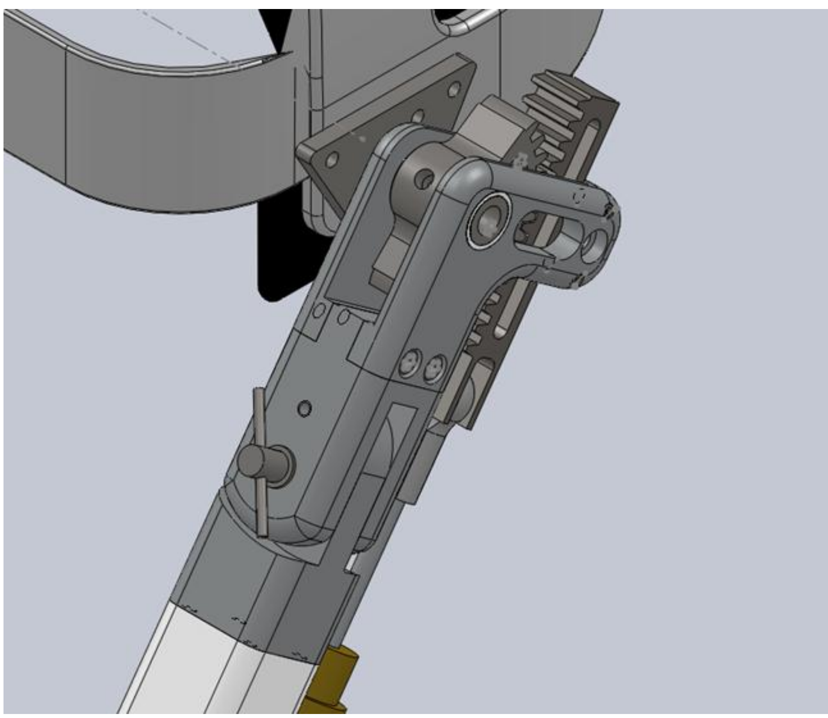

Figure 8 - Completed CAD for the new VHCM.

The carriers bolt onto the hip abduction joint. This joint is not used as functional part of the brace, but is necessary to easily don and doff the brace. Again, the parts are made of 6061-T6 aluminum, and were CNC machined to the final shape. The upper half of the joint is bolted to the two outer gear carriers, while the lower half forms the head of the primary composite upright section. The two are permanently joined together through a shoulder bolt riding on a bronze bushing pressed into the lower portion of the joint – this allows for the free range of hip abduction movement. The joint is held in its vertical position for brace operation by a drop pin that passes through both parts. Again, all outside edges were machined with the radius cutting endmill, to form the fnal outside profile for the remainder of the upright. Additionally, both the upper and the lower pieces have interior cavities machined into them that simply reduce weight of the component.

Both parts required five setups (and approximately eight hours each) to be fully machined, but the complexity is rewarded with a final result that is compact and performs the necessary functions for a minimum of weight.

The cylinder that acts on the knee joint of the user utilizes the same geometry as the previous incarnation of the exoskeleton. The shank strut of the exoskeleton utilizes the same rail construction as mentioned above – two aluminum guide rails run the length of the upright, locating the lower knee cylinder mount and AFO mount while using ABS plastic filler pieces elsewhere. The cylinder is carried at either end through shoulder bolts (with another spherical rod end on the cylinder shaft) through the two mounts. Again, the mounts are designed for simplicity and minimum number of moving parts, at the expense of complexity of manufacturing. These cylinder mounts are designed to carry a higher load than the hip joint, and to cope with the additional stress, these parts are machined out of 7075-T6 alloy aluminum, an alloy with a much higher yield strength than 6061, at the expense of higher cost. However, this cost increase is seen as an acceptable tradeoff for the simplicity and weight savings obtained through this design (as seen in Figure 9). 7075 aluminum still retains the ease of machining that 6061 does, allowing for these parts to be produced by CNC mill. These are again multiple setup parts, and also feature the .25” radius for user protection and stress concentration reduction.

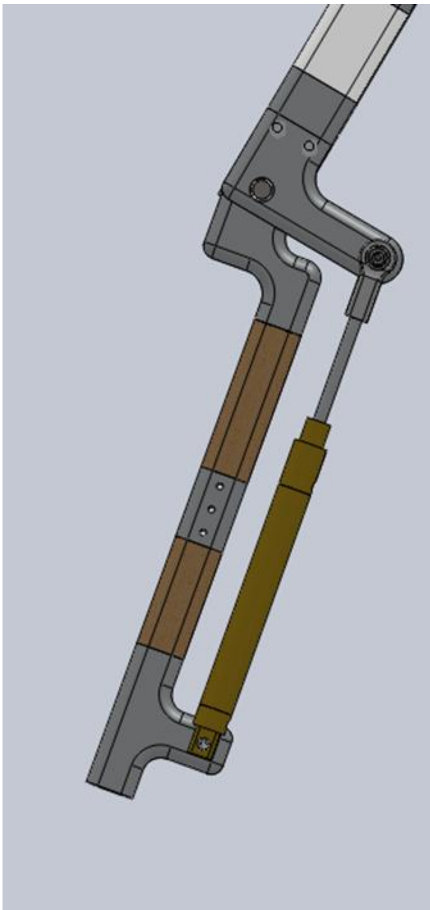

Figure 9 - Modified DKSM, showing the balsa wood spacers.

