Development of Bioinspired Exosuit Actuated with Hydro Muscles and Novel Compact Robotic Flow Control Valve

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Abstract: The biologically inspired, wearable, exo-muscular suit has been proposed as a cost-effective, fluidly actuated device for lower-limb physical therapy as well as for assistance with activities of daily living. The exosuit, actuated with 12 biomimetic Hydro Muscles independently controlled with 12 5-way inexpensive, off-the-shelf, on-off solenoid valves, has been designed, manufactured, and tested on a lightweight, biomimetic human skeletal model. The results from testing suggested a necessity for more advanced fluid flow management support system in the form of affordable, lightweight, and compact valves suitable for robotics applications. To meet these metrics and fulfil the requirements of the exosuits fluid flow management system the Compact Robotic Flow Control Valve was designed, manufactured, and tested. The CRFC Valve is lighter, more compact, more controllable, and less expensive than any other similar valve currently on the market.

1 INTRODUCTION

Because form and function are naturally intertwined, biologically inspired robots following the structure of the human body are an attractive direction for the advancement of a variety of biomedical applications. Such applications include prosthetic limbs, braces, exoskeletons, and exo-muscular suits that can be used for physical therapy, activities of daily living (ADL), and tasks requiring augmentation of common able-bodied physical capabilities (Popovic, 2013; Popovic 2019).

There are a number of biologically inspired muscles and corresponding systems (Popovic 2019). Series Elastic Actuators (Pratt and Williamson, 1995), i.e. position controlled actuators in series with elastic elements have been used in systems (Herr et al, 2012; Blaya and H. Herr, 2014) with conventional linear actuators as well as in the context of cable driven systems (Kesner et al, 2011; Hunt et al, 2012; Galiana et al, 2012; Mao and Agrawal, 2012; Asbeck et al, 2013; Asbeck et al, 2014; Saint-Elme et al, 2017). Similarly, soft and compliant fluid actuated muscles have been actuating devices (Ueda et al, 2010; Park et al, 2014; Kurumaya et al, 2016) utilizing McKibben Muscles and devices (McCarthy et al, 2014; Sridar et al, 2016; Bowers et al, 2017) employing Hydro Muscles (Sridar et al, 2016; McCarthy et al, 2014).

McKibben muscles are currently the most popular fluidly actuated soft artificial muscles (Popovic, 2019). Unfortunately, McKibben muscles are not very efficient and cannot support a biologically realistic muscle strain (Popovic, 2019; Sridar et al, 2016; Bowers et al, 2017). The Hydro Muscle, utilized here, has excellent strain and energy efficiency properties (Miriyev et al 2017) and can closely mimic biological muscle dynamics (Popovic, 2019).

Many robotics researchers in academic settings avoid hydraulically and pneumatically operated systems in particular due to leaks, need for custom parts, and complexities associated with a fluid circulation system in which the entire system may be

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affected by local changes or disturbances. However, fluid operated systems provide many advantages, especially for wearable robotics where size and mass matter significantly. Instead of having one strong and heavy dedicated electric motor per actuated degree of freedom, here only one strong and heavy electric motor (e.g. pump) is needed for all actuated degrees of freedom.

However, valves are necessary to operate pneumatic and hydraulic systems. Valves that are cost effective, lightweight, compact, can be electronically controlled, and support a reasonable range of pressures appropriate for wearable robotics applications are not widely available on the market. The Compact Robotic Flow Control (CRFC) Valve, addressed here, was created to resolve these market shortcomings, and to work in conjunction with the Hydro Muscle system. When integrated, Hydro Muscles and the CRFC Valve have the potential for implementation in a rehabilitation robot system or a wearable assistive exosuit that is lightweight, low-cost, and has capabilities for fine control and customization.

Presented here first is an overview of the design and testing of an exosuit utilizing Hydro Muscles (Curran et al, 2018; Moffat 2019) followed by an explanation for the need for an advanced novel flow control valve in Section 2. The details of the CRFC Valve design, testing, and discussion are addressed in Section 3.

2 EXOSUIT

The biologically inspired, wearable, exo-muscular suit has been proposed as a cost-effective, fluidly actuated device for lower-limb physical therapy as well as for assistance with activities of daily living.

2.1 Exosuit: Modelling and Mechanics

The exosuit was modelled based on a lower limb skeletal structure by 3B Scientific (Functional Physiological Skeleton Model) with bungee cord ligaments that allowed for lifelike degrees of freedom.

The exo-muscular suit was modelled with 6 custom-made Hydro Muscles per each leg. This retained anatomical integrity addressed the most active biological muscles during regular gait cycle: iliopsoas, tensor fasciae latae, quadriceps femoris, gluteus maximus, hamstrings (biceps femoris and semitendinosus), and gastrocnemius. Additional passive spring structures were used to model the extensor hallucis longus muscle (providing ankle dorsiflexion), as well as the iliofemoral and ischiofemoral ligaments.

