# Hydraulically Actuated Muscle (HAM) Exo-Musculature

Gregory McCarthy, Daniil Effraimidis, Brian Jennings, Nicholas Corso, Cagdas D. Onal, and Marko Popovic

*Abstract—* **The hydraulically actuated Exo-Musculature, consisting of a network of artificial hydro-muscles, can be rapidly assembled and utilized as either perform-alone or wearable, human body-symbiotic robotic system. Its fundamental unit is a novel hydraulically actuated muscle (HAM), which is inspired by the capabilities of biological muscles. The HAM design has certain advantages over natural muscles, such as being able to maintain a position without expending energy. This design uses an elastic element to apply tensile force, which is released when hydraulic pressure is applied. This gives the muscle the unique characteristic of storing elastic energy when pressurized and releasing it to contract. Other artificial muscles, such as the McKibben, are similar to HAM in the respect that they are fluid-actuated and can be locked in place, but the McKibben is contractile in operation. Additionally, HAM utilizes incompressible fluid (water) and it is limited to expansion in only one dimension, which offers a higher energy density. It is much more compliant than traditional hydraulic cylinders, making it better suited for use in human rehabilitation and augmentation. Finally, HAM is constructed using common materials, making it an extremely low cost solution for both medical and robotic applications.**

## I. INTRODUCTION

The term Exo-Musculature [1] refers to a soft, thin, lightweight, and compliant self-actuated garment without rigid links or singular joints.

Traditionally, assistive or augmentative systems like orthotic or exoskeleton systems consist of rigid links and joints for the lower [2] and upper-body [3] extremities. Similarly, most previously created actuated systems for upper-body rehabilitation use rigid exoskeletons or rigid-link manipulators [4, 5]. However, this traditional approach limits natural degrees of freedom (DoFs) and reduces comfort for the user. Further, misalignments between biological and artificial joints are inevitable [6]. Misalignments occur due to: (1) substantial skin-bone relative motion, (2) changes in volume of the limb, (3) initial imprecision when putting on the exoskeleton. Clearly, misalignments make exoskeletons uncomfortable, and in regards to the lower extremities can even lead to skin lesions and bone fractures due to the large forces that they are subjected to [6].

M. Popovic is with the Worcester Polytechnic Institute, Worcester, MA 01609 USA (corresponding author, phone: 617-470-8198; fax: 508-831-5886; e-mail: mpopovic@wpi.edu).

D. Effraimidis (e-mail: danefre@wpi.edu), B. Jennings (e-mail: bjennings@wpi.edu), G. McCarthy (e-mail: gmccarthy@wpi.edu), N. Corso (e-mail: ndscorso@wpi.edu), C. D. Onal (e-mail: cdonal@wpi.edu), are with the Worcester Polytechnic Institute, Worcester, MA 01609 USA.
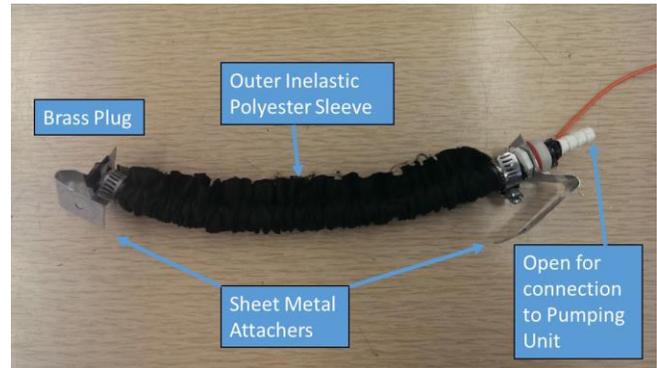
**Figure 1: Photograph of Exo-muscle with Parts Labeled**

Exo-Musculatures utilize natural anatomical structures (skeletal joints and bones) to provide support for the device and as a result, maintain the natural kinematic degrees of freedom (DoF) [7]. As there are no pre-specified synthetic rigid joints, an Exo-Musculature avoids misalignment problems at the joint level. Any misalignments that are still present in the system are less critical and can be addressed with more advanced sensory-motor control system [8].