Composite Material use

It was clear from the beginning that composites should play a large role in the weight reduction. Carbon fiber composite materials are strong, lightweight materials. Coupled with the fact that the Mechanical Engineering Department has the necessary facilities for the creation of composite parts, it made it an easy decision to use it.

Composite materials are not manufactured like other traditional metals or plastics used in manufacturing. They are made up of two parts – a fabric base and an epoxy resin, which is then baked under pressure to cure. The resulting material is quite strong. However, this also means that traditional manufacturing practices (specifically, machining techniques) cannot be applied.

To accommodate these unique properties of the composite material used in the brace, the rest of the design must be both lightweight and able to accurately locate all the necessary components. Specifically, it must accurately determine critical dimensions such as upright segment length, AFO mounting points, and cylinder mounting points. The structure carrying the carbon fiber does not need to be structural, but it must be able to support the composite material before it is cured, provide a shape and cross-sectional area that will form the carbon fiber, and provide a surface for the resin to adhere to.

These qualities were met by utilizing a rail based design – guide rods (rails) run the length of each segment, with pieces of aluminum and ABS plastic providing the correct spacing and forming the cross-sectional area. For simplicity's sake, that cross – section was chosen to be as easy to conceptualize and fabricate as possible, resulting in a square with a side length of 1.5". Additionally, the .25" radius is continued down the length of the device, to both make the device safer by reducing sharp edges, and to decrease the stress concentrations that would be present on a sharp, 90 degree edge.

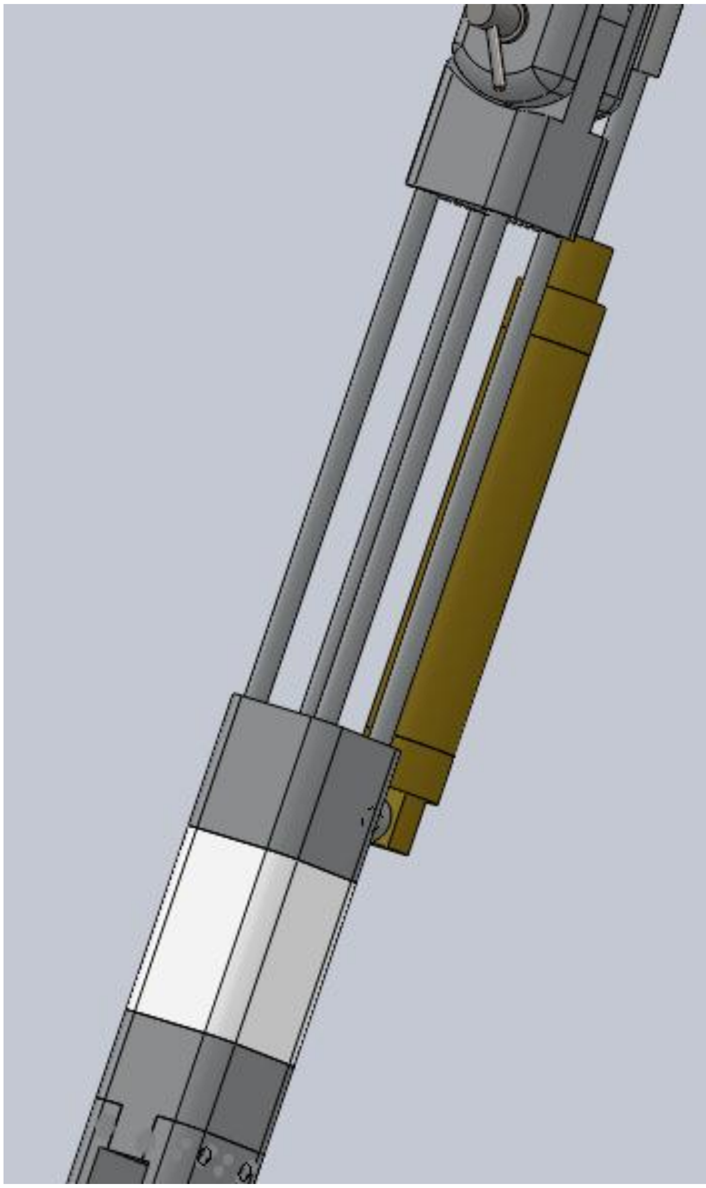

Figure 10 - Guide rail detail, with a plastic spacer removed.

The center guide rails are constructed of all purpose 6061-T6 aluminum, chosen for its ease of machining, ability to hold tight tolerances, and overall lightweight qualities. These pieces could be turned to a very precise length, allowing for the lengths of the individual upright segments (femoral and shank) to be controlled very precisely and accurately.

Forming a majority of the structure is ABS plastic, cut to the proper length to accurately place the necessary mounts such as the hip cylinder mount or the AFO mount. Again, this is not structural in any way – it simply fills the necessary space and forms a uniform cross section throughout the entire length of the upright. As such, the ABS pieces are hollowed out as much as possible, simply to reduce any unnecessary weight. ABS was selected because of its lightweight, cheap, readily available and easy to machine properties, while still able to be held to tolerances of .005”. It was certainly not selected for strength.

