Multi-Disciplinary Senior Design Conference
KateGleasonCollege of Engineering
Rochester Institute of Technology
Rochester, New York14623

Project Number: P11029

BIOMIMETIC CRAB

Casey O'Connell / ME, Project Manager

William Dwyer / ME

Shaynae Moore / ME

Joseph Mead / ME

ABSTRACT

The primary project objective includes the design, development and production of an underwater biomechanical device. The expectation of the device is to realistically imitate the arm movements and overall look of a crab. The scope of explored arm movements will cover: forearm flexion, extension and pinching. All movements are designed to be performed with the use of pneumatically actuated air muscles. The project motivation is to investigate the effectiveness of pneumatic muscles while being applied in an underwater environment. In order to achieve the project initiatives, an engineering team engaged in conceptual development, mechanical design, control systems, prototyping and construction. The final product is a demonstration artifact that anatomically resembles a crab and mimics natural arm movements.

NOMENCLATURE

Extension – Anatomical term for movement of an appendage away from the midline of an organism or entity.

Flexion – Anatomical term for movement of an appendage toward the midline of an organism or entity.

Brinkman Machine Lab – In house machine shop equipped with mill, lathe and machinery used to fabricate mechanical components.

CAD – Computer Aided Design, software used to model and constrain all components of the design in preparation for fabrication.

CNC – Computer Numerical Control, rapid automation process allowing the dimensions and contour of a part to be based on a mathematical equations or a CAD model.

BACKGROUND

For the past several years, Dr. Lamkin-Kennard has sponsored senior design projects to showcase the possible uses of pneumatic air muscles. Ancestors to this project have utilized these muscles to perform motions mimetic to human movements. Specifically the systems have included human joints (hands, elbows, wrists) in their models. In doing so a depth of understanding has been recorded pertaining to the characterization of air muscles, and controls. Many mechanical components of natural organisms are unique and adapted solutions to an environmental challenge. By artificially recreating movements and biological system processes it is possible to test the functionality of pneumatic muscles. Much research has considered the usefulness of pneumatic muscles in fluid environments such as air. Such devices have proven to be lightweight, highly repeatable and reliable mechanisms for generating tensile force. Such attributes may prove to be useful assistive devices and components in biomechanical systems. Another theoretical advantage of the mechanical muscle is its proposed ability to be effective in underwater environments where other electrical components are at risk. As such, further investigation of these actuators is needed in regards to performance and usefulness in an ambient liquid environment. The purpose of the biomimetic crab is to showcase the qualities and effective use of pneumatic muscles.

PROJECT REQUIREMENTS

In crafting such a design, specific customer needs presided over the direction of the project. Governing requirements were defined early on in the design process through a series of customer interviews.

Weighted analysis of proposed requirements were evaluated and strictly adhered to in order to ensure that the expectations of the customer were met efficiently.
Primarily, the most important goal of this project is to implement the pneumatic muscles in a device planned to be simultaneously operated and submerged underwater. It is also important that device must be equipped with a single supply cord. In order to design and mimic the muscular system of a crab, pneumatic actuators will perform all intended movements. The domain of movement will be restricted to the features of the claw. The primary goal and function of the crab claw design must feature simultaneous pinching accompanied by forearm extension and flexion. Aesthetics of the crab have less requirement however are still important in upholding the integrity of the machines functions. The movement and size of the crab as well as its components must be anatomically to scale in order to realistically challenge the application of the pneumatic muscles. It is intended that all muscles should be encapsulated neatly inside the device. Above all, components must be conducive and functional in a submerged underwater environment. In lesser orders it is expected that muscle functionality will be intuitively operated via acontrol system interface. In the spirit of transparency and professionalism, thorough documentation of working components and team decisions ought to be recorded for future endeavors.

