Biologically Inspired Legs and Novel Flow Control Valve Towards a New Approach for Accessible Wearable Robotics

A Thesis
Submitted to the Faculty
of the
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfillment of the requirements for the
Degree of Master of Science
in
Robotics Engineering
by

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Date: 4/18/19

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Abstract

The Humanoid Walking Robot (HWR) is a research platform for the study of legged and wearable robots actuated with Hydro Muscles. The fluid operated HWR is representative of a class of biologically inspired, and in some aspects highly biomimetic robotic musculoskeletal appendages showing certain advantages in comparison to more conventional artificial limbs and braces for physical therapy/rehabilitation, assistance of daily living, and augmentation. The HWR closely mimics the human body structure and function, including the skeleton, ligaments, tendons, and muscles. The HWR can emulate close to human-like movements even when subjected to simplified control laws. One of the main drawbacks of this approach is the inaccessibility of an appropriate fluid flow management support system, in the form of affordable, lightweight, compact, and good quality valves suitable for robotics applications. To resolve this shortcoming, the Compact Robotic Flow Control Valve (CRFC Valve) is introduced and successfully proof-of-concept tested. The HWR added with the CRFC Valve has potential to be a highly energy efficient, lightweight, controllable, affordable, and customizable solution that can resolve single muscle action.

Acknowledgements

I would like to acknowledge the invaluable work of Julia D'Agostino and Ellen Clarrissimeaux in supporting the research and development of the Compact Robotic Flow Control Valve and its implementation with the Humanoid Walking Robot.

I would also like to acknowledge the previous contributions of Mariah Sullivan, Kenneth Colpritt, and Andrew Curran to the original Humanoid Walking Robot prototype.

Thank you to my project advisor, Professor Marko Popovic, for his support and lab resources, and to my co-advisors Professor Selcuk Guceri and Professor Michael Gennert for investing their time in the completion of this project.

Executive Summary

Form and function are naturally intertwined, making biologically inspired robotics following the human body structure an attractive direction for the advancement of prosthetic artificial limbs as well as braces, exoskeletons, and exomusculatures for physical therapy, activities of daily living (ADL), and tasks requiring augmentation of the regular human physical capabilities. Presented here is an example of a fluid operated biologically inspired Humanoid Walking Robot (HWR) and a Compact Robotic Flow Control Valve (CRFC Valve) that may address limitations in the current valve market. Together, the HWR and CRFC Valve have potential implementations in a successful rehabilitation robot system or wearable exoskeleton that is lightweight, low-cost, and has capabilities for fine control and customization.

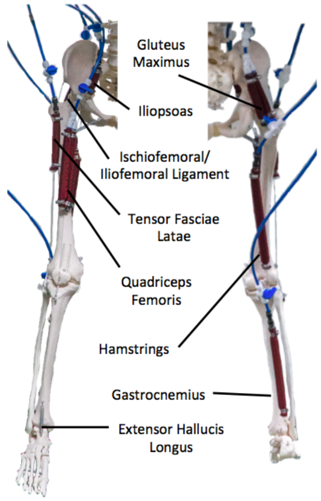

Figure 1: Muscle Placements on skeletal model for HWR.

The HWR uses a lower limb skeletal structure modelled with 6 custom-made Hydro Muscles and passive ligament structures per each leg retaining anatomical integrity and addressing the most active biological muscles during regular gait (Fig. 1). An on-off solenoid valve in series with a manual flow control valve directed air flow in and out of the Hydro Muscle. Since the solenoid valves functioned digitally, the manual flow control valves were necessary to produce a smoother motion, allowing the muscles to contract more slowly by controlling the size of the orifice through which air would flow back into the atmosphere. The joint angle trajectories of the lightly tethered HWR walking on a treadmill moving at a constant pace of 0.28 m/s were analyzed using IMU data and stereophotogrammetric techniques, and were found to be comparable to biological gait trajectories. The HWR was not designed to carry entire weight of the pneumatic system, which should not concern Lokomat-like applications in physical therapy with patients exercising on a treadmill while wearing a Hydro Muscle based exo-musculature at a hospital or at home. In comparison to conventional Lokomat, which can resolve joint level body movements, the proposed Hydro Muscle actuated exomusculature can even resolve the individual muscle level actuation. Still further, due to cost effectiveness, the proposed Hydro Muscle actuated exomusculature can also be affordable for at-home use.