There was one issue with the use of ABS plastic that arose during fabrication – In order to cure the resin, the pieces must be baked at approximately 225 degrees Fahrenheit under pressure – in this case, the piece was placed under vacuum. The melting point of ABS is slightly below that at approximately 210 degrees Fahrenheit. This fact, coupled with the one atmosphere of pressure being placed on the part, caused deformation of an early prototype. The solution to this issue was to complete the curing process at a lower temperature. This meant that the time spent in the oven was increased by a factor of two, but it also meant that the uprights could be cured without any deformation of the plastic inside. The cured and completed piece can be seen in Figure 11.

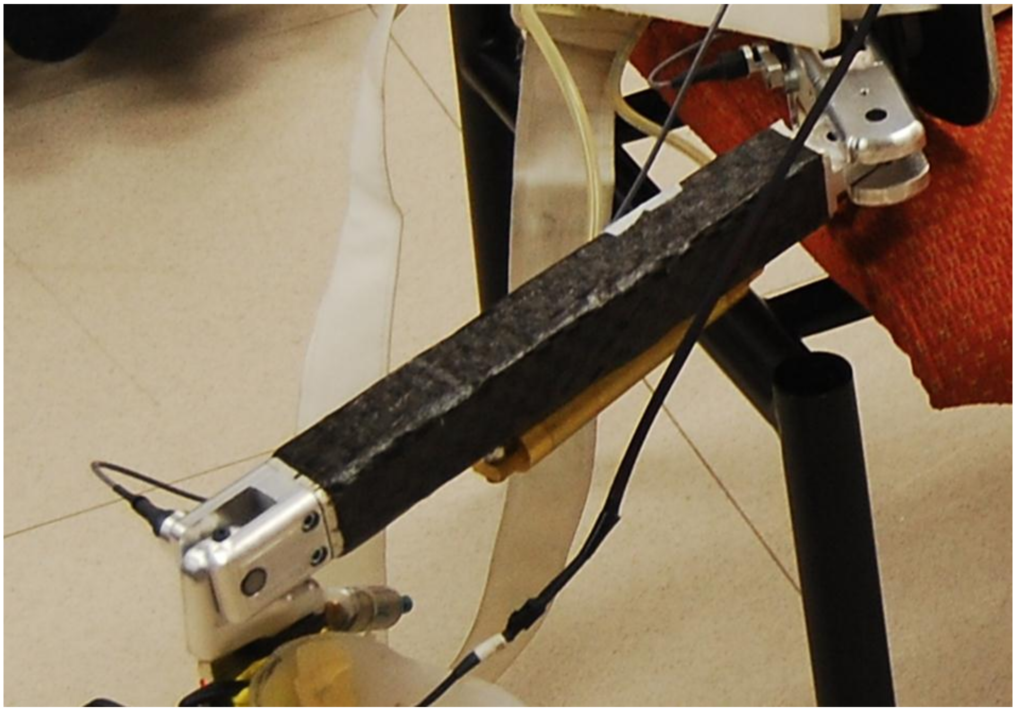

Figure 11 - Completed Carbon Fiber femoral orthosis.

The hip cylinder mounting is similar in construction to the ABS plastic filler pieces mentioned previously – it too is mounted on the internal guide rods, and features mostly hollow construction to keep weight down. However, unlike the plastic core pieces, the cylinder mount is made of aluminum, a strong enough material necessary to carry the reaction force of the pressurized cylinder resisting the movement of the hip joint.

Similar in design and construction is the AFO mounts, milled aluminum pieces with tapped holes that the thermoset plastic AFOs bolt into. They are also located by pieces of ABS plastic milled to precise lengths, and the shank uprights are also wrapped in multiple layers of the same bidirectional carbon fiber cloth.

In order to reduce the number of components (and thus complexity and weight), all length adjustability in the brace uprights has been removed. Each set of uprights are made specifically for an end user in mind. However, the uprights have been designed in such a way that most of the individual parts of the upright do not require modification to be adapted to different sizes. In fact, only three of the ABS plastic pieces need to have their length changed in order to fit the brace to another person. The gears, steel shafts, and aluminum pieces do not need to be redesigned or reshaped for adaptation to another user. So while on-the-fly adjustability may be lost, standardization of parts is maintained across different size ranges and a majority of the parts remain interchangeable.

From an overall perspective, the new HNP unit constructed trades ease of fabrication, ease of assembly, and loss of adjustability for reductions in both weight and part count. Many of the parts detailed here require multiple CNC setups, jigs, or even specialized tooling. The composite components required the resources of the Aerostructures Laboratory resources. All in all, the single prototype HNP cost approximately $1500 in materials, 100 hours of CNC machine time, 25 hours of composites work, and more in final fit and finish time. The end result and impact of this work will be discussed later.

Figure 12 – CAD model of the modified HNP design.

Evaluation

The driving motivation behind this advanced HNP was to explore how much weight could be shed from the exoskeleton within a reasonable cost. This design and build concept has shown just what was feasible without overextending or taxing available resources. Evaluation of the prototype will yield how effective these weight reduction efforts have been, and whether or not further, but more complicated and expensive measures should taken.

