HydroBone and Variable Stiffness Exoskeleton with Knee Actuation

by

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Abstract

The HydroBone is a variable stiffness load-bearing element, which utilizes jamming of granular media to achieve stiffness modulation, controlled by the application of positive pressure. Several compressive tests were conducted on the HydroBone in order to quantify the load-bearing capability of the system. It was determined that the stiffness of the HydroBone was a function of the internal pressure of the system. A controller was modeled based on this function to achieve automatic stiffness modulation of the HydroBone. An exoskeleton was designed based on the HydroBone and various actuators for the exoskeleton were considered. The HydroMuscle, a soft linear actuator was selected to provide knee actuation for the exoskeleton, based on several efficiency and force output test conducted. A knee brace was designed, capable of producing 15Nm of torque on the knee, actuated using Bowden cables coupled to the HydroMuscles.

Acknowledgements

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Chapter 1

Introduction

The potential applications of variable stiffness load bearing elements include but are not limited to active suspensions in automobiles, wearable devices with conformability when no required while stiff when in active state, and civil engineering structures. The HydroBone [1, 2], one of the few devices capable of being actively tuned to modulate stiffness is introduced in this chapter. To vary the stiffness, the HydroBone makes use of jamming of granular media [3, 4] which is also discussed.

1.1 Jamming of Granular media

Jamming is a phenomenon observed in some materials like granules and liquids to transition their physical state from semi-solid to solid or liquid to solid. Conventional jamming in particulate matter was achieved by enclosing the particles in a flexible container and vacuuming the container such that the particles stick together forming a solid structure [5, 6]. The advantage of this kind of jamming is that the particles can hold the shape it is set to before vacuum is applied.

Jamming in granular materials can be achieved using positive pressure as in the case of HydroBone [7, 8]. When granular media is enclosed in a non-stretchable yet flexible container and pushed outward from the inside using some medium of actuation, a column of jammed granular media is formed. The advantage of using positive pressure for jamming is that the stiffness or density of packing of the granular media can be actively tuned by applying more or less force on the inside.

1.2 HydroBone

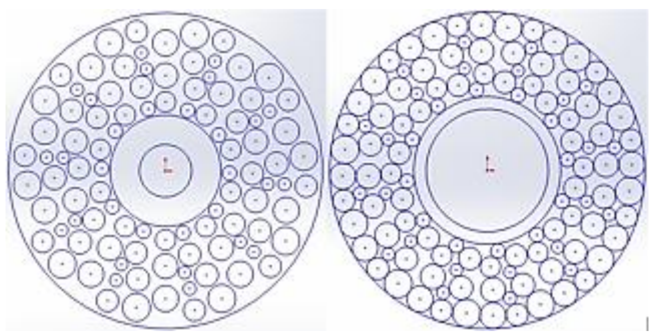

Figure 1: Un-actuated and Actuated HydroBone Crossection

The HydroBone is a variable stiffness load bearing element controlled by a positive fluid pressure. Unlike many devices that utilize granular jamming by the application of vacuum, the HydroBone utilizes positive fluid pressure in order to trigger the phenomenon. The HydroBone system consists of a latex tube core surrounded by column of granular media enclosed by a non-stretchable sheath. When pressurized, the latex core expands in all directions forcing the granular media towards the sheath causing the particles to jam, creating a solid column capable of bearing load.

1.3 Motivation

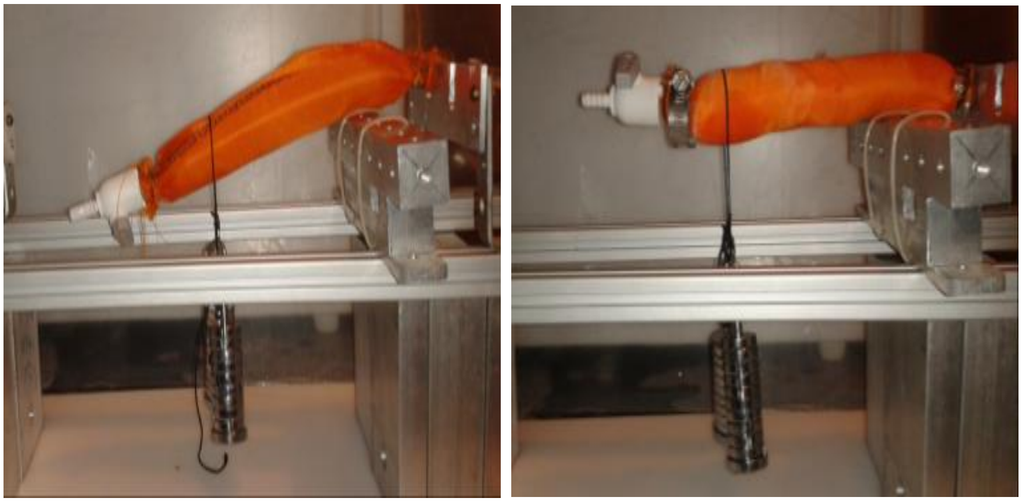

Figure 2: HydroMuscle without and with granular media

Jamming of granular media was initially utilized in order to eliminate the problem of bowing/buckling in a HydroMuscle [9], a linear fluidic actuator. Granular media (powdered coffee) was filled in the space in-between the latex core and the sheath. When pressurized, the HydroMuscle bent when under compression but did not buckle and hence the idea for the use of a similar setup for variable stiffness was considered.