The Hydro Muscles were placed in series with tendons made out of Spiderwire (Spiderwire Stealth), a thick fishing line. The series is attached to eye hooks with threaded inserts placed at the approximated anatomical muscle origin and insertion locations (Hoy et al, 1990) (Fig. 1 and 2).

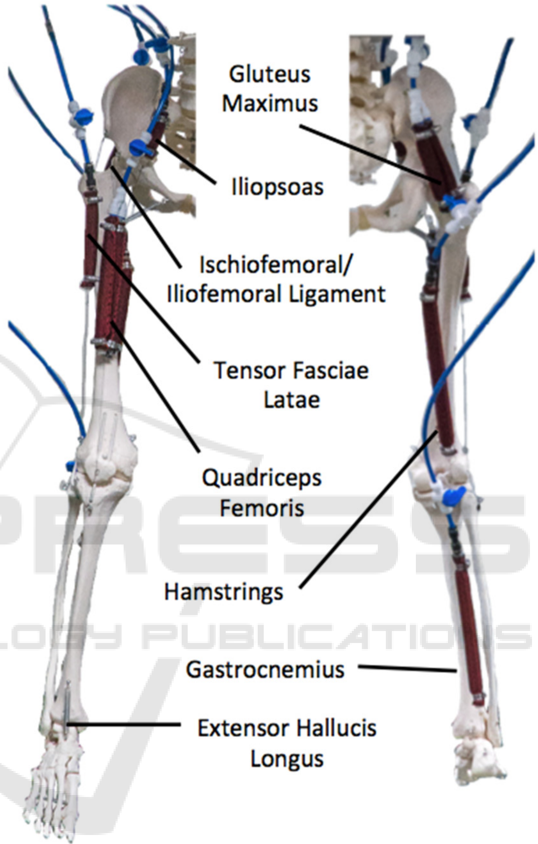

Figure 1: Exosuit muscle model.

Each Hydro Muscle length was uniquely determined for the cross sectional profile of the muscle. First, the maximal change in length of each Hydro Muscle was obtained (assuming an always slightly tensed inelastic tendon) based on average biological joint angle trajectories of 15 healthy individuals walking at a self-selected speed (Lewis and Sahrmann, 2015). Then, by relating pressure to Hydro Muscle length while assuming maximal pressure of 0.69 MPa (100 psi) the unpressurized, fully contracted Hydro Muscle length was determined.

All 6 Hydro Muscles were composed of surgical latex tubing and polyester Uber Hose (Uberhose153) sheathing. The tubing dimensions were 12.7 mm (1/2 in) outer diameter and 6.35 mm (1/4 in) inner diameter. The Hydro Muscle forces were adjusted using manual flow control valves (Elbow Pneumatic Flow Control Valve). The valve orifice was fine-tuned to provide for the most optimal force output of each muscle. After initial mechanical testing, the models gluteus maximus and quadriceps femoris were doubled up to provide more force, i.e. each of these two model muscles was added with an extra Hydro Muscle connected to the same valve as the original Hydro Muscle.

In the earlier stages of Hydro Muscle development, an electronically controlled, a 5-way on-off solenoid, pilot operated valve (Pneumatic Electric Solenoid Valve) was used in series with a manual flow control valve (Elbow Pneumatic Flow Control Valve) to direct air flow in and out of the Hydro Muscle. The gait was controlled through a state machine, in which each of the six major phases of the gait cycle was defined as a state to set each solenoid valve to high or low, to indicate that the corresponding muscle should be elongated or contracted, respectively (Table 1). The six phases for state control were obtained from eight standard biomechanics gait phases (Fig. 3) by grouping Loading Response, Mid Stance and Terminal Stance into a single phase. The state transitions were deduced by feedback supplied by Inertial Measurement Units (IMUs), (SparkFun).

The skeletal lumbar vertebra was connected via a light, elastic spring to a stand made from 80/20 T-slotted aluminum framing. A platform on the top of that stand held all of the pneumatic valves and the microcontroller (Arduino MEGA 2560). The Hydro Muscles pneumatic umbilical system consisted of 6.35 mm (1/4 in) in diameter tubing with push connects. The pressurized air was supplied from a compressed air tank operating at 0.69 MPa (100 psi). Finally, a 500W powered variable speed treadmill (Exacme 6400-0108BK Treadmill) was placed beneath.

2.2 Exosuit: Experiment

A biomimetic skeletal structure, driven by the exosuit, walked on a treadmill with the belt moving at a constant pace of 0.28 m/s (Fig. 2). Movements were recorded with IMU sensors and a high-speed camera.