The direct measure of success will be the reduction of component weight with no loss of component strength or factor of safety. But just as importantly, it is necessary to quantify the effect the weight reduction has on system performance – specifically in energy or torque requirement reductions. Given the variability in FNS assisted walking, these results will be calculated or simulated.

The net weight savings seen by using the new and updated uprights is 15 lbs. Overall weight of the first generation prototype is 50 lbs, making the weight of the updated exoskeleton 35 lbs, a 30% reduction. The user for which the exoskeleton was designed for is 160 lbs. So the overall weight reduction of the combined user and HNP is 7%. The reduction in weight of the components that were replaced is even more clearly significant. The original components weighed 11 and the new components that replaced them weigh 3.5, only 31% of the original. Table 2 summarizes individual piece contributions to the weight reduction, as well as center of mass placements. Of the remaining mass, the components not replaced make up the vast majority of the mass. The future work section will discuss how these components could also be reduced.

Weight Comparisons											
HNP 1.0						HNP 2.0					
Transmission	Weight	4	lbs.	1.82	kg.	Transmission	Weight	0.75	lbs.	0.34	kg.
	CG Distance (from hip)	0	in.	0.00	m.		CG Distance (from hip)	0	in.	0.00	m.
Hip Upright	Weight	4	lbs.	1.82	kg.	Hip Upright	Weight	2	lbs.	0.91	kg.
	CG Distance (from hip)	7	in.	0.18	m.		CG Distance (from hip)	7	in.	0.18	m.
Hip Cylinder	Weight	1	lbs.	0.45	kg.	Hip Cylinder	Weight	1	lbs.	0.45	kg.
	CG Distance (from hip)	8	in.	0.20	m.		CG Distance (from hip)	8	in.	0.20	m.
Knee Upright	Weight	3	lbs.	1.36	kg.	Knee Upright	Weight	0.75	lbs.	0.34	kg.
	CG Distance (from knee)	6	in.	0.15	m.		CG Distance (from knee)	5	in.	0.13	m.
Knee Cylinder	Weight	0.75	lbs.	0.34	kg.	Knee Cylinder	Weight	0.75	lbs.	0.34	kg.
	CG Distance (from knee)	6	in.	0.15	m.		CG Distance (from knee)	1.5	in.	0.04	m.
	Total Weight	12.75	lbs.	5.80	kg.		Total Weight	5.25	lbs.	2.39	kg.

Table 2 – Previous and new component weights.

These weight reductions translate into torque, energy, and power requirement reductions over the old exoskeleton. These reductions can be computed by considering the potential energy change of the individual components.

Given the future aims and goals of the project, consider the act of stair climbing. Stair climbing requires the individual to completely raise his/her body mass up a six or eight inch step. The gravitational potential energy is linearly proportional to mass:

$$PE = mgh$$

Given the 7% weight (and thus mass) reduction, the overall energy requirements of climbing stairs has been reduced by the same 7%. While this may not seem like much over a single step, the result has much more of an impact over a complete flight of stairs.

That first pass analysis shows a useful, if simplistic result. Deeper analysis reveals a more complete picture.

Initiating a stair ascent requires a high step, which results in a large hip flexion angle while the tibial portion of the leg remains vertical. Analyzing this focused action displays more clearly the effect of decreased upright weight than simply looking at the system as a whole.

This is represented by a simple open kinematic chain with two portions – a femoral and a tibial. Each piece has its own mass and center of gravity location – those properties are defined in the table above.

The motion of the femoral portion of both the user's leg and upright is defined directly by the hip flexion angle. The height gain of the center of mass for that segment is defined by:

$$\Delta h_u = l_{cg1}(1 - \cos(\Theta))$$

Similarly, the difference in height of the lower (tibial) segment is expressed as:

$$\Delta h_l = l_u(1 - \cos(\Theta))$$

The total energy requirement is therefore the sum of these two individual components:

$$PE = (m_u \Delta h_u + m_l \Delta h_l)g$$

These results can be seen graphically in Figure 13:

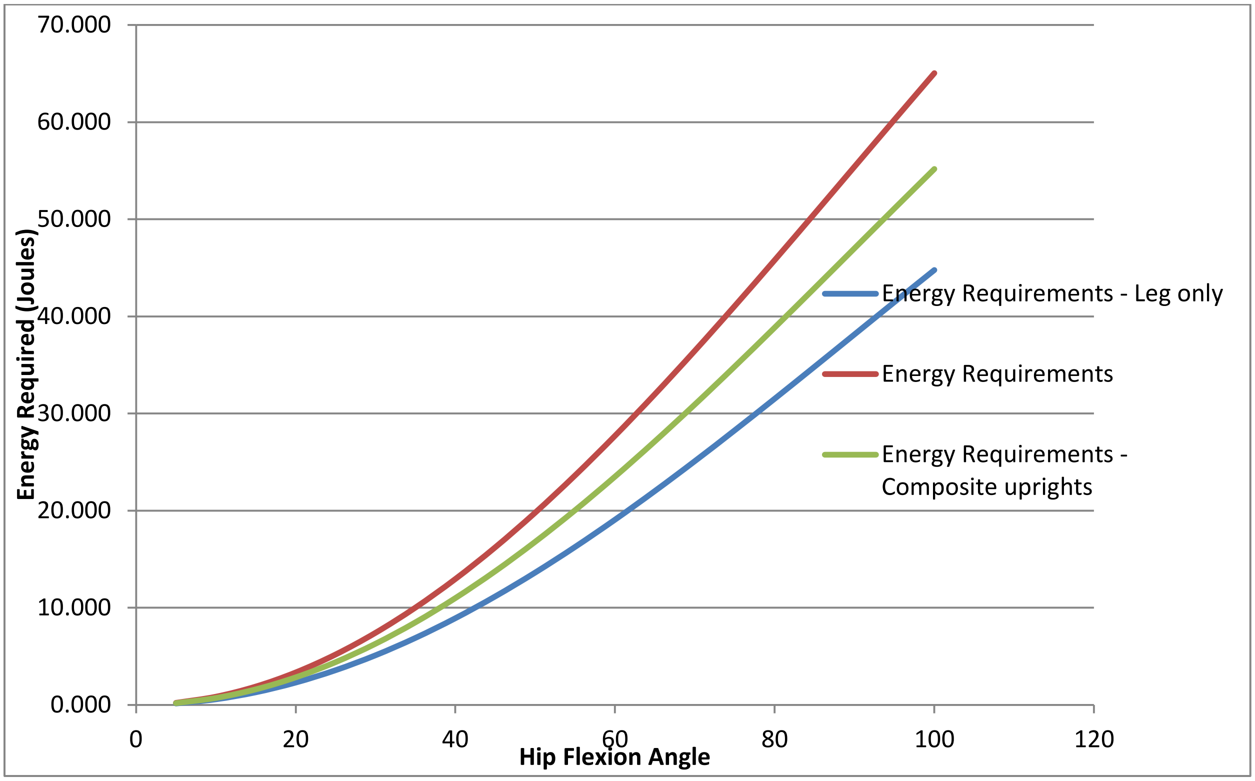

Figure 13 – Graph showing the energy requirements of a high step when equipped with the no, the original, and improved orthotic components.

This graph shows very similar shapes among all three cases considered – a human leg by itself, the original HNP device, and the HNP utilizing the composite uprights. In fact, the use of the composite uprights results in a constant 15.2% reduction in energy requirements, independent of flexion angle. If the torque produced by electrical stimulation of the hip flexors is considered a constant with respect to time (not valid over long periods of time due to fatigue, but valid for the short bursts found in FES assisted gait), then this result also implies a 15.2% reduction in stimulation time, and possibly a 15.2% increase in overall range.

The weight and performance increases that these numbers indicate would not be of any use if the structure could not safely withstand the loads placed on it. To verify that facet of the femur orthosis design, a test piece constructed to the same specifications as the femoral upright was constructed and destructively tested in 3 point bending by the civil engineering department. The load was placed in the middle of a 1 ft. test piece, with a strain gauge attached to the underside to measure the resultant deflection.

The results of the test showed a couple of interesting points. First and foremost, the beam could easily withstand the required loads – the specimen was loaded to over 200 lb-ft. of force (over twice the design requirement) without failing. In fact, catastrophic failure was never reached, despite a peak stress of over 60 MPa.

Secondly, the failure point of the material in compression was much lower than expected. It was known entering the test that the ultimate strength in compression was less than the ultimate strength in tension, but it turned out to be much lower than expected. Looking at the graph, the top of the beam (in compression) yielded at 44 MPa of stress, while the bottom held until the end of the test.

While both the top and the bottom were stressed, the modulus of elasticity was very high – over 100 GPa. Eventually, this number dropped to approximately 50 GPa after the compressively loaded top gave way.