1.4 Bio-Mechanics of the human leg

The human leg consists of four major bones that are as femur, tibia, fibula and patella. Each of the bones in the human leg is subjected to three types of forces – tension, compression and torsion.

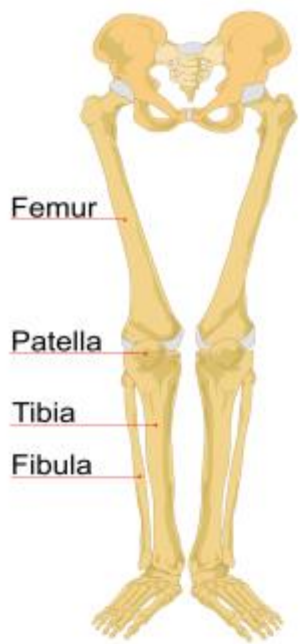

Figure 3: Bone structure of a Human leg

When carrying load, the bones go through a compressive force, which gets amplified during dynamic movements like running. Heavy loads and improper form while performing such activities can damage the joints and cause injuries like the patellar tendonitis. In stroke patients, loss of muscle function is common and causes significant weakness in the lower leg. In severe cases there may be complete paralysis of the legs.

Therefore, in case of post-stroke and injury rehabilitation, it is required that the load on such type of weak bones and muscles is kept to a minimum and assistance for motion is provided keeping into account reduced discomfort. Also, it is important the proper muscle movements are imitated in order to refresh muscle memory.

1.5 Exoskeletons

Exoskeletons as the name suggests, are external skeletons that provide some kind of support in terms of actuation or load bearing capabilities in order to augment or assist forces and movements of the actual human leg. Over the last decade, exoskeletons have become increasingly common and are heading toward day to day applications. Exoskeletons are being used in various applications such as industries to improve performance of workers [10] and reduce risk of accidents, rehabilitation for post-stroke victims [11], and military applications [12].

Figure 4: HULC Exoskeleton

Traditional exoskeletons are rigid and have a metallic structure to support and carry heavier loads. The most common problems with rigid exoskeletons like the HULC are the human interfacing and the inherent non-compliance due to the metallic structure. Since, exoskeletons and wearable devices are becoming more common, the issue of non-conformability and unwanted rigidity needs to be addressed

1.6 Overview

This thesis discusses the design and testing of a new type of variable stiffness, load-bearing structural member known as the HydroBone and its implementation to design a variable stiffness exoskeleton. The use of HydroMuscle, a soft linear artificial muscle is also discussed. Two design iterations of the HydroBone are described in Chapter 2. Chapter 3 discusses the compressive testing of the HydroBone under an Instron machine, in order to determine the load bearing capacity of the system. The design of a controller based on the load bearing capabilities of the HydroBone and its testing are discussed in Chapter 4. The design and actuation of the exoskeleton are discusses in Chapter 5 and 6 respectively. Chapter 7 concludes the thesis and provides recommendations to improve upon.

Chapter 2

Design of HydroBone

2.1 Initial design

The HydroBone design was inspired by the HydroMuscle, a biologically inspired linear actuator. To design the HydroBone, a latex core with 1.9cm OD and 0.85cm ID, was enclosed by a loose and flexible yet non-stretchable sheath [13]. The volume enclosed by the sheath and the outer surface of the latex tube was filled with granular media. Granular materials such as powdered coffee, hydrophobic sand, and granulated EPDM rubber [14] were used for testing.

Figure 5: 1st Generation HydroBone utilizing granulated EPDM rubber

The ends of the latex core were plugged by NPT barbed hose fittings [15] and the sheath and latex tube were fastened onto the barb using hose clamps. Therefore, when the latex core was pressurized, it would expand in all directions causing the granular materials to push against the sheath causing them to jam and hence creating a solid columnar structure capable of carrying weight.

The testing of this version of HydroBone revealed that the setup would fail at the edge of the sheath and the hose clamps causing the HydroBone to bend and subsequently take lesser weight. Therefore, it was proposed that end caps should be incorporated into the HydroBone to provide more support during the compression of the HydroBone. Also, it was observed that by decreasing the size of the latex core, and increasing the volume of granular media around it, the compressive strength of the HydroBone could be increased.

2.2 Redesigned HydroBone

The HydroBone was redesigned in order to overcome the issues that arose during the testing of the initial design. End caps were designed in SolidWorks as shown in order to distribute the load better and not cause bending in the hose clamp sheath junction. Also a smaller latex core was used in order to increase the volume of granular media in the HydroBone improving the load bearing ability. The end caps were 3D printed using a Makerbot Replicator [16].