The fundamental problem for mechanically actuated wearable Exo-Musculatures is the need for a large number of independently actuated and controllable DoF. For the human body, there are approximately 800 skeletal muscles, each of which is composed of one hundred or more individual motor units [1]. Consequently, if an artificial assistive Exo-Musculature is to mimic even a small percentage of the functionality of human musculature, the number of actuated DoF needs to be large. For mechanically actuated devices, conventional approaches involving one dedicated electric motor per actuated DoF results in systems that are large, heavy, and expensive.

The Hydraulically Actuated Muscle (HAM) Exo-Musculature [9] solves this problem as it allows for a single actuator, pump, to drive multiple independently actuated and controlled DoFs. In difference to standard hydraulic and pneumatic systems and similar to the One-To-Many (OTM) systems [1,10,11] the HAM Exo-Musculature has one controlled energy reservoir per each DoF. In difference to the General OTM system [12] the current HAM Exo-Musculature is always coupled to end-effector/load while reservoirs are only actively coupled to pump, the prime mover.

A hydraulically actuated Exo-muscle may have several advantages over a pneumatically actuated Exo-muscle. The system response times are typically much faster (sound propagates faster in water than in air), energy losses are much smaller, and for an incompressible fluid, forces per

unit area may be much larger allowing for more compact design of system with the same peak dynamical output force [13,6]. Further, the hydraulic Exo-Musculature directly interfacing with the human body, consisting mostly (>60%) of water, may provide mechanically more compatible media which is often considered as an advantage [14].

The hydraulic muscle uses elastic potential energy to provide pulling motion whereas the McKibben muscle uses air pressure to contract, therefore providing the pulling motion. While these two muscles work in opposite ways (McKibben contracts when pressurized while HAM extends), it is the McKibben that more closely imitates a biological muscle in cosmetics sense (bulging while contracting), but it is the hydraulic muscle that is a more efficient and responsive actuator due to solely longitudinal expansion/contraction and incompressibility of working fluid (water) [9].

The current realization of Hydro Muscle was somewhat inspired by the commercially available X-Hose [15] comprising of an elastic inner material surrounded by an inelastic material that limits the expansion of the elastic material in the radial direction, but not the longitudinal direction. Similar to hydro muscle the X-Hose retracts to its original size when the pressure is released. X-Hose closely relates to a class of systems [16-22] with corrugated walls that expand under fluid pressure. Other relevant systems include borescopes and endoscopes [23].

In difference to X-Hose, the hydraulic muscle has a single opening and utilizes smooth elastic walls for its tubing, rather than the corrugated elastic material. An additional non-stretchable sleeve is made of a soft, inelastic material, such as polyester, to limit radial expansion while promoting lengthwise expansion when pressurized. Therefore, the hydraulic muscle is inexpensive and convenient to manufacture and operate.

In comparison with conventional actuators with similar dynamical properties, hydro-muscles are drastically (roughly two orders of magnitude) more cost effective [9]. Moreover, they can be rapidly assembled and utilized as either perform-alone or wearable, human body-symbiotic robotic system.

## II. PROTOTYPES

### A. Prototype I

The first prototype was built with inexpensive, easily-accessible materials, such as common latex surgical tubing. One end of tube was sealed off by melting a small bit of latex on that end. On the other end, a barbed plastic connector was used to connect the muscle to a polyethylene tube. A small piece of polyester cloth was used as the inelastic outer wrap. A piece of the polyester fabric which measured approximately 15 in x 3 in was sewn around the latex tube. The ends of the fabric were secured to the ends of the latex tube by using small pipe clamps on each end.