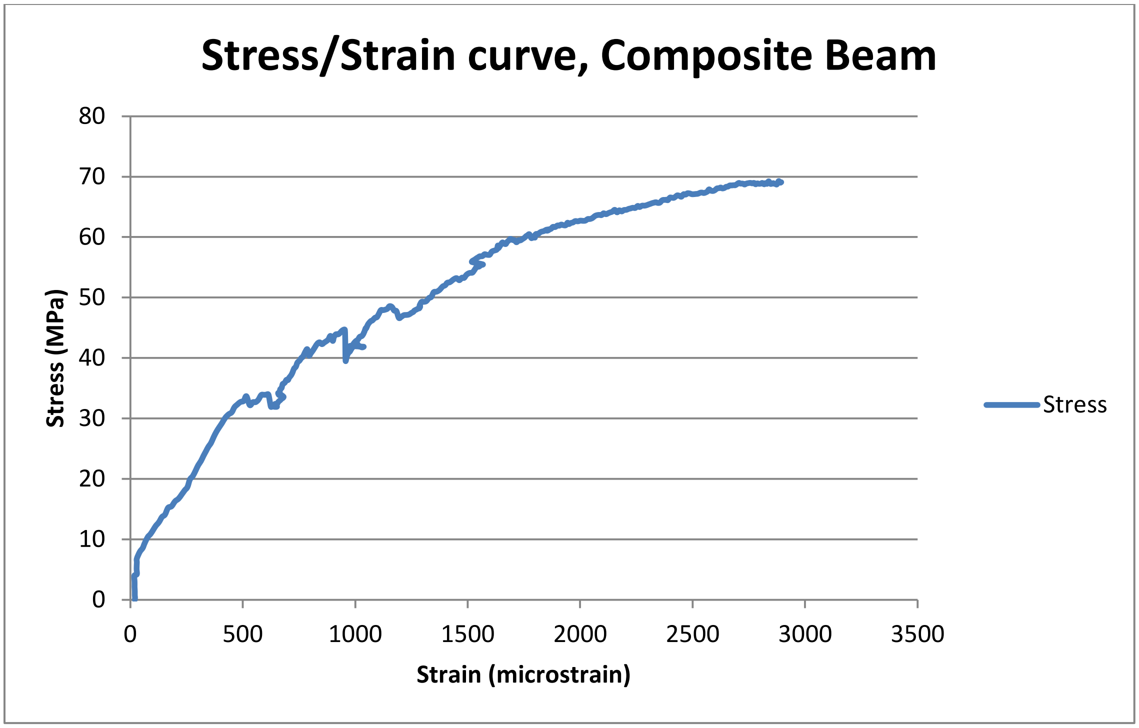

Figure 14 – Stress/Strain curve for the composite beam.

For comparison's sake, this beam is still favorably comparable to the 6061-T6 alloy aluminum that the original HNP is constructed from. It's modulus of elasticity is 68.9 GPa, and tensile yield strength is 276 Mpa. Clearly both materials can withstand the loads demanded of them, while the carbon composite holds an edge in terms of stiffness at the expected loads and weight.

Future Work

This 2nd generation HNP prototype has addressed some of the concerns and drawbacks of the 1st generation prototype by introducing advanced materials and manufacturing methods in the form of composites and CNC machining. This has enabled a fairly drastic weight loss of moving components while maintaining previous levels of functionality. However, there are still many avenues that can be explored to further enhance the existing attributes and add capability to the HNP. Specifically, weight reduction is still a very high priority, while adding functionality in the current research/interest areas of adding power assist and stair ascent/descent capability.

The hydraulic system of the 2nd generation HNP features the same components (valves, cylinders, and accumulators) as the first. This was partially because the hydraulic system fell outside the scope of this specific project, but also due to limited availability of ideally sized components. The operating pressures of the hydraulic circuits are not very high – 1000 psi – by the standards of most hydraulic systems. This severely limits the pool of useable hydraulic components, and the end product is something that is large, bulky, and very high weight. The next step in development of the HNP is to replace the existing hydraulic system with one that contains optimized components. Doing this would require cylinders with higher operating pressures, and replacing the valves with ones that draw less power.

The current cylinders can be considered the best cylinders currently available for the application, even though their pressure rating of 1000 psi is fairly pedestrian for a typical hydraulic system. The performance of small cylinders is limited by the internal seals – as the pressure increases, so does the force required to seal the cylinder, while efficiency and static friction force both suffer.

One proposed solution to this problem is the use of seal free cylinders. Simulation results show high volumetric efficiency and low leakage for cylinders which contain a gap between piston and cylinder wall of under 20 microns. This may the necessary solution for small, high pressure cylinders [15, 16]. There will surely be an increase in cost due to the high manufacturing tolerances, but the gains in performance would be substantial - doubling the operating pressure of the system while maintaining the same bore means halving the pitch diameter of the gear used in the hip joint, for instance.

Operating at a higher pressure means nothing but good things for the rest of the hydraulic system as well – more pressure means smaller joint geometry pieces, which translates into less stroke, which means smaller valves and accumulators – the effect cascades throughout the entire system. However, to fully take advantage of the new pressure, the rest of the hydraulic circuitry should be appropriately customized as well. Future research plans call for adding an active power source within the system – this can be accomplished by currently available and appropriately sized hydraulic pumps. Miniaturized, high pressure accumulators can be adapted from the cylinder design. The other major stepping stone for hydraulic optimization lies in the valves.

Solenoid valves are coveted for their simple, foolproof operation, and fast response time. But they also have the disadvantages of higher weight and higher power consumption. Both are a byproduct of the relatively large coil of wire required to produce the necessary magnetic field – the copper and iron core are heavy, and the low resistance of the wire mean a significant amount of power is wasted as heat compared to the power expended in opening and closing the valve. Quite frankly, the power expenditure of the HNP is quite high for a device that does not actually inject any energy into the system it controls. Ultimately, this will limit the range of the device.

A proposed solution consists of replacing the solenoid valves with a mechanically driven valve, controlled by a small motor or servo. If implemented with something not backdrivable such as a worm gear or ball screw, this hypothetical valve would only consume power when transitioning between states, and not draw any current to simply hold its position. This would greatly reduce the power requirements of the passive HNP, and serve to extend its range. In general, this is a large hurdle to overcome before fluid power can be accepted as a reasonable motion control solution for any small orthotic, prosthetic, or other robotic device.