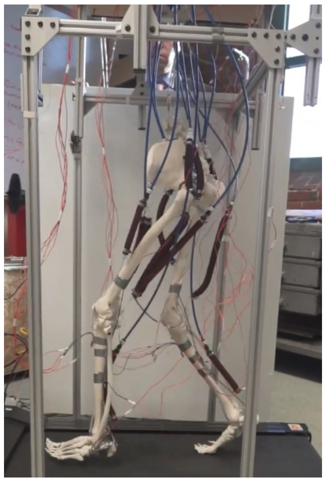

Figure 2: Biomimetic skeletal structure driven by the exosuit walking on a treadmill.

2.3 Exosuit: Results

The skeletal postures are compared (Streifeneder. Ortho lab) to biological postures (Fig. 3). The joint angle trajectories vs. percentage gait cycle are contrasted with biological gait data for normal (Lewis and Sahrmann, 2015), forward leaning (Lewis and Sahrmann, 2015), and toe (Olensek and Matjacic, 2012) walking (Fig. 4).

The stride length was 0.78 m on average. The biomimetic skeletal structure driven by the exosuit was able to stand upright on its own and the light tethering forces during the gait cycle were estimated to be less than 20% of the skeletal weight (approximately 3.3 kg) based on inverted pendulum

Table 1: Muscles' States.

Muscles' States	Heel Strike	Stance Loading-Terminal	Heel-Off	Pre-Swing	Mid-Swing	Terminal Swing
Iliopsoas	Expanded	Expanded	Expanded	Contracted	Contracted	Contracted
Tensor Fasciae Latae	Contracted	Expanded	Expanded	Expanded	Contracted	Contracted
Quadriceps Femoris	Contracted	Contracted	Expanded	Expanded	Expanded	Contracted
Gluteus Maximus	Expanded	Contracted	Contracted	Contracted	Expanded	Expanded
Hamstrings	Expanded	Expanded	Expanded	Contracted	Contracted	Expanded
Gastrocnemius	Expanded	Expanded	Contracted	Contracted	Contracted	Expanded

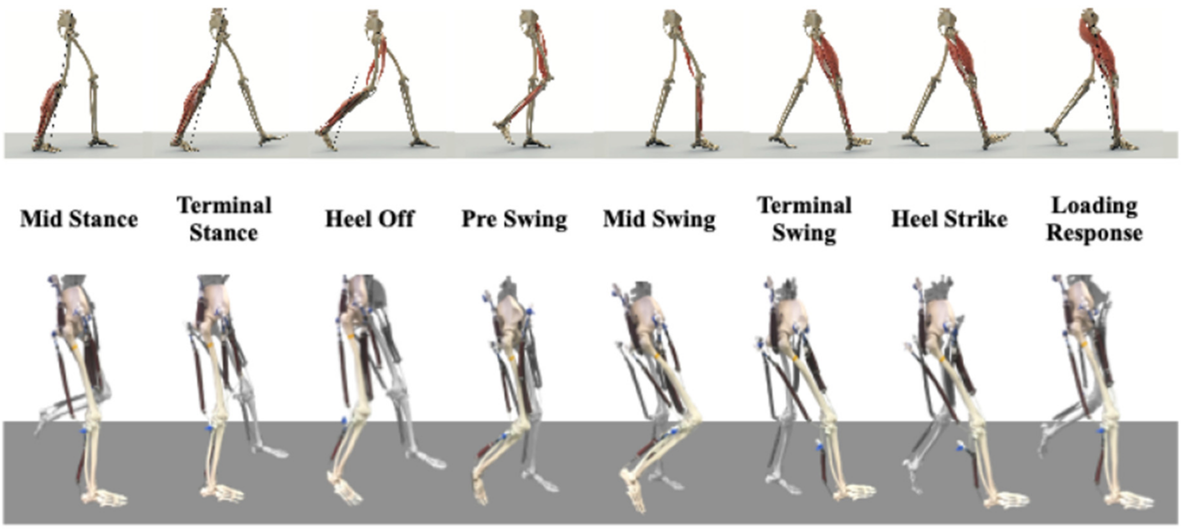

Figure 3: The eight gait phases: numerical simulation (top) and actual physical model in motion (bottom).