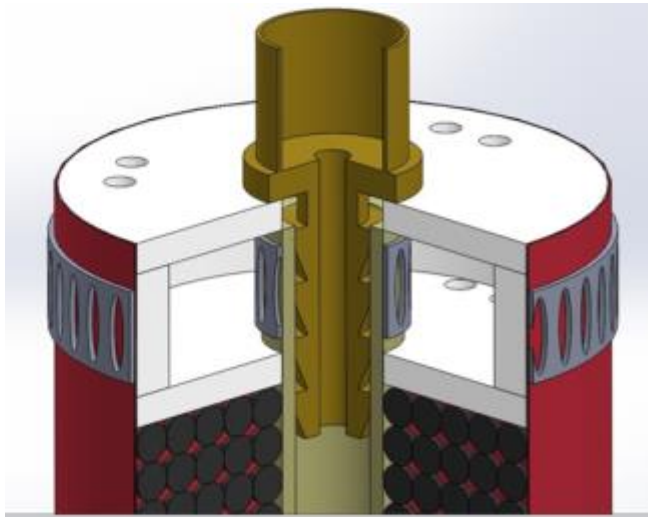

Figure 6: End Cap Design for the HydroBone

To construct a HydroBone, the first plate is slid onto the barbed end of the hose connector, followed by the rubber tubing. The hose clamp is then placed over the tubing overlapping the connector barbs and tightened, with the second end cap plate placed on the other side of the hose clamp. Next, fishing line is woven through the holes of the two plates, tightened, and tied to prevent them from separating, with the two support plates positioned between the pieces. Finally, the nylon sleeve is placed over the two curved supports and attached using another tightened hose clamp. This process is repeated on the other end, ensuring that the sheath is filled with the support element before tightening the second outer hose clamp.

Chapter 3

Compressive Testing

3.1 Instron Testing

It was decided that the HydroBone had to be tested under compression, in order to estimate the maximum force that could be applied onto it. For testing of the HydroBone, two aluminum blocks were machined with 1.27cm NPT threads in order to screw in the HydroBone to the blocks and provide better support during compressive testing. One of the two blocks was given a provision to for fluid inlet to the HydroBone, connected through a pressure gauge and a ball valve, placed in series to control the flow of water. A supply of 110psi was connected to the HydroBone and the system was gradually pressurized to better quantify the internal pressure of the HydroBone.

Figure 7: Instron 5567A

The HydroBone was then pressurized to a particular pressure and placed under an Instron 5567A [17] running Blue Hill 2. Multiple tests were conducted on the HydroBone at a single pressure as well as varying pressures in order to model the system. Multiple data sets were collected and analyzed to design a control system for the HydroBone to enable it to modulate stiffness on the fly.

The Instron machine base grip and adapters were removed and replaced by flat compression platen to facilitate compressive testing. The internal load cell was calibrated in order to determine the exact force acting on the HydroBone. The pressurized HydroBone was then placed in between the compression platen and centered accurately. The crosshead of the Instron machine was then adjusted to just touch the top of the HydroBone setup, not exceeding a tare load of 9N. The load and displacement readings were then zeroed to prep for the test.

The machine crosshead speed was set to 0.508cm/min in the downward direction. The HydroBone was compressed and data was collected until the system was visually verified to be buckled which was again crosschecked with the sudden increase in the force after the HydroBone had failed. The test was repeated immediately to determine the load bearing performance of the HydroBone once it had failed.

For each of the test performed on the HydroBone, force-displacement curves were generated and the experimental buckling forces were calculated. Using these curves, the stress-strain data of the HydroBone were calculated, inputting the dimensions of the HydroBone which were 30cm long and 3.8cm thick.

3.2 Test Results

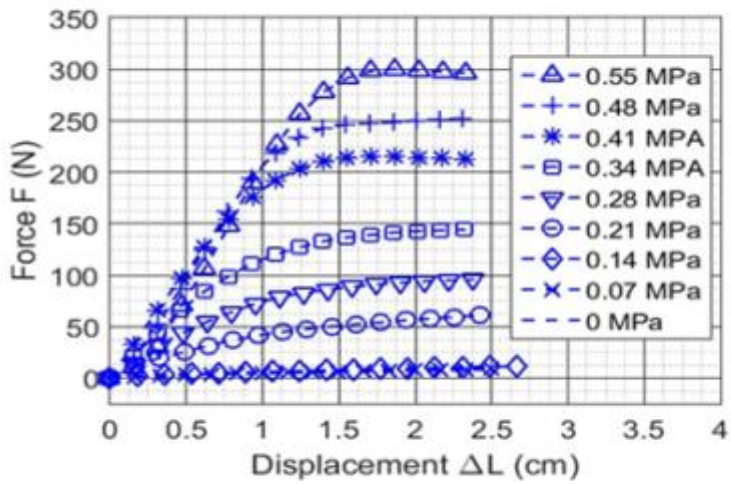

Figure 8: Force-Displacement curves at 0 MPa to 0.55MPa using EPDM granules

Extensive tests on the HydroBone revealed that with the increase in the pressure, the strength increases. Also, the observed maximum displacement of the system was 0.025m. . The experimental Young's Modulus increased from 0.70 MPa at 0.21 MPa fluid pressures, to 3.53 MPa at 0.55 MPa fluid pressures. The Young's modulus of the HydroBone was not calculated under the pressure of 0.21MPa as the system would just bend under its own weight.

0.35 MPa	Maximum Force	Buckling Force
Test 1	152N	130N
Test 2	146N	120N
Test 3	145N	120N

Table 1: Successive tests on the HydroBone at a single pressure (0.35 MPa)

The tests also revealed that the buckling force of the HydroBone also decreased once the system had failed but, remained the same for the third consecutive test performed.