For stand-alone humanoid robot applications and for more mobile wearable assistive devices with humans in the loop, however, it appears critical that weight, size, and controllability of the fluid circulation system be improved. The described HWR pneumatic system uses 12 cm by 10 cm by 2 cm, 276.2g, on-off flow control modules operating individual Hydro Muscles. To address these deficiencies and address humanoid robot and wearable assistive device applications, the patent pending CRFC Valve was designed, built, and proof-of-concept tested.

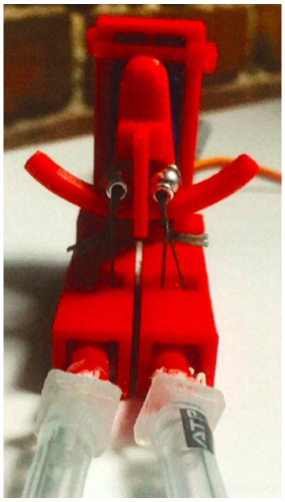
Figure 2: Compact Robotic Flow Control Valve.

The valve uses a servo motor attached to a choking mechanism that controls an entry and exit port for fluids (Fig. 2). The valve is meant to have three distinct states: (1) The servo horn is at neutral position, with both ports closed, (2) The servo horn rotates in the clockwise direction, with the right-side port open and left-side port closed, and (3) The servo horn rotates in the counterclockwise direction, with the left-side port open and right-side port closed. The rotation of the servo proportionally widens or narrows the orifice, thereby changing the fluid flow velocity. This relationship was found to be linear. The angle of rotation is also linearly related to the average elongation rate of the Hydro Muscle.

In comparison to the original solenoid valve system, the new CRFC Valve system takes up less than a volume of 6cm by 5cm by 2cm and has a mass of just 28.5g. The compact and lightweight design of the valve allows for more wearable applications. There is potential to expand Hydro Muscles and soft robotics within a variety of fields, and the CRFC Valve enables these technologies to be more compact and comfortable for the user. The CRFC system is $1/10^{\text{th}}$ of the weight and is $1/6^{\text{th}}$ of the volume of the original HWR pneumatic system. In addition, the CRFC Valve is also incredibly easy and cost-effective to manufacture. The cost of the valve with a standard high-torque servo is around $14 USD.

The musculoskeletal approach to the Humanoid Walking Robot and the innovative design of the Compact Robotic Flow Control Valve, when combined, show potential to inspire a new class of wearable robotics, in particular rehabilitation robotics, prosthetic limbs, and assistive devices for ADL or augmentations of human physical capabilities.

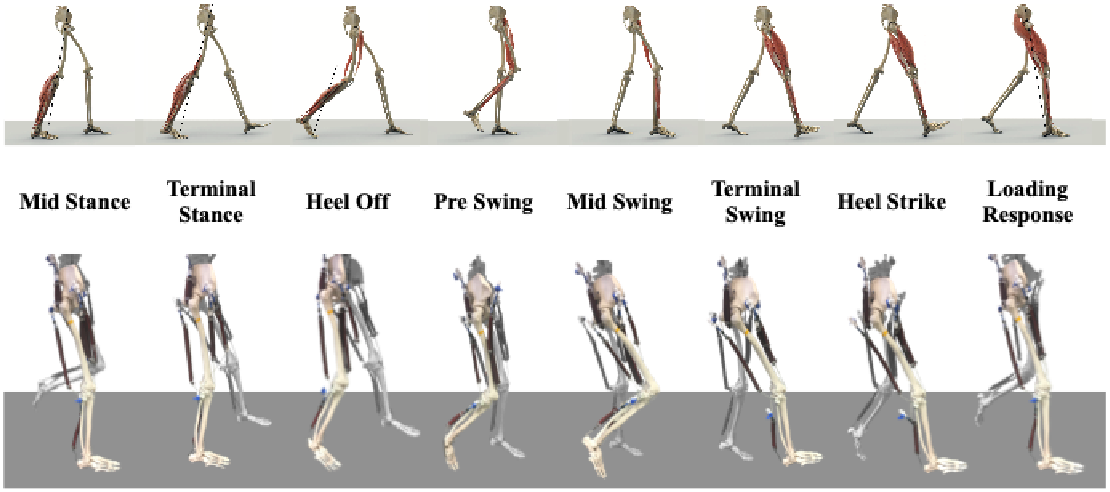

Figure 3: HWR driven through biologically realistic joint trajectories: computer model (top) and physical prototype (bottom).