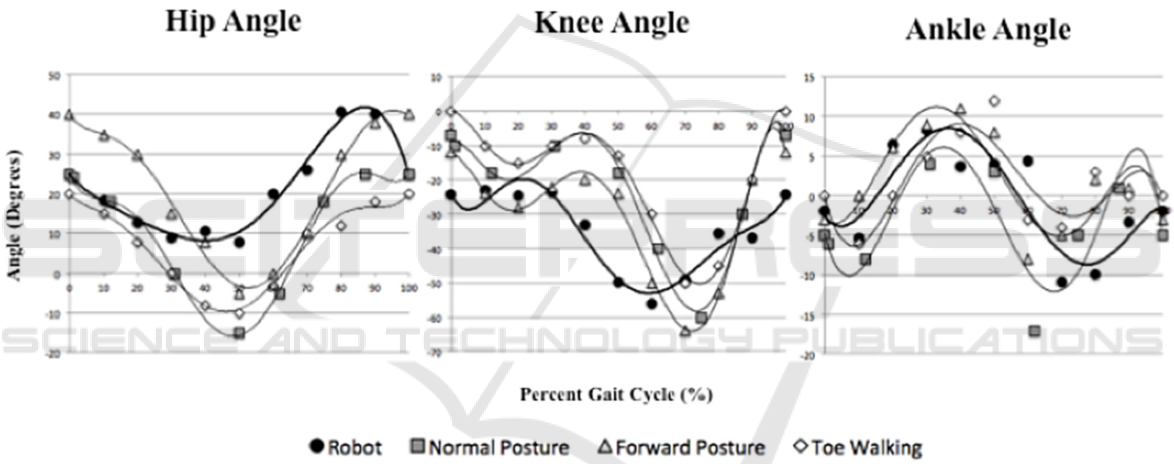

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Figure 4: Joint angle trajectories for exosuit (Robot) and biological (Normal Posture, Forward Posture, Toe Walking) gait.

dynamics and estimated Center of Pressure and Center of Mass locations.

2.4 Exosuit: Discussion

The lightly tethered biomimetic skeletal structure driven by the exosuit was able to execute multiple steps at a slow, steady pace and emulate close to human-like walking trajectories.

The gait somewhat resembles a toe walking, upper body forward leaning posture gait, similar to a downhill walking gait. This was primarily due to lack of active dorsiflexion and mechanical deficiency of the skeletal model; that is the inability of the knee to fully extend, resulting in a more bent hip in order to provide enough foot clearance. Also, motion was not as smooth due to the on-off, digital nature of solenoid valves.

This preliminary system was clearly not designed to carry the entire weight of the pneumatic system (e.g. heavy air compressor), however, this should not concern Lokomat-like applications. The Lokomat is a robotic gait training system that helps people who have suffered from various neurological or physical conditions to regain the ability to walk. In comparison to conventional Lokomat, which can resolve joint level body movements, the proposed Hydro Muscle actuated exosuit can even resolve the individual muscle level actuation. Due to cost effectiveness, the proposed Hydro Muscle actuated exosuit could possibly be available for inexpensive, at-home use. However, for more mobile wearable assistive devices, weight, size, and controllability of the fluid circulation system must be improved. Hence a closed (likely incompressible) fluid circulation system with lightweight, small, and cost-effective flow control valves is needed for an affordable, finely controlled system. The next section proposes the use of the Compact Robotic Flow Control (CRFC) Valve to meet these expectations.

3 CRFC VALVE

The Compact Robotic Flow Control (CRFC) Valve was designed, manufactured, and tested to fulfill the requirements of the exosuit's fluid flow management system.

3.1 CRFC Valve: Methods

The patent pending CRFC Valve is a simply operated flow control mechanism, with the ability to manipulate liquid and gas. It uses a servo motor attached to a choking mechanism that controls an entry and exit port for fluids (Fig. 5). The CRFC Valve consists of a servo motor, a 3D printed servo horn CAM mount, 3D printed casing, two tubes incased in fabric, and two CAM-follower beads which are connected to strings that choke off the tubing (Figure 5 and 6).

The valve is controlled by a 0.215 Nm, 0.08 sec/60 degree @6V, ~$10 USD priced servo motor (MG90D High Torque Metal Gear), which allows the CRFC Valve to quickly and robustly handle over 0.69 MPa (100 PSI) of pressure. This valve replaces and improves upon the overall performance of the previously used valve unit addressed in Section II.

Current construction of the CRFC Valve consists of a 3D printed motor and tube casing, and a curved element. The curved element is used similarly to a cam mechanism, with two spherical cam followers (beads), the servo motor, and two tubes serving as the flow channels, which allow for bi-directional fluid flow (Fig. 6). Of the two tubes, at least one or both are closed at any given point in time. One tube serves as a fluid input for an attached system, and the other tube is the release tube.

For one-directional flow operations, only one of these tubes would be necessary to serve as an inlet and outlet. On the anterior side of the valve, the two tubes merge with a Y connector to attach to the desired device. On the posterior side of the valve, the tubes are separate, allowing one to be connected to a pressurizing device, while the other releases the fluid when the tube is opened. This is the operational configuration of a three-way valve used to conduct

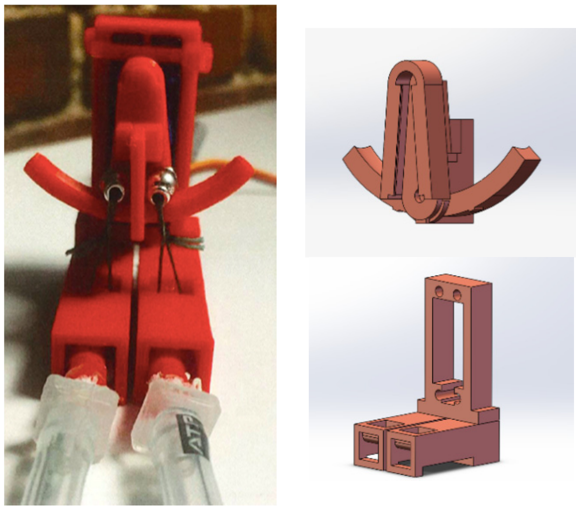

Figure 5: CRFC Valve: physical model (left) and CAD of motor casing (bottom right) and attachment (top right).

flow and control tests; however, this valve is capable of a few other operational configurations due to its mechanical layout as a two-position, parallel, two-way valve (i.e. constrained 4-way valve).