This first prototype could exert a maximum tensile force of about 25 N. However, Prototype I had some leaks, and that motivated need for the more robust Prototype II.
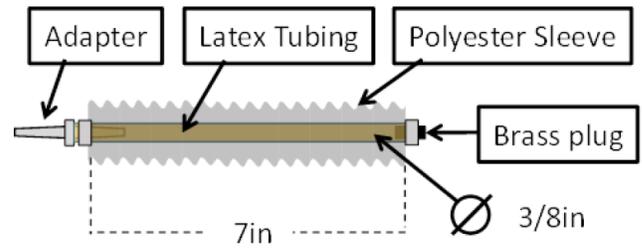


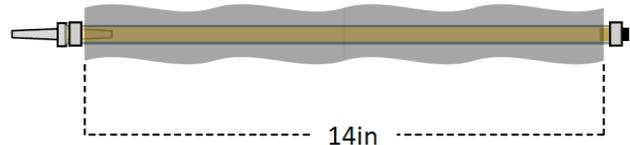Figure 2: Relaxed Exo-muscle with Parts Labeled



Figure 3: Fully Extended Exo-muscle

### B. Prototype II

The second prototype was designed as a continuation of the first prototype. The elastic muscle used for the second prototype was the final design of the actuator. The design features a latex surgical tube on the inside and a polyester fabric on the outside. The muscle has a brass plug on the proximal end and a plastic adapter on the other end. The plug and the adapter are concentric and tightly installed. The fabric is attached to the tube with common metal hose clamps. See Figs. 1-3 for images of the second prototype.

Latex was chosen for its exceptional resistance to wear and tear, high tensile strength, resilience, and elongation. The main disadvantage is the susceptibility to corrosion due to heat, sunlight, and oxygen. However, here, effects of corrosion are regarded as negligible as the tubing is not fully exposed. The outer sleeve is made out of polyester and has an approximate length of 16 inches. It is ideal for this application as it is rigid, tough, and has low absorption of moisture. Additionally, it has a high flexural linear strength.

The pump used for the system is SHURflo 8035-963-239 12 Volts, direct current (VDC) diaphragm manual demand pump [25]. It is a positive displacement, 3-chamber diaphragm pump that utilizes maximum discharge pressures to deliver high flow rates. The check valve is 2-way operational and prevents reverse flow while providing 6ft head of forward flow. The pump was running at a discharge rate of 0.7 gallons-per-minute (GPM), which produced a pressure of 120 psi [25]. The specified discharge range was chosen for safety purposes, as well as to make sure that the muscles receive a pressure of 30 psi after head loses.

The solenoid valves used for the system were plastic water solenoid valves 12 V, ½-inch nominal [26]. The resting position was closed. The valve required 12 VDC supply across the terminals to open and allow flow in one direction. The gasket arrangement inside the valve requires a minimum pressure of 3 psi to operate. This is because they are one-way valves. The 3 psi of pressure keeps the valve closed. When the 12 V difference is sent to the solenoid, it forces the valve to remain open against the fluid flow.

The three exo-muscles were attached to a synthetic skeleton in order to display the use of the muscles as exo-musculature. See Fig. 4 for the attachment of the exo-

muscles and Fig. 5 for diagram of the mimicked muscles. The hydraulic artificial muscles could not be directly connected to the bone of the skeletal model so a custom, latticed device was created. The device was attached to both the upper arm and forearm of the skeleton and allowed for the position of the muscle attachment points to be varied up and down the arm because of the lattice structure. Attachment of the muscles to lattice device itself was accomplished using rectangular sheet metal cutouts. The thin sheet metal was cut into approximately 1 in x 3 in pieces and then bent a third of the way down at a 90° angle. On one third of the piece, the cutout was aligned between the adapters of the elastic muscle and polyurethane tubing for a sturdy and permanent attachment. The polyurethane tubing connected the exo-muscles to the valves. The other half of the cutout was bent as a hook so that it could be fastened around any segment of lattice structure that is desired. Finally, because of the malleability of the sheet metal, the bend angle was adjusted such that the open end of the muscle and adapters stayed parallel to maintain the structural integrity of the elastic. This design allowed for easy detachment and attachment at both ends so the muscles could be arranged in a variety of configurations.