The biologically similar trajectories (Fig. 3) show that this approach could be effectively used in gait training, and could even be customized to target specific muscle functions. In addition, this system would be affordable, lightweight, and comfortable, making them ideal for interfacing with the human body; the system has the potential for commercial, technological, and social value due to its accessibility and innovation. The CRFC Valve can have numerous applications in a wide variety of fields that all require fine control of fluid flow and that clearly may benefit from a lightweight, compact, and cost-effective valve; e.g. medical and pharmaceutical industry, military, automotive, aerospace, agriculture, civil engineering, oil and gas, etc. The synergy of the CRFC Valve with the cost-effective, energy efficient, and excellent strain properties Hydro Muscle opens a door into a new age of very interesting, useful, and accessible/affordable fluid operated robotics solutions.

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Chapter 1

Introduction

1.1 Background and Motivation

Robots are anticipated to work alongside humans while being able to address even very delicate tasks like nursing infants or tending to the elderly [1, 2]. Wearable robotics in particular are often approached with the idea that the robot should be thought of as a true extension of the human body.

Because form and function are naturally intertwined, biologically inspired robotics following the human body structure is an attractive direction for the advancement of prosthetic artificial limbs as well as braces, exoskeletons, and exomusculatures [3, 4, 5] for physical therapy, activities of daily living (ADL), and tasks requiring augmentation of the regular human physical capabilities.

There are a number of biologically inspired muscles and corresponding systems including those that utilize more conventional position controlled actuators in series with elastic elements, like Series Elastic Actuators [6, 7, 8], cable driven systems also added with elastic elements [9-14], and inherently soft and compliant fluid actuated muscles like McKibben [15-17] and Hydro Muscles [4, 18, 19].

Many robotics researchers in academic settings avoid hydraulically and pneumatically operated systems in particular because of the nuisance of leaks, need for custom parts, and complexities associated with fluid circulation system where the entire system may be affected by local changes or disturbances. However, on another hand, fluid operated systems also provide many advantages especially for wearable robotics where size and mass really matter. 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, cost effective, lightweight, and small valves that can be electronically controlled with short response times and that can support a reasonable range of pressures appropriate for wearable robotics applications are still an issue; judging based on what is currently offered on the market, all above mentioned characteristics can still be drastically improved.

1.2 Scope

The scope of this project includes the implementation of the Compact Robotic Flow Control Valve with the Humanoid Walking Robot to explore new techniques in wearable robotics.

The objectives for this project are as follows:

1. To design a functional bio-inspired bipedal robot actuated by HydroMuscles.
2. To demonstrate the application of HydroMuscles in wearable robotics.
3. To develop a fluid flow control valve that is small, lightweight, affordable, and implements proportional flow control.

4. To demonstrate a proof of concept of the implementation of Hydro Muscles and flow control valves in wearable robotic applications.
5. To construct a robotic platform for future research on accessible, wearable, soft robotics.

1.3 Overview

Presented here is an example of a fluid operated biologically inspired humanoid legged platform that can branch off in the future either in the direction of more biomimetic custom built artificial limbs or braces for therapy as well as assistance with ADL. This is an attractive direction as an assistive system may resolve even individual muscle level (vs. joint level as with conventional systems) and could also drive prices down. Hydro Muscles [4, 18, 19], which have excellent strain and energy efficiency properties [20], were utilized here.

Closely related work to the one presented here is the work of Park et al. [16] and Kurumaya et al. [17] which both utilized the McKibben type of artificial muscles. Unfortunately, McKibben muscles are not very efficient and they cannot support biologically realistic muscle strain (Fig. 1.1) [2, 18, 19]. The Hydro Muscle, utilized here, performs much better in that respect (Fig. 1.2). Initial exploration of the Humanoid

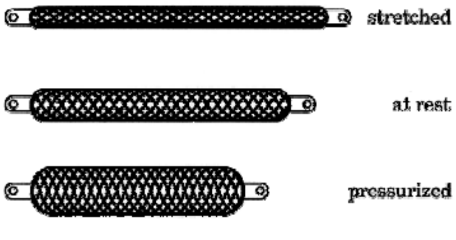

Figure 1.1: McKibben Muscle.

Figure 1.2: Hydro Muscle.

Walking Robot was conducted by student researchers beginning in 2017 [21].