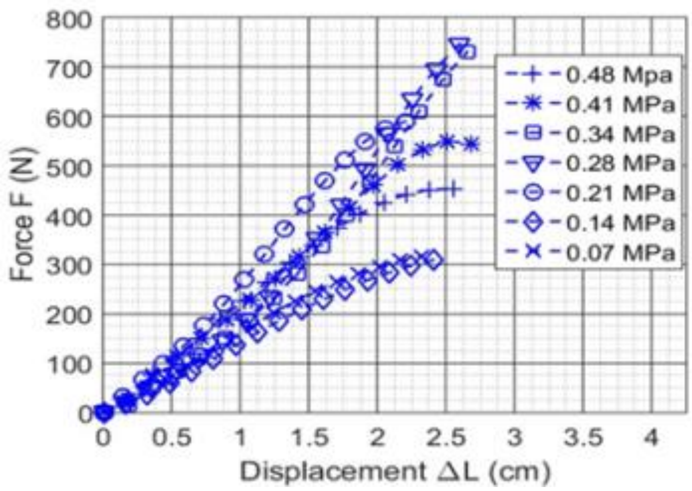

Figure 9: Force-Displacement curves at 0.07 MPa to 0.48MPa using sand

Other granular media such as sand were also experimented with but the test results showed a lack of controllability in the HydroBone. To improve the load bearing capacity of the HydroBone, a mixture of granulated EPDM and sand was also tested. The test revealed that the sand had settled at the bottom of the HydroBone due to the large size difference in the granules.

Chapter 4

Controller Design

4.1 Modeling

The system consists of an inlet pump in series with the HydroBone and a branched exit controlled by a solenoid valve. A controller was designed and implemented to control the solenoid valve, based on the critical bending forces collected on the HydroBone. An Arduino Uno microcontroller [18] was used in order to actuate the solenoid valve. The critical bending forces for the HydroBone at different pressures were plotted and a 2nd order polynomial curve fit was applied to compute the equation of critical bending force as a function of pressure.

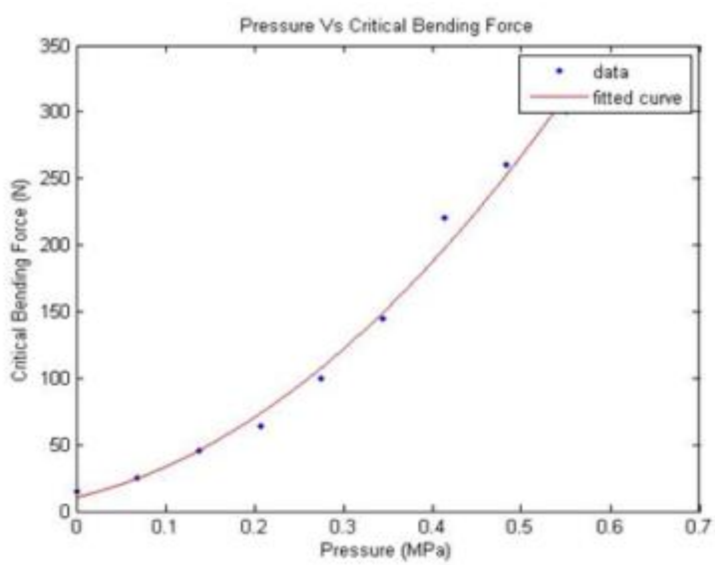

Figure 10: Pressure (MPa) Vs. Critical Load (N)

In the real time implementation of the controller, the pressure and load data were collected and the critical bending force for the corresponding pressure was calculated using the following equation

$$F_C = 715.5P^2 + 155.7P + 10.44 \quad (1)$$

An allowed load threshold was provided such that the actual force exerted on the bone was 9.071kg (20lb) lower than the critical bending at all times. This ensured that the HydroBone was under the linear loading regime to prevent the system from buckling and subsequently cause a reduction in the critical bending force. The error between the load acting on the HydroBone and the allowed load was calculated and minimized for control. If the external load acting on the system changes, the new allowed load is recalculated and the exit valve is opened or closed respectively.

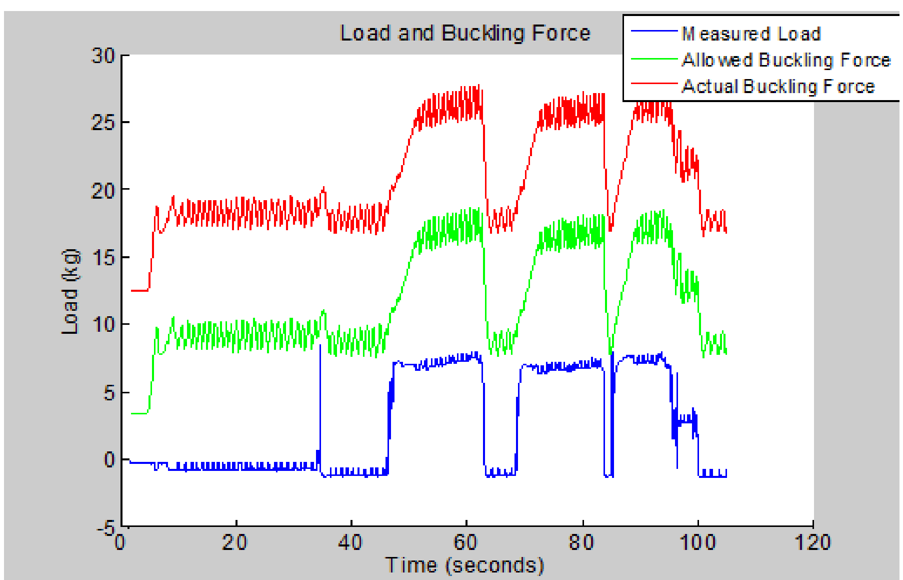

Figure 11: The measured load, allowed bucking and the critical buckling force over time.