Operation of the valve involves actuating the servo motor to tilt the curved element, on which the beads roll along a smooth track (to minimize friction), so that a finely controlled choking or opening of the flow channels is achieved. String looped around each tube is attached to each corresponding bead, which allows the flow to be controlled by the angle of the servo motor. The string pulls the tubing upwards against the proximal portion of the casing, which is curved to provide a more gradual decline in the choking angle while preventing fluid flow.

The current design incorporates 5mm wide, 1mm thick surgical tubing encased in kite fabric, which prevents ballooning and the possible bursting of the tube, as well as adding additional protection against friction from the string.

In the resting state, the servo is at a neutral, symmetrical position, with Tube A and Tube B both closed, as depicted in State 2 (Fig. 6, top). This prevents flow to pass through either tube, as they are both constricted in this state. Rotating the servo counterclockwise will cause the string to loosen, allowing Tube A to open, while Tube B will remain constricted, and thus will remain closed (State 1). This will allow flow only through Tube A in this state. Rotating the servo clockwise will cause Tube B to open, but Tube A will remain closed (State 3). This will allow flow only through Tube B in this state. The range of operational servo angles change the size of the tube inlet/outlet, thus introducing intermittent, analog stages of operation and flow.

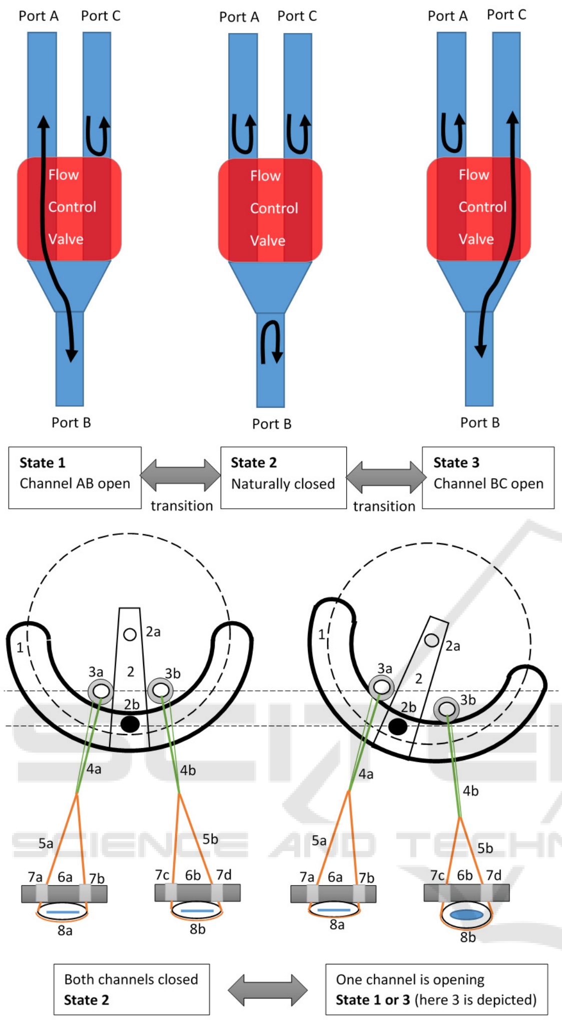

Figure 6: CRFC Valve: three states of the 3-port valve (top) and principle of operation, front view (bottom). Curved element (1, 2), CAM beads (3), Connecting strings (4, 5), Casing base with holes (6, 7), Tubes (8).

3.1.1 Optimized Geometric Model

The valve model is dependent on the necessary movement of the string to allow a tube to fully open, the strain on the string on a side that is already closed, and the desired dead-band angle for valve operation. As shown, (Fig. 6 bottom), the curved element rotation causes one bead to roll away from the valve's symmetry axis, thus reducing the distance between the bead and the string's anchor position above the tube, and allowing the tube to open.

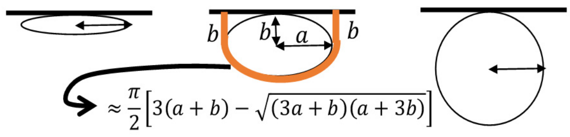

Figure 7: Tube choking - simplified elliptical model.