Presented here is also an example of a Compact Robotic Flow Control Valve that may address the above mentioned issues. When integrated, Hydro Muscles and appropriate valves have the potential for implementation in a successful rehabilitation robot system or wearable exoskeleton that is lightweight, low-cost, and has capabilities for fine control and customization. This paper will describe the design and testing of a Musculoskeletal Humanoid Walking Robot and a pneumatic Compact Flow Control Valve, and will explore the implications for accessible clinical and at-home applications.

Chapter 2

Methodology

2.1 Humanoid Walking Robot (HWR)

2.1.1 Design and Build

The HWR uses a lower limb skeletal structure by 3B Scientific [22] with bungee cord "ligaments" allowing for lifelike degrees of freedom. The leg musculature was modelled with 6 custom made Hydro Muscles [4, 18] per each leg retaining anatomical integrity and addressing the most active biological muscles during regular gait: iliopsoas, tensor fasciae latae, quadriceps femoris, gluteus maximus, hamstrings (biceps femoris and semitendinosus), and gastrocnemius. Hydro Muscles could also be used to model other muscles if a more elaborated approach is required, or if a different range of motion were desired.

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, in series with "tendons", that is thick fishing line, Spiderwire [23], were attached to eye hooks with threaded inserts placed at the approximated anatomical muscle origin and insertion locations [24] (Fig. 2.1).

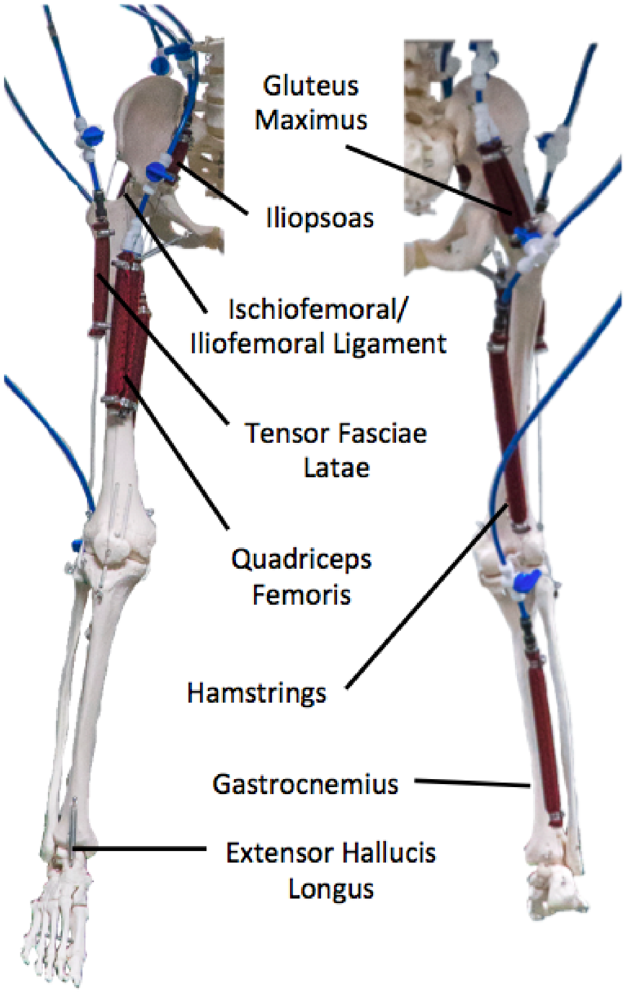

Figure 2.1: Muscle Placements on skeletal model for HWR.

Each Hydro Muscle length, for the chosen Hydro Muscle cross sectional profile, was uniquely determined. First, the maximal change in length of each Hydro Muscles was obtained (assuming always slightly tensed inelastic "tendon") from average biological joint angle trajectories of 15 healthy individuals walking at a self-selected speed [25]. Then, by relating pressure to Hydro Muscle length [18] while assuming maximal pressure of 0.69 MPa (100 psi) the unpressurized, fully contracted Hydro Muscle length was determined.

All 6 Hydro Muscles, composed of surgical latex tubing and polyester sheathing, had identical cross sections; the tubing dimensions were 12.7 mm (1/2 in) outer diameter and 6.35 mm (1/4 in) inner diameter. Uber Hose [26] sheathing fitted snugly with the tubing.

The Hydro Muscle forces were adjusted using manual flow control valves [27]. 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.

2.1.2 Pneumatic System

An on-off solenoid valve [28] in series with a manual flow control valve [27] directed air flow in and out of the Hydro Muscle (Fig. 2.2). Each of these valve configurations weighed about 280 grams, with each of the twelve muscles requiring its own valve. Since the solenoid valves used functioned digitally, the manual flow control valves were necessary to produce a smoother motion, allowing the muscles to contract more slowly by controlling the size of the orifice through which air would flow back into the atmosphere.