The exo-musculature system is controlled by an Arduino Uno microprocessing board, based on the ATmega 328 [24]. The Arduino communicates with a computer via a USB cable. The Arduino Uno was programmed to control the solenoid valves based on instructions from the computer. The Arduino would listen to the keys pressed, and it then would open or close the valves depending on which key was pressed. The freeware, PuTTY, was utilized to interface between the computer and the Arduino. PuTTY was used to simply provide a bare, basic graphical user interface when controlling the Arduino.

To drive the valves, transistors were used to provide a 12-V supply to the solenoids. Specifically, six NPN bipolar junction transistors (BJTs) were used.
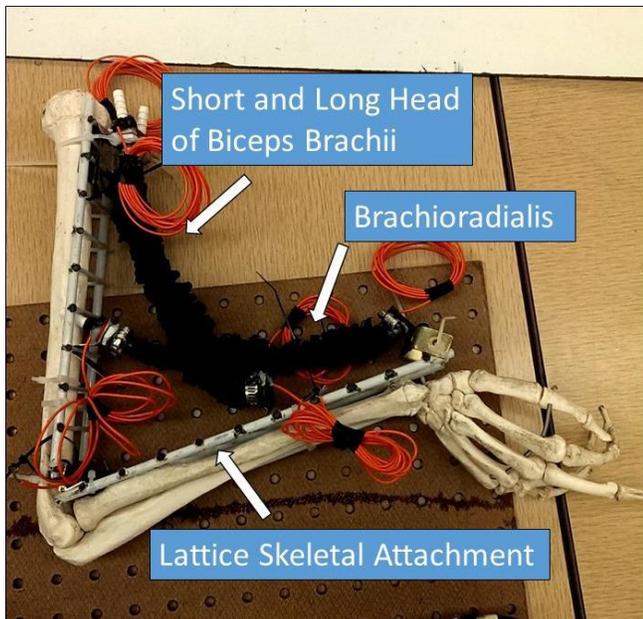


**Figure 4: Attachment of the Exo-muscles to the Skeletal arm, with Mimicked Muscles Labeled**
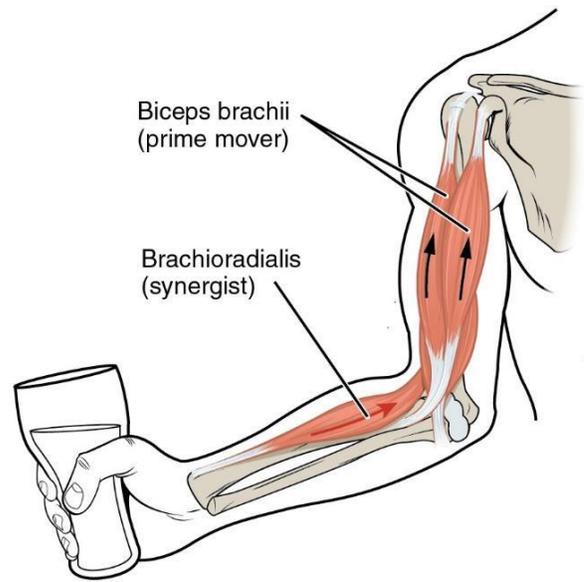


**Figure 5: Diagram of Mimicked Muscles**

III. EXPERIMENTAL RESULTS

*A. Second Prototype: Constant Force Experiment*

To test the final prototype, two types of test were performed. The muscle was suspended horizontally between two posts. One end of the muscle was held in place, while the other is tied to a string that runs over a pulley on the second post. Weights were tied at the end of the string to simulate the forces the muscle might experience during operation. For each experimental run, a different weight was attached. The muscle began in equilibrium at atmospheric pressure. For each data point, the muscle pressure was recorded from the internal pressure gauge, and the muscle length was measured.. After each measurement, the valve between the muscle and running pump was opened for 50 ms. The process was repeated until the muscle was fully extended.