In addition to the pure mass reductions brought on by the new system, an effective by product of that has been the reduction of rotating inertia – a very important factor that directly lowers the joint torque requirements and necessary stimulation time. In that frame of mind, new plumbing and hydraulic lines can help. By moving some of the components from the knee hydraulic circuit onto the corset (namely the valve and small accumulator and not the cylinder, for obvious reasons), they still contribute to the overall bulk and mass of the cylinder, however they no longer contribute to the mass or rotational inertia of the uprights. While this does not change the overall energy requirement for a single gait cycle (be it level ground ambulation or stair climbing), it does further minimize the torque requirement of the joints, allowing for the stimulation to be active for a shorter amount of time and again having the effect of increasing endurance and delaying the onset of fatigue.

In fact, the hydraulic system itself could make use of a hydraulic manifold to give the device a much cleaner appearance while eliminating a large number of bulky brass fittings. The weight of those fittings is not insignificant in its own right, and their use should be minimized in an ideal design.

The mounting for the hydraulic cylinders used in the VCHM have much room for improvement. The cylinder is capped with a spherical rod end bearing, that both allows for the necessary hip abduction movement for donning and doffing of the brace, and also allows for angular misalignment between the rack gear and the hip cylinder. Initially, the rod end was selected for that reason exactly – allowing for the angular misalignment due to manufacturing tolerances. However, it was not until after construction that it was realized that this arrangement allows for excessive deflection under load. In truth, the gear rack/cylinder combination is not fully constrained under load, specifically due to the angular degree of freedom offered by that rod end. This effect is multiplied due to the fact that the connection between cylinder and the gear rack carries a significant amount of force transmitted from the hip joint.

That rod end, initially considered to be a necessary item to accommodate for manufacturing tolerances, can be replaced by a solid connection between the cylinder and gear rack – the rod of the cylinder is threaded on the end, and could be directed by inserted into a tapped hole on the gear rack, effectively making a solid connection between the two. This eliminates that degree of freedom causing much of the compliance in the current design, and overall offers a much stronger joint.

However, if a solution such as the above proposed was to be implemented with the current mounting post system, it would eliminate the ability to abduct the upright, a necessary design feature. Thus, this would necessitate a change in the mounting system used. The reality is also that the mounting post is appropriately sized for its purpose, but as operating pressure increases, so will the force transferred to the mounting post, so a more robust mount must be devised anyway. Additionally, since the proposed cylinder/gear rack connection eliminates that pin joint, the hip abduction ability would need to be redesigned in such a way that the cylinder does not abduct with the rest of the upright.

The proposed design is more complex than the existing system, but because it allows for the stronger, stiffer connection between the gear rack and the cylinder. Additionally the new mounting is stronger, a necessary condition for taking advantage of future, higher operating pressure hydraulic cylinders. This is at the cost of more complexity, but the potential benefits outweigh the costs.

The second generation of the HNP was designed to explore what the application of advanced design, materials, and manufacturing methods could bring to the table. When deciding initial design parameters, it was determined that the second generation prototype would not alter the geometry of either the VCHM or the DKSM at all. A lot of consideration and optimization went into the selection and optimization of the geometry utilized in the initial prototype, and without the selection of new, higher operating pressure components, alteration of the geometry would not make the second generation HNP any better at its intended purpose than the first. However, the aims and directions of the HNP project as a whole have become more clearly defined, and as such, new geometry may better suit future projects.

Specifically, the HNP project has expanded to theoretically encompass stair climbing and the addition of a power assist unit. The stair climbing capability means that a larger range of motion will be utilized, while the power assist requires something a little bit different out of the joint geometry, particularly the knee joint.

Recall that the nature of the four bar linkage used in the knee joint means that there is a singularity of zero moment arm at 72 degrees. While this is not an issue during level ground walking, as the knee typically does not flex quite this far, it may be an issue during stair ascent or descent. Even if 72 degrees (and thus zero holding capacity) is not reached, the moment arm does decrease and approaches zero at a much lower flexion angle. Additionally, that nonlinearity may pose issues and increase complexity of any proposed controller for the Power Assist System.

The hip joint does not have this issue, as the rack and pinion gear set ensures that the moment arm at the joint is consistent throughout the entire range of motion. This both eliminates the singularity in the four bar linkage, but also potentially simplifies any future control related computations. It would be ideal if this solution could be implemented at the knee joint as well.

The issue with the rack and pinion comes largely down to weight. The gears found in the first prototype HNP are large and heavy pieces of steel. When placed at the hip joint they contribute to the overall weight of the brace, but do not add anything to the rotating inertia of the leg upright. However, when placed at the knee, those same hefty gears will contribute significantly to the inertia of the system and have a negative effect on overall system performance.

However, recall one of the improvements made to the HNP was to the hip transmission – reducing the weight of the gears, eliminating unnecessary teeth to reduce the overall weight. If those same principles could be applied to a hypothetical rack and pinion gear set in the knee joint, the weight and inertia gains could be minimized. Furthermore, with this transmission arrangement, the inertia gain could quite possibly be offset by moving the knee cylinder higher up the upright, towards the corset. This arrangement would reduce the rotating inertia of the upright, and thus the dynamic torque necessary to move the upright is reduced.