The total change in length needed for the tube to fully open is obtained from the elliptical model (Fig. 7) as:

$$\Delta l \approx \left\{2b + \frac{\pi}{2}\left[3(a+b) - \sqrt{(3a+b)(a+3b)}\right]\right\}_{b=0}^{b=a} \qquad (1)$$

The general valve geometric model (Fig. 8) for the initial resting state (with the servo at a neutral, zero-degree angle) can be used to relate string slackening, for the tube that is opening, and string strain, for the tube that is closed, to the servo angle for a set of specified valve parameters. This general configuration includes two separate, symmetric, curvature radii (of which only one R is shown in (Fig. 8)), and a dead band angle, which prevents the bead from rolling until points R, B, and A are collinear.

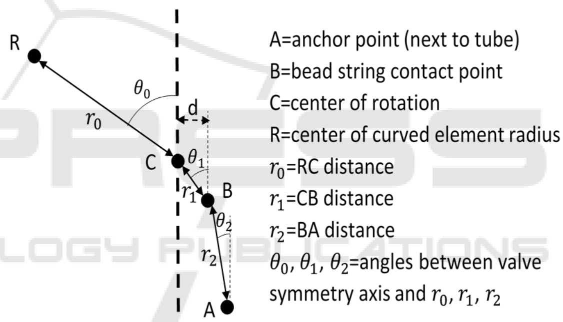

Figure 8: The general valve geometric model.

The model's parameters were optimized such that: (1) the valve volume is minimized and scaled to the appropriate operation conditions. (2) The slackening for the fully open condition is attained within a rotation range. (3) The amount of strain on the closed side is minimized. (4) The dead band is sufficient to account for servo positioning errors, to prevent undesirable flow, while not being so large as to substantially affect simple control. (5) The servo motor can have sufficient torque as to easily close the tube for the desired operational pressure.

The optimized geometric configuration has coinciding R's (Fig. 8) positioned on the valve symmetry axis, i.e. $\theta_0 = 0^o$, AB axis (r_2) parallel to the symmetry axis with $\theta_1 = 135^o, \theta_2 = 0^o$. The values for r_0, r_1, r_2 are dependent on the dimension of the tube, overall valve, and moment that servo motor can produce. As this model can be scaled, the optimization procedure can be easily reproduced with

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different tube diameters, fluid pressures, and desired valve dimensions for given servo.

The current CRFC valve has a curvature radius of 20 mm and a total operational angle span of 42 degrees that can be used to finely control flow. Its dimensions are $6cm \times 5cm \times 2cm$, though it only occupies 2/3 of that volume due to its L-like shape, and it has a total mass of only 28 grams. This compares favorably to the $12cm \times 10cm \times 2cm$, 276 gram, on-off flow control modules addressed in Section II.

3.2 CRFC Valve: Experiments

1) *Response Time*: To test system response time, end-stops were placed at the CRFC Valve's maximal operational angle and neutral position. Contact with these end-stops triggered or stopped an internal timer for the channel open and channel close movement at 100 psi of fluid pressure. Ten tests were recorded for both air and water.
2) *Flow Rate*: The flow rate across a range of servo angles was determined by taking the steady state flow rate readings at 6 degree increments from 0 (fully closed) to 42 degrees (fully open). The test setup for air consisted of a compressed air reservoir connected to a valve inlet and a digital anemometer at the outlet. Similarly, the test setup for water consisted of a 12V diaphragm pump connected to a valve inlet and a digital paddle-wheel flow meter at the outlet.
3) *Hydro Muscle speed*: To address the servo angle in relation to the Hydro Muscle elongation speed, the rate of elongation was collected with the curved valve attachment being rotated at various degrees and timing the full elongation of a 10.4cm Hydro in contracted state.
4) *Controllability*: The controllability of the CRFC Valve using both air and water were evaluated with the test setup seen in Figure 9.
A simple rigid element ('leg') was attached with a pin joint to a fixed base, and actuated by a Hydro Muscle. A desired 'leg' angular trajectory was specified in the form of absolute value of the sine function over period of 2π seconds. A simple proportional, dead-band adjusted controller was developed for control of the servo motor. The 'leg' angular displacement values were provided by a potentiometer. The same test was performed with 5-way pneumatic solenoid valve, which utilized a custom, pseudo-analog, PWM loop with a cycle time of 5 ms and a tuned P-controller.

For the air test, an air compressor maintained a constant pressure of 0.69 MPa (100 psi), and the exhaust was vented into the ambient space. For the water test, a 12V pump with an accumulator maintained steady fluid pressure in closed loop hydraulic system.

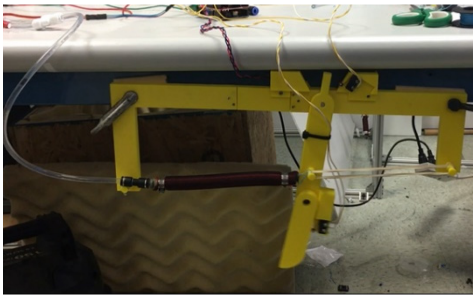

Figure 9: Test setup for controllability of CRFC Valve with 3D printed rigid element.