MUSCLE CHARACTERIZATION & THEORY

The pneumatic muscle is a complex non-linear system and can be described with respect to its constituents. Theoretical modeling is conducted by Chou and Hannaford [1] with cylindrical approximation and energy conservation. Where V is volume, F is force yield of muscle, P' is input pressure, θ is braid angle of mesh, and L is the muscle length the following relationship is used to describe the physical state of the muscle.

$$F(P,\theta) = -\frac{P'(dV/d\theta)}{(dL/d\theta)}$$

Because output force differs with respect to two differentials ($dV/d\theta$) and ($dL/d\theta$,) it is difficult to predict muscle output during transient movement. Due to the fact that the relationship between volume and braid angle is not certainly known, the expected length cannot be predicted for all instances of contraction. Shortage of materials and time did not allow for explicit testing and classification of muscles. In the interest of design, muscle parameter relationships are examined under research of static conditions. Since muscle deflection is a key feature of our device automation, a specific interest is placed upon optimizing this parameter. It was shown by Kothera and Jangid [2] that the allowable free contractile length of a pneumatic muscle quadratically increases as the initial length of the muscle increases. Experimental results were conducted for different given input pressures and constant resistance forces. In the following experiment it should be noted that the muscle specification are as follows: Length: 4", 6", 8", Inner Diameter: 3/8", Braid Angle: 42.9°, and Number of turns: 108.

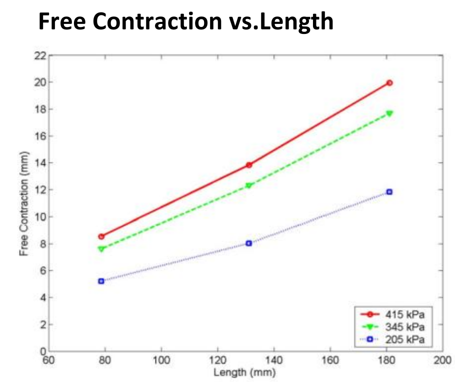

Figure [1]: Free Contraction vs. Length

From Kothera and Jangid [2]
From research data it was observed that original muscle length is the critical factor in creating displacement during a muscle stroke.

DESIGN PARAMETERS

For smaller muscles it has been observed that a theoretically obtained model may not accurately predict final state conditions of a pneumatic muscle. Elastic properties of the mesh and inner tubing create factors that force the muscle to deviate from the expected results. Combined with the complexity and thoroughness required in developing an exact model, a better use of time is spent using the aforementioned theoretical principles as a guiding heuristic. For example, if it is known what feature of the muscle affects the design criteria, in this case deflection, catalogue testing can be performed for a sample set of different muscle lengths. Given archives of previous muscle testing from MSD Group P08024 [3,] the largest length muscle was selected in which its characteristics were known. For actuator design, a 7" muscle was selected. By replicating test data, it was observed that the rubber tubing has a large impact on the performance of the muscle. Thin walled tubing provided better instances of contraction while thicker walled tubing was better suited for increasing force output. Since the deflection of the wrist, flexion and extension was more of the focus, and not force output, the thin walled tubing was the perfect candidate for muscle construction.

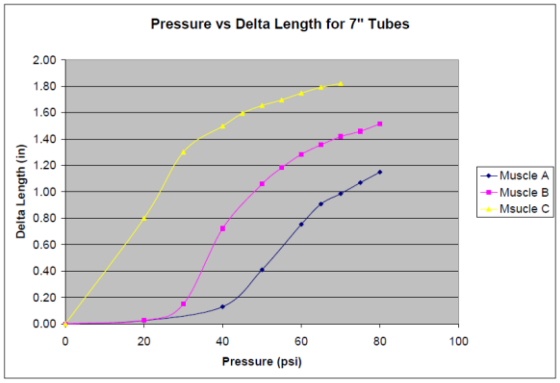

Figure [2]: P08024 Muscle Length Data

For a 7" muscle with thin walled elastic tubing, a deflection of 1.8 inches could be expected at 60 psi. This pressure is significant because a pressure cap for service air exists for most buildings approximately between 60 -75 psi. Input air pressure will be limited to 60 psi for the ease and repeatability of this design actuator.