The results of this experiment are displayed graphically, in Fig. 6. The results of this experiment seem fairly linear after 15 PSI.
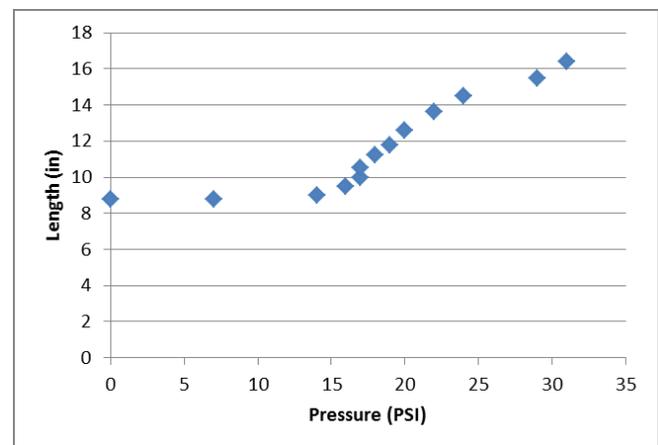


**Figure 1: Results of First Experiment on Second Prototype**
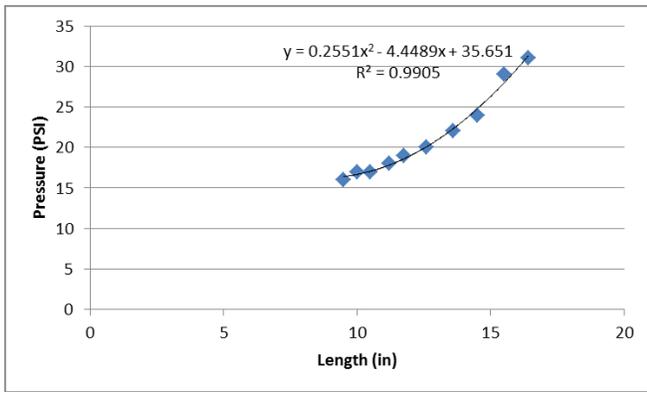
Figure 2: Inverted Results of First Experiment of Second Prototype

However, an inverted graph shows a more accurate relation of pressure to length, in the form of a polynomial regression. This graph can be seen in Fig. 7.

### B. Second Prototype: Constant Length Experiment

For the constant length experiment, the muscle was once again suspended between the two posts, but this time both ends were affixed. At one end, there was a force sensor [27] connected to Logger Pro. The muscle was stretched to several different lengths for each experimental run. The experiment began with the muscle stretched to the given length at atmospheric pressure. For each data point, the muscle pressure was recorded from the integrated pressure gauge and the force was read from Logger Pro. For each successive measurement, the valve between the muscle and running pump was opened for 50 ms of a second. This process was repeated until the muscle began to buckle and sag due to expansion (at which point the data became unreliable).

This experiment was used to find a relationship between force, length, and pressure. This experiment kept the length constant, while increasing the pressure. Fig. 8 shows that a linear relationship was found between the tensile force exerted by the muscle and the pressure inside the muscle. As the pressure inside increases, it produces an outward force on the muscle. This counteracts the tensile force produced by the muscle when it is in tension.
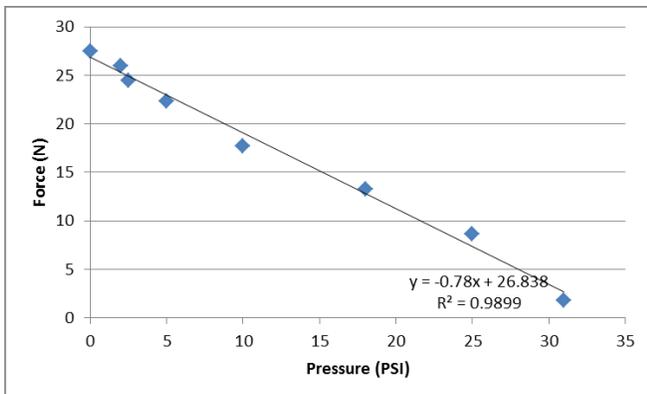


Figure 3: Results of Second Experiment on Second Prototype

### C. Muscle Resistance vs. Length

It was intended that the exo-muscle would use the internal resistance of the water to sense the length of the muscle. Fig. 9 shows a very linear relationship between the distance between two probes submerged in water and the resistance measured across the two probes. This experiment was done to test the plausibility of using the conductivity of water to sense the length of the exo-muscle. The intent was to measure the resistance of the water within the latex tube in order to determine the length of the muscle.