4.2 Controller Testing and Results

To test the controller performance, a load of 9.071 kg (20 lb) was randomly applied to and removed from the load cell [19] and the system response time was determined. From Figure 11, it can be inferred that the average response time to pressurize the bone was 3.37 seconds while the average time during depressurization was 1.19 seconds.

The entirety of the tests performed on the HydroBone revealed that the measured load was lower than the allowed buckling force of the system. With the system set up having a virtual load threshold of 9.071kg added to it, the critical buckling force of the system was never reached.

Volumetric Flow Rate (cm^3/sec)	Error			
	Mean	Std. Deviation	Min	Max
12.2	0.455	0.736	-0.562	1.687
15	0.297	0.589	-0.621	1.288
24.6	0.838	0.784	-0.522	2.109
44.4	0.937	0.796	-0.535	2.413
92.3	0.876	0.797	-1.461	2.254

Table 2: Mean, Standard Deviation, Minimum, and Maximum values for Error volumetric flow rates at no load.

The controllability of the system was measured under various flow rates. Due to the fixed opening of the solenoid valve, the exit flow rates varied significantly even though valve was opened instantaneously. Therefore, individual no-load tests for the error were performed at varying flow rates and the mean, standard deviation, minimum, and maximum errors are listed in Table 2.

Chapter 5

Design of Exoskeleton

5.1 Exoskeleton Design and Fabrication

A lower body exoskeleton was designed using HydroBones to achieve variable stiffness depending on the load applied on the system. The design of the exoskeleton was based on the approximate measurements of human limbs made adjustable using 80/20 [20] Aluminum extrusions. The HydroBones on the system were measured to be 30cm and designed taking into consideration, the comfort of the user.

Figure 12: Exoskeleton Joints with Femur and Tibia-Fibula

The HydroBones were constructed using a latex tube with 1.9cm ID and specially sewn sports nylon fabric with granular EPDM rubber as the medium. The ends of the

HydroBones were secured using hose clamps. The fittings for the HydroBones were specially designed in order to make the attachments easier and ergonomic. Cylindrical aluminum was drilled and tapped to provide inlet of water and screw into the L-channels used for securing the HydroBones.

Figure 13: Variable Stiffness HydroBone Exoskeleton

80/20 Aluminum extrusions were used in order to secure the fixtures for the HydroBones. For the specific purpose of smaller fixtures, the first generation HydroBones were used and placed in a pairs in parallel to the femur and tibia-fibula pair. A knee joint from a standard knee brace was used for the knee joint of the structure. The tibia-fibula pair of the exoskeleton was attached to an ankle brace to divert the forces from the load exerted on the exoskeleton, directly to the ground.

The fabrication of the attachment points for the hip were horizontal 80/20 pieces connected by a beam on the back to take load. The fabrication of a hip joint was avoided to reduce the complexity of the system but would be a future scope for the project. To secure the user into the exoskeleton, Velcro straps were used to hold structure to the human leg. The insides of the metallic pieces were lined with clothing and rubber sheets in order to prevent discomfort caused due to metal-skin contact.

5.2 HydroBone Actuation

Figure 14: Users with the exoskeleton

The initial actuation mechanism for the HydroBones consisted of a set of manual valves used for allowing the exoskeleton to pressurize and depressurize based on external actuation. This required an external element to control the exoskeleton when a user would wear the device.

The manual valves were then replaced by using solenoid valves to control the inlet and outlet of the exoskeleton. The solenoid valves were actuated using an Arduino Uno microcontroller supplying signals to switch the states of the solenoid. This significantly reduced the size of the system by decreasing the size of the tubing that was attached to the exoskeleton.

Chapter 6

Knee Actuation

Various studies suggest that the torque requirement at the knee for preforming squats is about 60Nm [21]. Therefore, to provide actuation to the knee joint, many options like motors and linear operators were explored. It was decided that the exoskeleton would assist the user in lifting weight or walking by providing a torque of 15 Nm using an actuator.

The initial choice for the actuation was use of motors to drive a Bowden cable attached to the lower leg through a pulley attached to the knee joint. Various motors capable of producing 15 Nm of torque were researched. The most common motors capable of providing the required torque were CNC stepper motors which were as heavy as 20lb each.