DESIGN DECISION

Size/Shape

As part of the customer needs, it was specified that the size of the crab was not critical, and would be left up to the discretion of the project team. During the design decision process, it was determined that the size of the body of the crab would be dictated by the length of the muscles. As stated above, a 7" muscle was selected in order to achieve desired muscle deflection based on theoretical and experimental data that was available. The baseplate design was drawn to fit the full length of the air muscles and umbilical attachment bracket. The size and shape of all other body parts of the crab were designed to proportionally match the baseplate and resemble a generic crab.

Claw Mechanics

Due to the complexity of making the claw design functional, an in-depth concept development process was used to compare different mechanical designs and select the best one. The designs that were considered for claw function differed mainly in the muscle layout. The top three competing designs included: (1)One muscle with an opposing spring. The muscle would be actuated through a full range of motion with a variable pressure regulator. (2)Several opposing muscles of different lengths activated in different combinations to achieve incremental stopping points through a full range of motion. (3) Two opposing muscles with a centering spring. Wrist will have three stopping points:one at the center, and fully deflected on each side.

Lack of available funds to purchase a pressure transducer eliminated the first design option. It was decided that the second option was unsatisfactory to the customer because of the bulk of muscles that would be contained in the device. Design number three was chosen because of its relative simplicity, and therefore its probable reliability.

BASIC DESIGN

The mainstay of the body design was to ensure that our model resembled an actual crab. Research was done in MSD I on various crab types. The blue crab is the most commonly known along the eastern coast of the U.S. While the shape is very complex, its visual distinction is clear and played a role in the overall composition. Since the system would be submerged in water, proper material selection was of critical concern. It was important that the material was resistant to corrosion, but mechanically strong. While mechanical deformation due to water pressure was negligible (crab was only submerged in 2 ft of water), the crab must be heavy enough to oppose buoyancy forces. In this regard, added buoyancy force from inflated muscles must be acknowledged and quantified. At most, 4 inflated muscles may operate at once increasing the overall weight requirement. Acrylic was chosen as the material used for the chassis. The chassis purpose is to support the loads of the claws and legs while being transparent enough to show off the muscles during operation. Therapid prototyped shell, made from WaterShed XC 11122 plastic also allowed one to see the effectiveness of the pneumatic muscles in action. The visor and leg mounting brackets were rapid prototyped in the RIT Brinkman Lab and were also constructed out of plastic. In this case the manufacturing method is ideal because the lead time for parts was much shorter and greater manufacturing accuracies were achievable for their complex shape. The aluminum legs main function was to support the weight of the entire mechanical system. Figures 3-5 are tables of mechanical properties for the materials used.

Mechanical Properties	Metric	English	Comments
Hardness, Vickers	15	15	Annealed
Modulus of Elasticity	68.0 GPa	9860 ksi	
Poissons Ratio	0.36	0.36	calculated
Shear Modulus	25.0 GPa	3630 ksi	

Figure [3]: Material Properties for 100% Aluminum

Physical Properties	Metric	English	Comments
Density	1.19 g/cc	0.043 lb/in³	ASTM D792
Mechanical Properties			
Tensile Strength, Ultimate	54 MPa	7830 psi	ASTM D638
Elongation at Break	2.4 %	2.4 %	ASTM D638
Modulus of Elasticity	2.8 GPa	406 ksi	ASTM D638
Flexural Yield Strength	81 MPa	11700 psi	ASTM D790
Thermal Properties			
Maximum Service Temperature, Air	73 °C	163 °F	Deflection temperature at 1.8 MPa
Deflection Temperature at 1.8 MPa (264 psi)	73 °C	163 °F	ASTM D648
Vicat Softening Point	90 °C	194 °F	ASTM D1525
Flammability, UL94	HB	HB	
Optical Properties			
Transmission, Visible	92 %	92 %	Luminous Transmittance, ASTM D1003