3.3 CRFC Valve: Results

1) *Response Time*: The average CRFC Valve response times for both air and water at 0.69 MPa (100 PSI) are shown in Table 2. According to information obtained directly from the manufacturer, the specified solenoid valve has a response time between 1 and 2 seconds to fully transition between closed and open states.
2) *Flow Rate*: The flow rate vs servo angle (Fig. 10).
3) *Hydro Muscle Speed*: The result of test relating servo angle to the Hydro Muscle elongation speed exhibits R^2-value of 0.967 (Fig. 11).
4) *Controllability*: The results of the controllability experiments (Fig. 12).

Table 2: CRFC Valve response time for full state transition.

Response	Open to Closed	Closed to Open
Water	75 ms	70 ms
Air	70 ms	65 ms

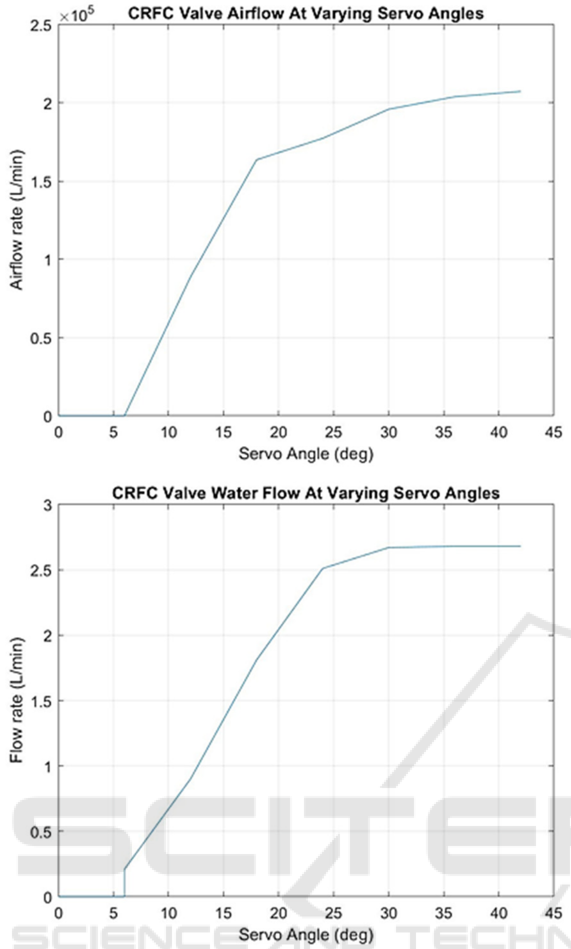

Figure 10: Flow vs. angle; water (bottom) and air (top).

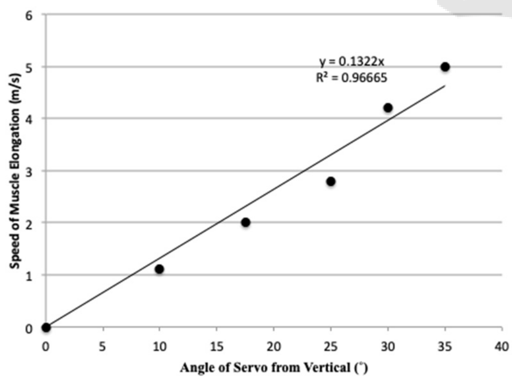

Figure 11: Hydro Muscle speed vs. servo angle.