Since there was a linear relationship between water resistance and distance, it was necessary to test this principle with the actual exo-muscle. The exo-muscle was iteratively filled with water. After every iteration, the resistance of the water inside the latex tube was recorded along with the length of the exo-muscle.

While the initial experiment to determine the relationship between the conductivity of water and distance successfully showed that there was a linear correlation between the two, this experiment showed non-linear dependence between the range of muscle lengths and the exo-muscle's internal resistance. This is due to the muscle not being fully actuated when the elastic tube is expanding both radially and longitudinally, hence producing less reliable resistance readings. Fig. 10 shows the results of the resistance of the water inside the exo-muscle at different lengths of the exo-muscle.
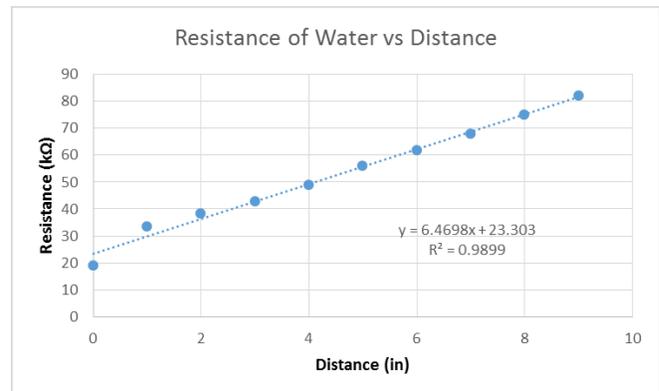


Figure 4: Results of Submerging Two Metal Probes in Water and Measuring Electrical Resistance between the Probes
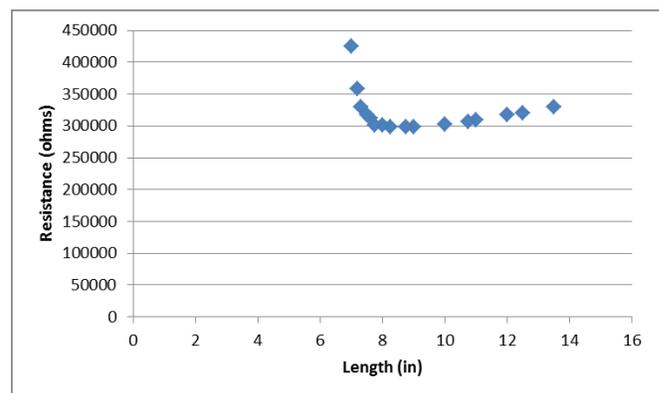


Figure 5: Results of Internal Resistance of Exo-muscle with Respect to Length of Exo-Muscle
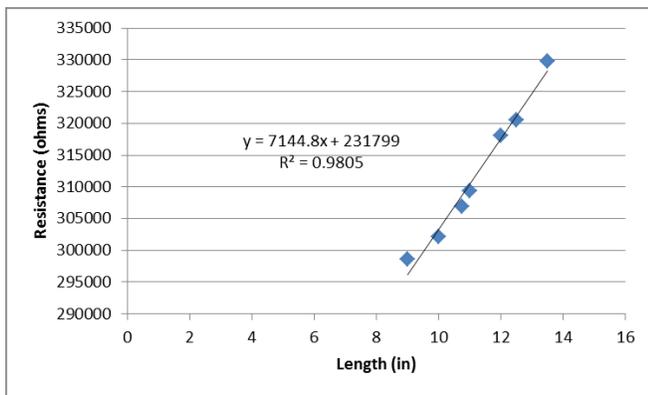
**Figure 6: Only the Linear Results after Length of Exo-muscle Reached 9 inches**

The resistance seems to plummet at the start of the extension of the muscle, but then it steadily climbs upwards. Fig. 11 shows that after the length of the muscle reaches about nine inches, the increase in resistance is very linear.