This improvement offers more capability over the current linkage arrangement, for a minimum of added weight. However, this improvement really cannot be properly implemented without some of the improvements discussed in producing the second generation prototype, and even some improvements not implemented in this iteration. Higher rated cylinders and high quality, EDM cut rack and pinion gears can implement this improvement quite well.

As stated previously, a higher operating pressure means that the gear geometry used in the HNP must be changed as well. Specifically, a higher operating pressure translates into higher force capacity in the cylinder. To properly take advantage of that, the gears used in the

HNP should decrease in pitch diameter. In order to accomplish that, it would be necessary to manufacture custom gear sets out of material with a higher yield strength than the low carbon steel currently used.

Making custom gears is not a cheap proposition, but it is fairly straightforward. Doing so would require the gears to be cut on a wire EDM machine – this is the necessary process for cutting out the correct tooth profiles.

Composites were utilized in order to reduce the weight of the uprights of the HNP. However, the loading conditions found in the uprights are not ideal for composite use. Recall that carbon fiber composites are composed of the carbon fiber and an epoxy resin bonding agent. When loaded in tension, the carbon fiber strands are the component that provides strength to the material. When in compression, or even bending (when half of the member is in compression), the carbon fibers do not contribute much to the overall strength – it is instead the resin that resists the stress. This is a problem, as the resin used does not have as high a yield strength as the carbon fibers. As such, it is not uncommon to find that a carbon fiber composite material will have an ultimate strength in compression of approximately 60% of what it is in tension. And in this particular application, the loads present on the uprights are primarily bending and compression loads. To overcome this non-optimal application, more layers of carbon fiber are used. Even so, the weight reductions are impressive, but clearly from a cost perspective, it would be ideal to use as little of the carbon fiber as possible.

One possible method of getting around this is by preloading the carbon fiber, as is done with prestressed concrete. Done correctly, the beams would gain a much higher compressive ultimate strength.

Accomplishing this in practice seems difficult. Initially, it was considered that this could be done during the manufacturing process. Instead a new theory was formed: it might be possible to use the uprights as high pressure hydraulic accumulators, or at the very least pressurize them with compressed air. This would preload the carbon fibers in tension, giving them more strength and reduce the amount of material needed. Clearly there would be safety protocols to establish and fully understand, but the long term cost reduction implications might outweigh the costs in this matter.

One final piece of added functionality can be achieved through adding passive torsional springs to the hip joints. Recall that the entire purpose of the exercise is to decrease the energy consumption of the user by decreasing the weight (and therefore potential energy increase and inertia) of the device. However, this is not the only way of achieving that goal. In addition to weight decrease, preloaded torsional springs can bias the hip joint of the device by providing a passive hip extension torque. Correctly sized springs would still allow the weight of the device upright and the user's limb to provide a restoring flexion torque, but could still contribute a portion of the necessary extension torque. This would also have the effect of decreasing overall energy requirements from the user, increasing range and decreasing fatigue.

These proposed changes represent a cross section of ideas to improve the current HNP. They are aimed at expanding the capability of the device, while ensuring safety and decreasing the extra energy and power burden the exoskeleton places on the user.

Conclusions

This thesis has documented the design and fabrication of an improved and updated version of the Hybrid Nueroprosthetic. The initial prototype HNP successfully demonstrated the concept of combining a Functional Electrical Stimulation system with a semi – active hydraulic exoskeleton. This combined approach has promise as a rehabilitation device, exercise device, and hopefully as a means of personal transportation someday. That being said, the proof of concept prototype does have its limitations, chief among them the high weight and bulk of the device.

In order to explore some methods of overcoming those barriers and producing a marketable device, this second prototype was commissioned with the aim of exploring various methods of achieving the goal of less weight with a minimal increase in cost, by utilizing in house design and manufacturing methods. Despite these restrictions, significant weight savings could be made through the use of FEA analysis, CNC machined pieces, and composite material integration. Future directions include incorporation of more custom componentry in order to further reduce weight and add capability.

These improvements are effective in their intended purpose – reducing the energy requirements of the user, but they do come at a cost. Incorporation of these custom components, both current and future, is expensive, driving up the cost of a hypothetical market product. However, the HNP as a commercialized product does have a couple of factors working in its favor.

Firstly, it is not uncommon for medical devices to cost a lot of money. High end mobility aids, such as orthotics, prosthetics, and wheelchairs can cost upwards of $50,000. Current exoskeletons destined for market are projected to carry price tags of over $100,000.

Furthermore, the reach of the development work put into the HNP extends beyond its current intended purpose as a mobility device for individuals with spinal cord injuries. Recall that the HNP is fundamentally different from other developed exoskeletons in one very important aspect – it is a motion augmentation device, rather than a motion replacement device. This is achieved due to the backdrivable nature of the hydraulics. The impact of the reach on an application level is important: as an augmentation device, the technology could be applied to a variety of medical conditions beyond spinal cord injury. The HNP, or even specific parts of the HNP can be applied to treat and rehabilitate conditions that leave the patient either partially paralyzed or with weakened muscles. Stroke survivors, for example, would benefit greatly from a single DSKM. By opening up a larger number of markets and potential units sold, the increased expenditure found in using composite materials or developing some of the advanced hydraulic units mentioned in this paper is more easily justified.

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