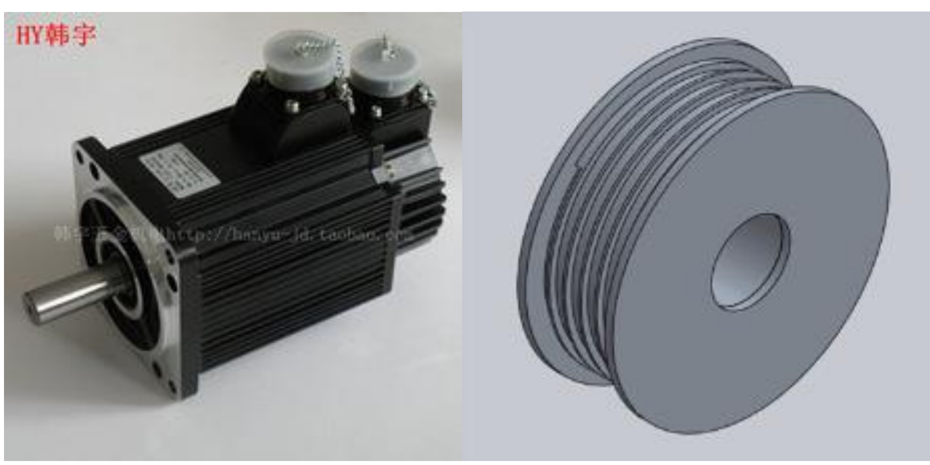

Figure 15: Spool and motor to pull on the Bowden cable

The motor would drive a spool as shown above coiling in the Bowden cable causing the knee to flex as if a person was recovering from a squatted position. A spool was designed on SolidWorks and was attempted to be fabricated using a 3D printer as shown in figure above.

This idea was dropped because of the high weight and cost of the CNC stepper motor and added weight to the system since the actuation system was to be mounted onto the backpack frame of the exoskeleton. Also, the motor provided far less power to weight ratio as compared to linear actuators. The use of an electric motor to provide actuation to a single joint would also mean that scaling the system to multiple joint actuation would increase the overall weight of the system, being counterproductive.

Therefore, it was decided to actuate the exoskeleton using HydroMuscles which are linear actuators actuated by pressurizing it with fluid. The viability of HydroMuscles was tested by conducting efficiency tests on the actuator.

6.1 HydroMuscle Efficiency and Force Output Testing

A test setup was developed to calculate the efficiency of actuation of the HydroMuscles to characterize the muscle better. HydroMuscles of appropriate sizes were fabricated and tested using the test setup. The setup included the a fixture for one end of the HydroMuscle which would be attached to an NPT barbed fitting while the other end supported by linear guides in order to prevent the muscle from sagging due to its own weight leading to non-linear force transmission.

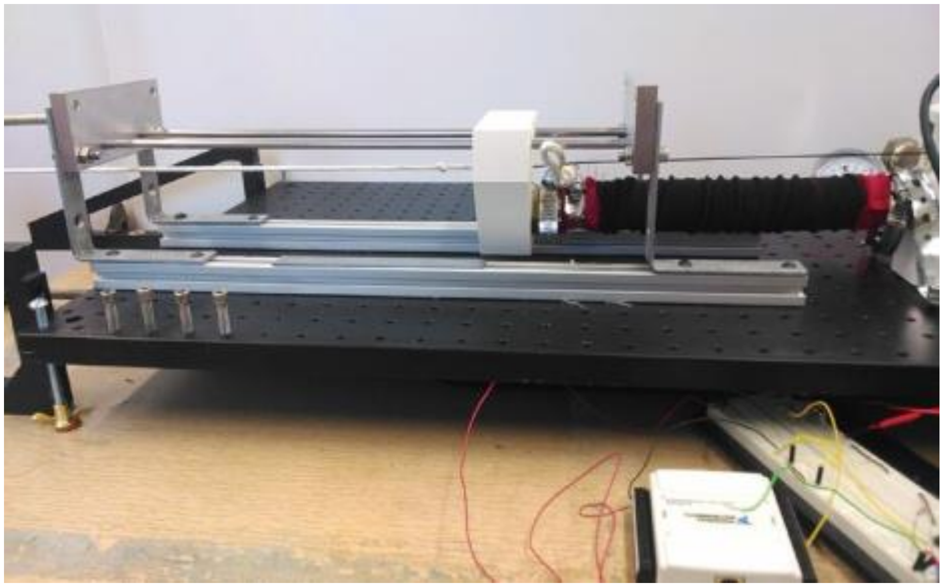

Figure 16: HydroMuscle Test Setup

A mass was hung on one end of the rope that was connected to the free end of the muscle passing over an almost frictionless pulley. It was ensured that the rope would not freely slide over the pulley, changing the actual displacement of the load. The test bed was set up to measure pressure, volume, and length of the HydroMuscle at any point in time. The length of the HydroMuscle was initially calculated using a wire spool attached to a rotary encoder. The muscle would pull on the wire which would rotate the spool and in turn the encoder giving us the length. This method was accurate yet caused the HydroMuscle to be pulled upward causing loss in force transmission. Therefore, measurements were conducted using a calibrated steel ruler keeping parallax to a minimum at all times. A digital pressure sensor was integrated into a system giving out accurate pressure at each point.