Between seven inches and nine inches, the elastic tube is expanding both radially and longitudinally. At the start of the expansion of the latex, its radial expansion is much larger than its longitudinal expansion. As the length approaches nine inches, the radial expansion decreases, and the longitudinal expansion increases. Once the length of the muscle is about nine inches, the latex tube can no longer expand radially at all, so the muscle only extends longitudinally after that. This accounts for the nonlinear decrease in resistance at the start and then the linear increase after nine inches.

## IV. CONCLUSION

As research in robotics continues to progress, actuators which are lightweight, small, efficient, fluid, fast, and cost-effective become more and more critical. HAM [9] is a simple novel actuator that confronts these requirements. It may be utilized as a building block for an Exo-Musculature that can be rapidly assembled and utilized as either perform-alone or wearable, human body-symbiotic robotic system. There are many attractive avenues for future work, development, and applications for this technology. For example, it has applications in the medical field as a device to assist in rehabilitation and physical therapy, it can be used in both labor and the military as method of augmenting strength, and it can be used as a soft-robotics alternative to virtually all rigid robotic motors and actuators that currently exist. Further research and development can advance this device from a proof of concept to one of the most commercially-feasible soft robotics actuators.

## ACKNOWLEDGMENTS

## REFERENCES

[1] T. R. Hunt, C. J. Berthelette, G. S. Iannacchione, S. Koehler, and M. B. Popovic, "Soft Robotics Variable Stiffness Exo-Musculature, One-To-Many Concept, and Advanced Clutches", IEEE ICRA 2012 WORKSHOP: Variable Stiffness Actuators moving the Robots of Tomorrow, St. Paul, Minnesota, May 14, 2012. http://www.ce.utwente.nl/car/ICRA2012/workshop.html

[2] Dollar, A and Herr. H. "Lower Extremity Exoskeletons and Active Orthoses:Challenges and State-of-the-Art" IEEE Transactions on Robotics (2008) Volume: 24, Issue: 1, Pages: 144-158

[3] Gopura, R.A.R.C.; Kiguchi, K.;and Bandara, D.S.V., "A brief review on upper extremity robotic exoskeleton systems", 6th IEEE International Conference on Industrial and Information Systems (ICIIS), 2011.

[4] H. I. Krebs, N. Hogan, et al., "Overview of clinical trials with MIT-MANUS: a robot-aided neuro-rehabilitation facility", Technology Health Care. vol. 7, 1999, pp. 419-23.

[5] L. E. Kahn, et al., "Robot-assisted reaching exercise promotes arm movement recovery in chronic hemiparetic stroke: a randomized controlled pilot study", J Neuroengineering Rehabil., vol. 3, 2006.

[6] M. B. Popovic, "Biomechanics and Robotics", 364 pages, Copyright © 2014 Pan Stanford Publishing Pte. Ltd., Singapore, ISBN 978-981-4411-37-0 (Hardcover), 978-981-4411-38-7 (eBook), www.panstanford.com

[7] S. B. Kesner, L. Jentoft, F. L. Hammond, R. D. Howe and M. B. Popovic (2011). "Design Considerations for an Active Soft Orthotic System for Shoulder Rehabilitation" 33rd Annual International IEEE EMBS Conference , August 30 - September 02, 2011, Boston, USA.

[8] Ignacio Galiana, Frank L. Hammond III, Robert D. Howe, and Marko B. Popovic, "Wearable Soft-Orthotic Device for Post-Stroke Shoulder Rehabilitation: Identifying Misalignments" International Conference on Intelligent Robots and Systems, IROS 2012, October 7-12, 2012. Vilamoura, Algarve, Portugal. (demo available at http://walltrust.com/ALL/SoftRoboticsSuitWeightLifting.AVI )

[9] Daniil Effraimidis, Brian Jennings, Gregory McCarthy, and Nicholas Corso, "Hydraulically Actuated Muscle (HAM) Exo-Musculature", MQP report, advisor Marko Popovic, co-advisor Cagdas Onal, The Winner of the 2014 WPI Robotics Engineering Program Provost's Runner Up Award, WPI May 1st 2014.