Figure [4]:
Material Properties for Acrylic

MPP MATERIAL PROPERTIES

Mechanical Properties	Specific Gravity	Tensile Strength	Tensile Modulus	Elongation at Break	Flexural Strength	Flexural Modulus	IZOD Impact - Notched	Heat Deflection Temp	Vical Softening Point
Units		psi	psi	%	psi	psi	ft•lb/in	°F	°F
ABS Machinable Sheet	1.04	6,500		25%	10,600	331,000	5.51	190°	210°
Injection Molded ABS (Sabic MG47)	1.04	6,400	330,000	24%	10,500	340,000	6	180°	210°
Injection Molded PC (Sabic Lexan 121)	1.2			7%	14,000	340,000	15	270°	310°
Acrylic Machinable Sheet	1.2	7,000	340,000	2%	12,000	340,000	0.3	170°	

Figure [5]:
Common Materials & Properties for rapid Prototyping

The umbilical plate was machined from the same material as the chassis plate. Modeling the stresses using CAD software eliminated any concerns with the mount not being mechanically strong enough to handle the pressures forces acting on it in the worst case scenario. In Figure 6, 80 psi of pressure has been applied to each hole. At this amount of pressure running through the mount the maximum stress is 233.8 psi, while the material yield strength is 29 times that amount. In reality the worst case scenario is 60 psi with only four holes stressed at once. This is because the wrist muscles cannot flex and extend simultaneously. This will be discussed more in the controls section.

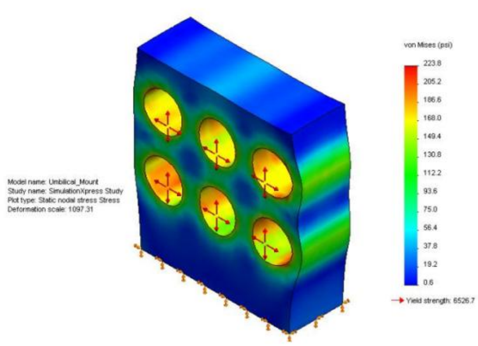

Figure [6]: Stress/Deformation simulation in CAD

PROTOTYPE

A working prototype of the claw was developed to test the feasibility of the wrist and pincher design. The principle of the prototype was formed from geometry and allowable deflection of pneumatic muscles. After testing the prototype, it was discovered that the amount of deflection created by the muscles was not as great as initially assumed. Future modifications would need to be made from the initial design to achieve the target muscle deflection. Due to this discovery, it was decided that muscles with a smaller wall thickness would be used, along with a slightly longer muscle. In addition stiffness springs positioned to return the claw assembly to neutral positions proved to be effective and reliable. Overall, the prototype proved that the basic design was feasible, and helped to solidify design proposals. Specifically, the development of the umbilical mounting bracket was advanced.

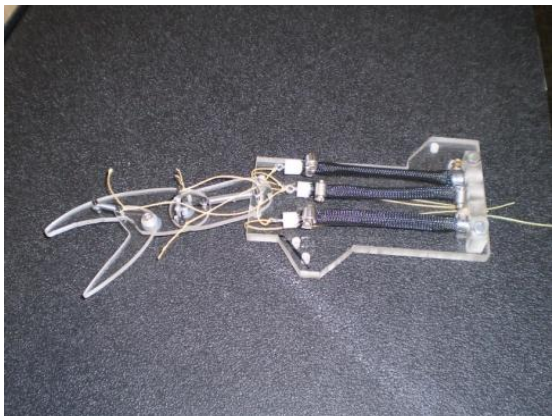

Figure [7]: Prototype Model

CAD MODELING

Once a basic design for the crab was finalized and then proven and refined with a prototype, a fully constrained CAD model needed to be developed before proceeding to manufacturing. All drawings and part models were made in SolidWorks. Parts that would be machined by hand were intentionally drawn using simple geometries, while parts that would be manufactured using rapid prototyping were drawn and modeled to be more aesthetically pleasing. All part models were assembled in SolidWorks and constrained in order to demonstrate that the parts would fit together as intended. Pictures of the assembled CAD model were shown to the customer to verify that the aesthetics met the customer's needs.