The volume of fluid or water that was supplied to the HydroMuscle was quantified using a syringe to input 10ml of water in steps to a total of 150ml. The hydraulic work input to the HydroMuscle was obtained by integrating the product of the measured pressure and the incremental volume change. The muscle was initially pressurized to the length by inputting 150ml of water from its initial length S_p i.e. without any weight applied. The load is then added to the HydroMuscle and then allowed to settle. The length is then measured to get S_{min}, which is the length of the muscle under the influence of gravity and pressure i.e. minimum height of the load. The muscle is then depressurized pulling the load against gravity and allowed to settle. This length is measures as S_{max} i.e. maximum height of the load.

$$\varepsilon = \frac{mg(Smax - Smin)}{\int pdV} \tag{2}$$

The work output of the HydroMuscle is calculated as $mg(S_{max} - S_{min})$ and the work done by gravity is calculated as $mg(S_{min} - S_p)$. To calculate the efficiency of the muscle without return flow work,

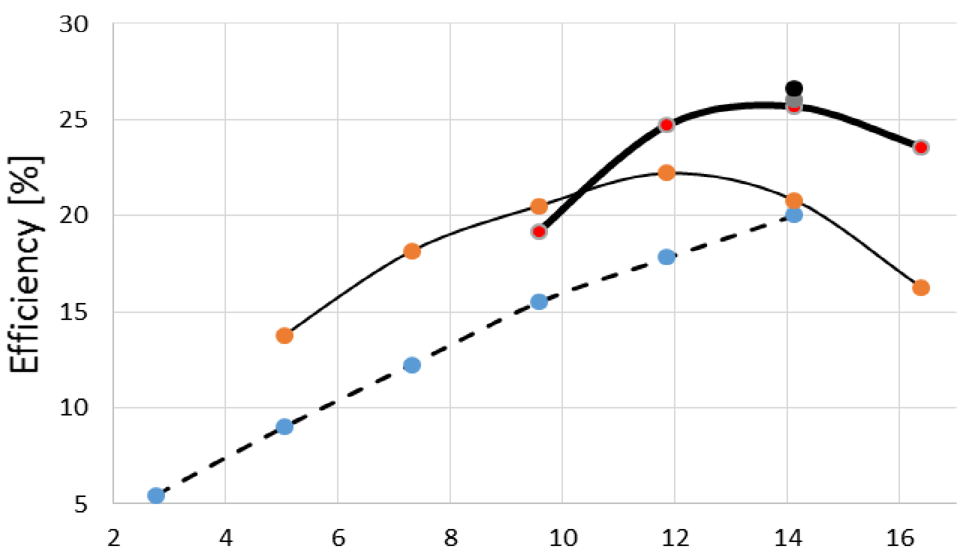

Figure 17: Efficiency of HydroMuscle without return flow work

$$\varepsilon = \frac{mg(zmax - zmin) + |W - (zmin \rightarrow zmax)}{mg(zp - zmin) + W + (zmax \rightarrow zp)} \quad (3)$$

If return flow work is considered, then the HydroMuscle is filled up to the Sp position and the work is added to the pdV work.

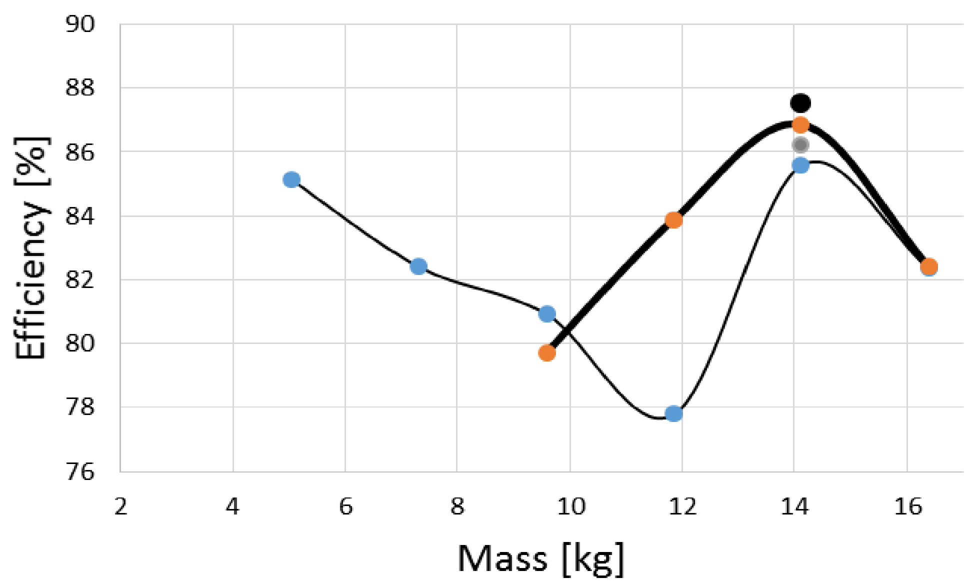

Figure 18: Efficiency of HydroMuscle with return flow work

HydroMuscles have several practical advantages over standard hydraulic and pneumatic actuators. These muscles are soft, lightweight, inexpensive, easy to manufacture from commercially available materials, easy to modify both in terms of mechanical properties and in the way they interface with supporting "skeletal" structure. Moreover, they have inherent elasticity which in turn makes them suitable for power augmentation paradigm; release of muscle's stored energy onto load can be much faster than transferring a pump's energy into the muscle.