[10] T. R. Hunt, C. J. Berthelette, and M. B. Popovic (2013), "Linear One-to-Many (OTM) system: Many degrees of freedom independently actuated by one electric motor", 5th Annual IEEE International Conference on Technologies for Practical Robot Applications (TePRA), Greater Boston Area, Massachusetts, USA, April 22-23, 2013,http://users.wpi.edu/~mpopovic/pages/TePRAfinalsubmission(finished)1YES.pdf .

[11] C. J. Berthelette, M. DiPinto, J. D. Sareault, (primary advisor M. B. Popovic), Rotary "One-To-Many" (OTM) Novel Actuator; The Winner of the 2013 WPI Mechanical Engineering Department Best MQP in Robotics Engineering Award. WPI, April 25, 2013.(MQP Report) https://www.wpi.edu/Pubs/E-project/Available/E-project-042513-153455/unrestricted/Rotary_One-to-Many_OTM_Novel_Actuator_Final_Report.pdf

[12] Christopher Berthelette, Matthew DiPinto, Thane Hunt, and Marko Popovic, "The General One-To-Many Concept", submitted to Actuators, Open Access Journal, 2014.

[13] Mori, Mayuko, Koichi Suzumori, Masayuki Takahashi, and Takashi Hosoya. "Very high force hydraulic McKibben artificial muscle with a p-phenylene-2, 6-benzobisoxazole cord sleeve." Advanced Robotics 24, no. 1-2 (2010): 233-254.

[14] Richard M. Greenwald, Robert C. Dean, and Wayne J. Board. "Volume Management: Smart Variable Geometry Socket (SVGS) Technology for Lower-Limb Prostheses" JPO Journal of Prosthetics and Orthotics Vol 15, N 3, 2003, page 107-112.

[15] X-HOSE - the Original Kink Free Lightweight Expandable Garden Hose. (n.d.). Retrieved April 2014, from XHOSE - the Original Kink Free Lightweight Expandable Garden Hose. (add link)

[16] Ragner, G. D., & deRochemont, R. (2001). Patent No. US 20030098084 A1. United States of America.

[17] Ragner, G. D. (2003). Patent No. US 7617762 B1. United States of America.

[18] Ragner, Gary Dean, and Robert Daniel deRochemont Jr. "Pressure-actuated linearly retractable and extendible hose." U.S. Patent 6,948,527, issued September 27, 2005.

[19] Degen, C., Gregorian, A., & Siber, R. (2007). *Patent No. US 20100300569 A1.* United States of America.

[20] Ragner, Gary Dean. "Flexible hydraulic muscle." U.S. Patent 7,617,762, issued November 17, 2009.

[21] Berardi, M. (2011). *Patent No. US 20130087205 A1.* United States of America.

[22] Berardi, Michael, "Expandable garden hose", US patent office publication number US 20130087205 A1, Application number US 13/690,670, Filing date Nov. 30, 2012.

[23] Lia, Raymond A. "Borescope or endoscope with fluid dynamic muscle." U.S. Patent No. 4,794,912. 3 Jan. 1989.

[24] Arduino. (2014). Arduino Uno. Retrieved April 2014, from Arduino: http://arduino.cc/en/Main/arduinoBoardUno

[25] SHURflo. (2002, November). 8035-963-239 Product Data Sheet. Retrieved April 2014, from Pump Agents: http://www.pumpagents.com/pdf/ShurfloPumps/8035-963-239.pdf

[26] Plastic Water Solenoid Valve - 12V - 1/2" Nominal. (n.d.). adafruit industries blog RSS. Retrieved April 1, 2014, from http://www.adafruit.com/products/997

[27] Dual-Range Force Sensor Owner Manual. (2014). . Retrieved April 1, 2014, from http://www.vernier.com/files/manuals/dfs-bta.pdf