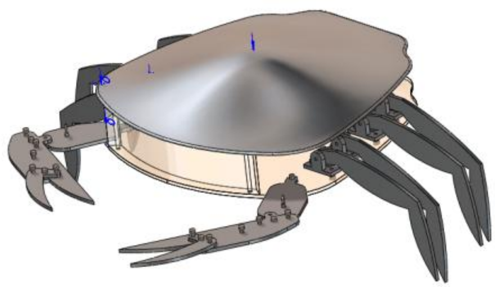

Figure [8]: CAD model

MANUFACTURING

Pneumatic Muscle

The pneumatic muscle was constructed using thin-walled silicone tubing cut to a specified length. The tubing is encased in a nylon mesh sheath, and fixed to plastic end caps on either end with stainless steel hose clamps. The plastic end caps were machined manually on a lathe. Each muscle has one solid plug end cap, and another with a hole drilled through the center to allow air to flow in and out of the muscle.

Shell

It was determined that the outer shell of the crab served aesthetic purposes only, so structural integrity was not critical. The shell was made using rapid prototyping via FineLine prototyping. This ensured that it would not float, yet stay rigid and intact in an underwater environment.

Body

The body parts of the crab were made using CNC machining and laser cutting equipment in the Brinkman Lab at RIT. The material for the base of the body was acrylic, while the rest of the parts were manufactured using an aluminum sheet. Part drawings that had been made in SolidWorks were refined and sent to the lab to be machined.

Umbilical Mount

The umbilical cord mounting bracket was machined manually in the ME machine shop by team members. The band saw and drill press were utilized for this task. The plugs used to attach the umbilical cords to the bracket were also machined by hand using the lathe.All parts were built to specifications and dimensions shown in the CAD drawings.

CONTROLS

The controls GUI and program were designed and built in Labview 2009. The objective was to create a very simple user friendly interface that would allow the user and crab to be interactive.

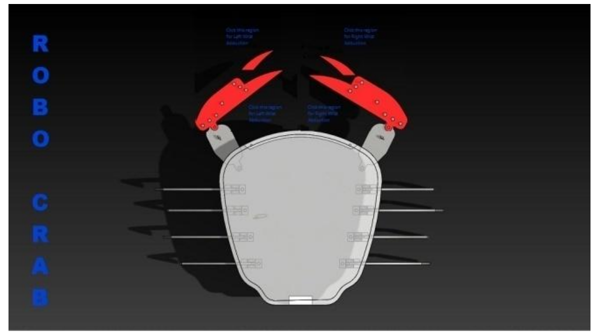

Figure [9]: User Interface GUI

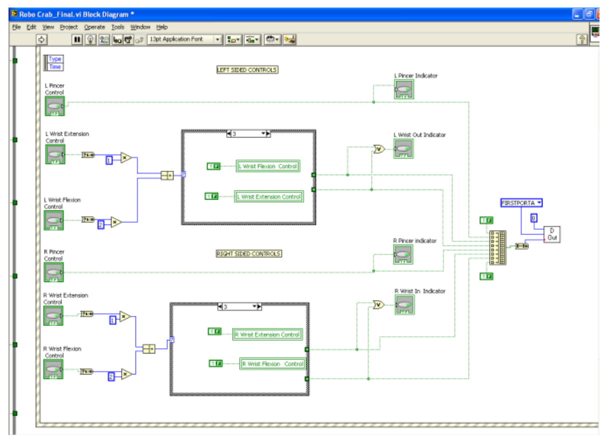

Figure [10]: LabView block diagram

Figure 10 shows only a portion of the block diagram. The main controllers, indicators, and communication vi are nested within an event structure. The event structure tells the subprogram to execute when a control is activated. This prevents the program from continuously checking whether or not the user has activated a control. There are also two case structures that control the activation of flexion and extension for each wrist. It is important that the user cannot simultaneously activate these for a single side as it can cause mechanical damage to the system and possibly communication failures. In the event that the user activates right wrist flexion while extension is occurring, the latter will automatically turn off. The former would then have to be pressed twice to enable movement.