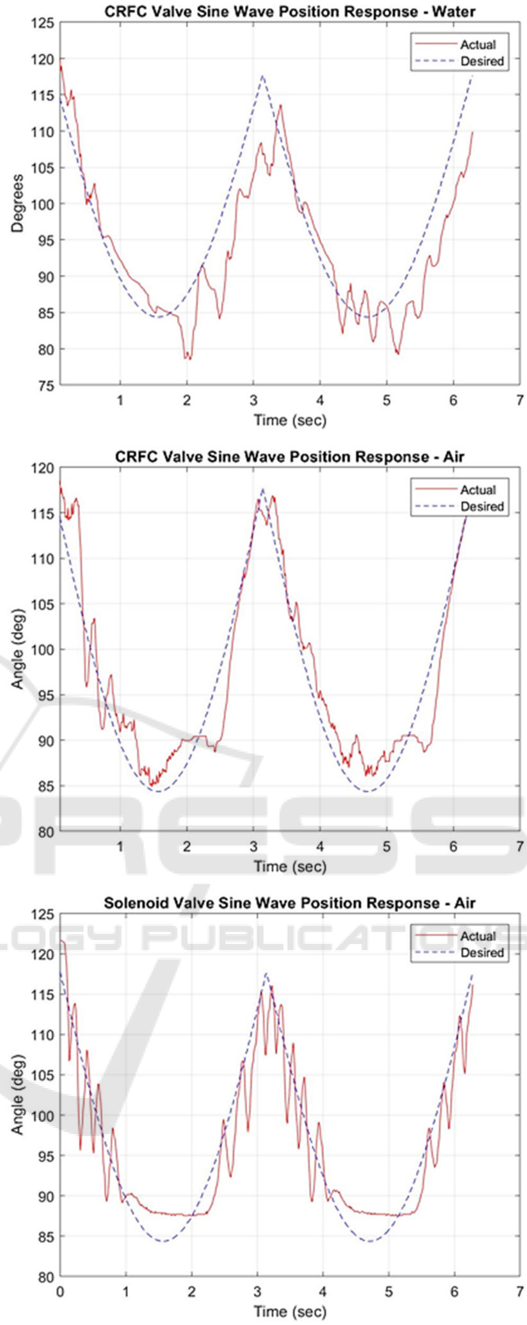

Figure 12: Controllability tests: water CRFC Valve (top), air CRFC Valve (middle), air solenoid valve (bottom).

3.4 CRFC Valve: Discussion

The exosuit, addressed in Section II utilized heavy 12cm by 10cm by 2cm on-off flow control modules [26,27] that had a pre-set orifice size. When the exosuit was first constructed, these were the most practical, affordable solution on the market. To

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address already specified limitations of such flow management system, the CRFC Valve was created.

This new valve is small, lightweight, cost-effective, and can operate using both air and liquid. The new CRFC valve takes up only 1/6th of the original valve's volume, and has a mass of only 28 grams (i.e. 1/10th of the original weight). Additionally, the CRFC Valve exhibits a relatively fast response time with very little difference between water and air mediums.

Based on reviews of commercially available valves (ASCO, Engineering Solutions), the quick response times for fully opening and fully closing of 4-8 mm inner diameter, commercially available, pilot solenoid valves operating at ~100 PSI air pressure range from 10ms to 20ms and 20ms to 80ms respectively. In the case of liquids these ranges are typically 15ms to 30ms, and 30ms to 120ms respectively. The valves with these parameters are typically valued at greater than $100 USD.

In comparison, the CRFC valve costs about $10 USD to produce. The full closing and opening times for the same conditions are approximately 65ms for air and 70ms for water. Additionally, the CRFC Valve allows for continuous fine control of flow. The CRFC Valve's speed is well suited for wearable robotic actuation systems, as it takes about 250ms for a skeletal biological muscle to develop a peak force.

The CRFC flow is reasonably large with $> 2.5 l/min$ and $> 2 \times 10^5\ l/min$ for water and air respectively. The flow can be increased by using different tube dimensions. The flow results exhibit a 6^o deadband angle, which addresses potential servo inaccuracies and introduces control delays. Before it saturates, the flow is roughly proportional to valve angle.

The result of the test relating servo angle to the Hydro Muscle elongation speed exhibits an R^2-value of 0.967. There is a strong linear relationship between flow rate and servo angle. This largely linear behavior is a characteristic of an optimized valve design. This linear control of the flow allows for better control of the Hydro Muscle than with the original on-off solenoid valve.

The CRFC Valve operating with air has a more precise and accurate tracking than the original 5-way on-off solenoid valve. There was significantly less oscillation in the CRFC Valve tests when compared to the original solenoid valve due to the CRFC Valve's mechanism preventing sharp, jerky movements. While both valves had oscillations, the CRFC Valve's were mainly due to sensor noise, while the solenoid valves oscillations were due to the 2-state nature of the valve. However, with improved sensors and a revised control scheme, the response of the CRFC Valve could be drastically improved.

From the response tests of the CRFC Valve, it is clear that the choice of fluid impacts the response of the system, however, the valve is still able to follow the desired trajectories in a smooth and controlled manner. The main issue in the system operating with water was the inexpensive diaphragm pump being used. The pump would frequently turn on and off, hence creating an oscillatory behavior throughout the system; it is likely that with improved system components the results would be more indicative of the valves capabilities. Additionally, due to the CRFC Valve's significantly reduced size and weight, the exosuit has improved portability.

Due to the precise control over the fluids in the actuators, the design has potential to create highly controllable robotic systems.

4 CONCLUSIONS

The bioinspired exosuit strives to be a cost-effective, fluidly actuated, wearable robotic device that can be used for physical therapy and/or assistance with activities of daily living. The bioinspired exosuit has been designed, manufactured, tested on a lightweight biomimetic human skeletal model. This initial study motivated a need for better flow management system, which inspired the creation of the CRFC Valve.

The CRFC Valve is lighter, more compact, more controllable, and less expensive than any other similar valve currently on the market. Now that the CRFC Valve has been developed, future work will be focused on constructing a wearable exosuit with the CRFC Valves. Other applications for the CRFC Valve will also be explored. The synergy of the CRFC Valve with the cost-effectiveness, energy efficiency, and excellent strain properties of Hydro Muscle opens a door into a new age of very interesting, useful, and accessible/affordable fluid operated wearable robotics solutions.

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