HydroMuscles are highly efficient actuators; there are almost no losses due to heating of working fluid, and latex within 100% strain range performs almost as an ideal spring. The hypothesis that the HydroMuscle has a greater efficiency than the McKibben muscle [22] is also confirmed. The maximal efficiency is 33% greater than that of the McKibben muscle, which is a very common fluidic muscle, despite the latter having larger fluid input volume. This is as expected due to fact that a large portion of the McKibben's hydraulic energy is not transferred onto the load as it is instead used for radial expansion of the muscle. This loss is significantly less in the case of the HydroMuscle due to the non-stretchable sheathing preventing elastic tubing from substantial radial expansion.

A notable feature that the HydroMuscles have in common with conventional hydraulic and pneumatic actuators are that a single motor unit (i.e. a pump) can power many actuated degrees of freedom while electrical motors with non-fluidic actuation can typically only actuate a single degree of freedom. Moreover, in case of a wearable system, a conventional pump can be easily positioned more proximally to the center of mass without adding distal masses close to the joints. Finally, hydraulic based transmissions are often more easily implemented than gearing mechanisms for pure mechanical transmissions.

Also, the HydroMuscles were not pressurized in excess of 1Mpa in any of the tests, which limits the maximum loading limit of the muscle to 100N/cm^2. Also, to augment the force of the HydroMuscle, many muscles can be placed in a parallel fashion to achieve multiplied force. The use of HydroMuscles for dynamic applications would require the use of a high quality pump leading to increase in the mass of the system but proves that the use of HydroMuscles as a tethered system would be a viable option.

Extensive testing of the HydroMuscles proved that use of the actuators in case of the exoskeleton. It was contemplated to use the HydroMuscles were to be placed in parallel with the HydroBones on the exoskeleton and cables would be attached to the lower leg in order to actuate the knee.

6.2 Modeling the HydroMuscle

Through mathematical modeling of latex tubing, it was observed that the relaxed wall area of latex rubber, A_{W0} shrinks under strain, μ, by a factor

$$(\mu) = [1 - (1 + \mu)^{-0.5}]^2 \quad (4)$$

independent of fluid pressure. As the outer diameter is constant due to the non-stretchable sleeve, the net muscle force in terms of pressure, p, and strain μ, is with constant muscle area, A_M, defined by the outer maximal diameter (for fully radially pressurized state) and elastic tube wall's Young modulus, E_{RW}. Therefore, the muscle force output was modeled as

$$(p, \mu) = [A_M - (\mu)_0] - E_{RW}\, c(\mu) A_{W0}\, \mu \quad (5)$$

A muscle was modeled for a torque output of 15Nm on the knee, which is 25% assistance on walking. The young's modulus of 1.34 MPa was determined through experimentation on latex. A latex tube of 1 ¼" OD and 1" ID was selected and a strain of 100% was estimated. On calculating required parameters, it was determined that a force output of 275.5N would be generated using this muscle. Therefore, a radius of 5cm was required to generate the required torque.

6.3 Knee Design and Actuation

A conventional knee brace was used as the basis for the knee joint. 80/20 aluminum extrusions were used in order to mount attachment points on the knee. Also, a special joint was designed in order to eliminate the problems caused by the multi-joint system of the original brace joint. Therefore, aluminum pieces were machined and attached to the 80/20 pieces to create a pseudo center as shown.

Figure 19: Front and Side view of the knee joint

Attachment points for a Bowden cable were machined and attached to the joint with provisions to hold the cable in place. A backpack frame was used in order to mount the HydroMuscles. An L-channel aluminum piece was used to mount 2.54cm hydraulic T-fittings by drilling clearance holes. The latex tube was sandwiched with the aluminum and clamped using hose clamps. The muscle end caps were provided with eye-bolts in order to secure the end of the Bowden cable. The other end of the Bowden cable was attached to the bottom of the backpack frame. The cable was secured at the lower leg by looping it through a metallic stop.

Figure 20: HydroMuscle attachment to backpack frame

Upon actuation of the HydroMuscle, the system would give the user freedom to squat down or bend the knee. Once the muscle is depressurized, the HydroMuscle pulls the lower leg causing a torque of 15Nm to be applied on the knee. The knee stop mechanism was integrated into the original knee brace hence eliminating the problem of knee damage.

Chapter 7

Conclusions and Recommendations

This thesis presents a novel approach to achieve variable stiffness in load bearing structures in the form of the HydroBone. There have been many devices utilizing Jamming of Granular media in order to trigger phase change from semi solid to solid, but an approach to tunable stiffness is provided in this paper. As it can be confirmed by the test results from the compressive testing of the HydroBone, the stiffness of the system can be modulated by varying the internal pressure of the system.

The design of a variable stiffness exoskeleton with knee actuation, utilizing HydroBones and HydroMuscles is also presented. The exoskeleton was successful in eliminating the discomfort caused by traditional rigid exoskeletons. The knee actuation of the exoskeleton was successfully capable of providing an assistive torque about the knee during actions such as lifting weights from a squatted position, hence alleviating the torque applied by the human knee joint.

The exoskeleton currently utilizes the initial design of the HydroBone which is more prone to failure. Therefore, the use of redesigned HydroBones to construct the exoskeleton may provide better load bearing capabilities. Also, higher quality solenoid valves and pumps could be made use of to create a tethered system capable of providing rehabilitative actions for the lower body.

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