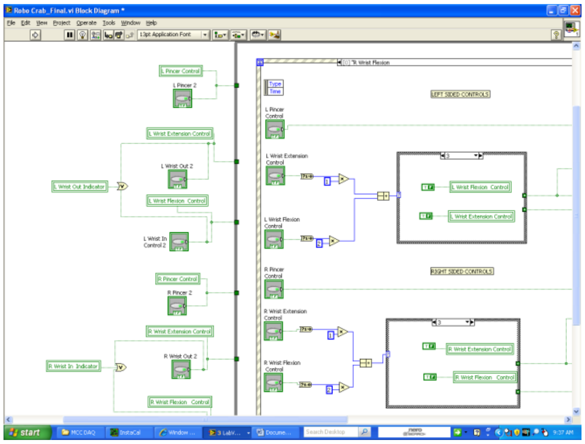

Figure [11]:
Left claw controllers wired to a "While Loop"

Figure 11 also only shows only a portion of the block diagram. The important feature to be shown is the secondary controls wired in to the loop. They control the initiation of communication from the computer to the relay board. The loop also enables a continuous run of the program, without using the continuous run control located on the toolbar. You can see on all of the figures that this button as well as the abort button has been removed.

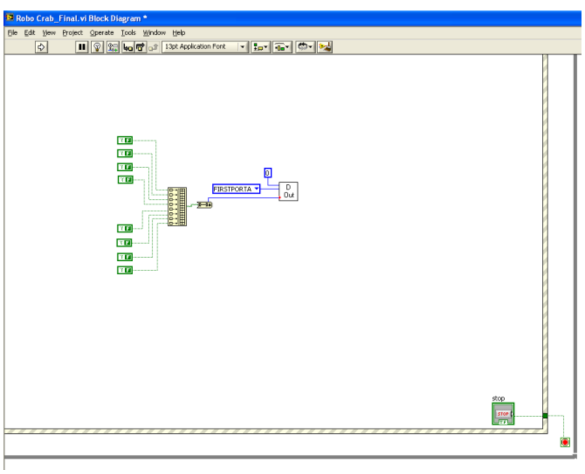

Figure [12]: Case 2 in the Event Structure

In Figure 12, the latter portion of the event structure is shown. At the bottom right hand corner is a stop control internal to the structure, but wired out to the stop indicator for the loop. When the stop is true, all of the control values are then change to false, which essentially stops the program. This particular feature enabled the removal of the abort button on the toolbar. Sudden abortion with the toolbar stop can cause communication failures to the relay board unbeknownst to the user, until rerunning the program and attempting to control the system.

TESTING/VERIFICATION

Underwater Muscle/Umbilical Test

Initial testing was performed on the umbilical cord and air muscle setup prior to the construction of the crab. This was due to concern over the buoyancy of the umbilical cord and air muscles underwater, and potential adverse effects on the functionality of the crab. In order to conduct the umbilical cord tests, various muscles were inflated underwater with varying air pressure. A spring force gauge was used to determine the change in buoyancy under pressure, and general observations were made regarding the operation and reaction of the umbilical cord and muscles underwater. This test conclusively showed that buoyancy of the muscles or the umbilical cord would not impede operation in this case. Under all pressures applied on all muscles that would reasonably be considered for use on the biomimetic crab, buoyant force was negligible. In many cases a force did not even register on the scale used. One observation made was that leaks in the muscles were very noticeable underwater. Care needs to be taken to insure that muscle clamps are made extremely tight in order to prevent such leaks. Another concern was in the rigidity of the umbilical cord bundle. The testing showed that using thinner, more flexible air lines allows for the crab to be more easily manipulated underwater. This umbilical cord and air muscle testing was an important step in verifying the feasibility of underwater air muscle operation.

Testing of Mechanical Operation of Crab

To meet the functionality requirements of the mechanical operation of the biomimetic crab: the wrist must flex and extend, the pincher must open and close fully, and the movements should generally mimic and give the feel of a real live crab. These mechanical movements must be repeated through many cycles without noticeable deterioration in functioning. Testing was done by operating all mechanical motions underwater while visually confirming consistent functioning and a general mimicking of a biological crab. The crab performed as expected, and met customer needs and requirements.

Operation of System Through Control Interface

A key condition for the biomimetic crab is that it be operated via a simple control interface. As mentioned previously, this crab is operated through a graphical LabView interface. The functionality of the control system was tested and proven by cycling through all controls repeatedly, and visually verifying muscle operation. Evidence of the simplicity of the control interface was shown as many users unfamiliar with the system were able to operate it effectively without instruction.

CONCLUSIONS AND RECOMMENDATIONS

The bio-device successfully meets the criteria established in the customer specifications and conforms and operates effectively. The muscles perform analog actuation and fire reliably and a repeatable manner. Muscle behavior is relatively unaffected by the submerged liquid environment. Overall the mechanical device appeared to work better due to the following observed behavior of our machine. Muscles that once slid along the base plate and grinded against each other during movement floated underwater relieving contact and friction. The lateral muscles that were the most prone to getting hung up on the most foreword leg bracket were never observed to get hung up underwater. The liquid environment provided a lubricant for interfacing parts and allowed our design to perform much more effectively. Lubrication benefits affected all surfaces and washers in the claw assembly as well as muscle rubbing within the mechanical frame. Pneumatic muscles demonstrated comparable force outputs in underwater settings as well as contractile speed. As expected, the device achieved faster cycling rates for the pincher assembly than movement of the claw. The muscle responsible for pincher movement had to oppose less mechanical mass and resist the force of a smaller spring. While the device demonstrates how pneumatic muscles are not compromised by a shallow water environment, there remains unexplored terrain specifically featuring the extent of muscle control. The ability to control the muscle dynamically would allow for varying states of actuation and therefore varying states of posture. In the current setup, the muscles may either relax or contract to a full expected deflection. This pneumatic muscle behavior is thus akin to the microscopic contractile muscle spindles of the human anatomy. Conceptually the stimulation of thousands of muscle spindles allow for dynamic contractions of a natural muscle. Because the size and scale of pneumatic muscles are significantly larger, arrangement in this means is not an effective approach. However, with next generation projects and design models in mind, there are possible characteristics of the pneumatic muscle that would allow a device to generate a similar result. It was researched in the development phase that a pneumatic muscle varies linearly with pressure. If the pressure in a given pneumatic muscle could be controlled, increased states of deflection and movement could be realized. Theoretically a complete and continuous interval of muscle states could be realized for a muscle by incorporating a pressure transducer and an advanced control-feedback system.

REFERENCES

[1] Chou, C.P., Hannaford, B.: McKibben Artificial Muscles:Pneumatic-Actuators with Biomechanical Intelligence. In: Proceedings of the IEEE/ASME International Conference on Advanced Intelligent Machatronics 1999, pp.221-226 (1999)

[2] Curt S. Kothera, Mamta Jangid, Jayant Sirohi, and Norman M. Wereley, J.:Experimental Characterization and Static Modeling of McKibben Actuators. Mech. Des. 131, 091010 (2009), DOI:10.1115/1.3158982

[3] Felicia Haverty, Win Maung, Aaron Moore, at el.:MSD2 Project Team P08024, "Air Muscle Artificial Limb," 2009, http://edge.rit.edu/content/P08024/public/Pressure%20vs%20Delta%20Length%20for%207%20in%20Tubes

[**4**] Matweb Material property Data. *Aluminum, Al*. February 21, 2011. http://www.matweb.com/search/DataSheet.aspx?MatGUI

[**5**] K-mac Plastics. *Acrylic Data Sheet*. February 21, 2011. <http://k-mac-plastics.net/data%20sheets/acrylic-data-sheet.htm>.

[**6**] Quick Parts. *MPP Material Properties*. February 21, 2011. <http://www.quickparts.com/UserFiles/File/MPP_Material_Properties.pdf

ACKNOWELDGEMENTS

Finally we would like to thank Dr. Lamkin Kennard, Bill Nowak, Professor John Wellin, John Bonzo and the RIT Brinkman Lab, Chris Fisher and the MSD program, Dr. Kempski, Sylvan Hemmingway, Yateen Shembade, and Fine Line Prototyping. Through your generosity and time we were able to successfully complete our project. .