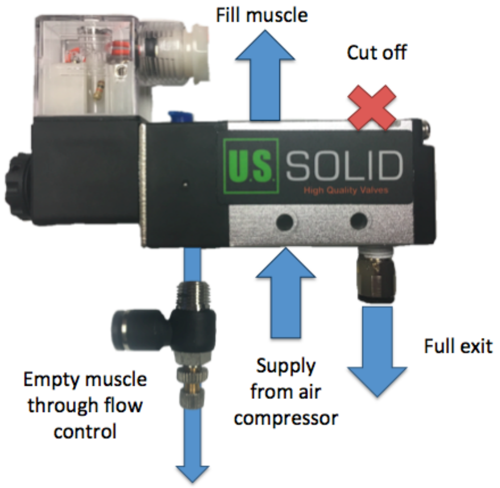

Figure 2.2: Solenoid valve configuration.

The HWR's gait was controlled through a state machine, in which each of the 6 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 2.1). The 6 phases for state control were obtained from 8 standard biomechanics gait phases, by grouping Loading Response, Mid Stance and Terminal Stance into a single phase.

Table 2.1: Muscle Contraction in Phases of Gait Cycle

Muscle	Heel Strike	Stance	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

The state transitions were controlled by position feedback supplied by Inertial Measurement Units (IMUs) [29] equipped with gyroscopes and accelerometers. Data from these sensors was analyzed to report the joint angles and orientation of the legs [30] and assist in deducing transitional time.

The HWR's lumbar vertebrae 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 Arduino MEGA 2560 microcontroller [31]. 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 the compressed air tank, placed next to the stand, operating at 0.69 MPa (100 psi). The Hydro Muscles were vented into the atmosphere. Finally the 500W powered variable speed treadmill [28] was placed beneath the HWR.

Here, the manual flow control valve [27] was necessary for the control of the Hydro Muscles' contraction speed and force output. However, instead of using a manual control valve with fixed orifice in series with an on-off solenoid valve controlled in real time, a single continuous flow control valve controlled in real time might be even more beneficial. The HWR and natural extensions of the HWR concept in the form of a musculoskeletal wearable exoskeleton or an exomusculature can be all advanced with a lightweight and small, autonomous flow control mechanism. Hence, a new Compact Robotic Flow Control Valve is proposed next.

2.2 Compact Robotic Flow Control (CRFC) Valve

The patent pending Compact Robotic Flow Control Valve (CRFC Valve) is a simply operated flow control mechanism, with the ability to manipulate liquid and gas. The CRFC Valve uses a servo motor attached to a choking mechanism that controls an entry and exit port for fluids (Fig. 2.3).

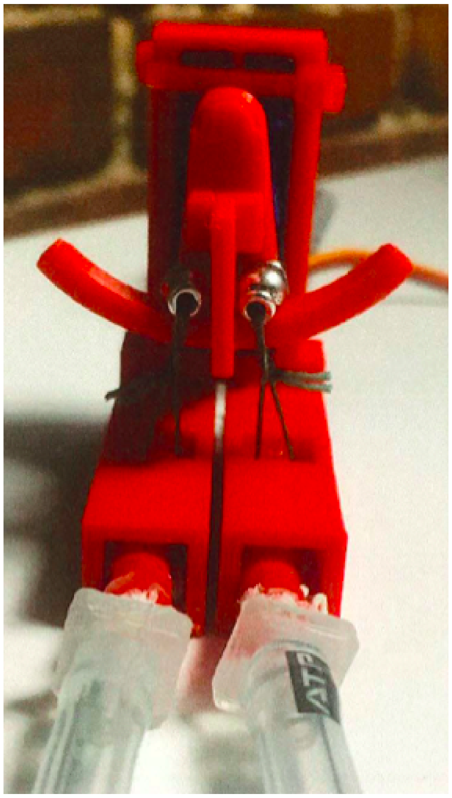

Figure 2.3: Compact Robotic Flow Control Valve.

2.2.1 Design Specifications

The goal for the CRFC Valve was to make it more lightweight and cost-effective than the originally used solenoid valves, and for it to have the capability for proportional flow control. Table 2.2 shows the minimum design specifications for the CRFC Valve.

With these specifications, the CRFC Valve can be used to address limitations in the valve market in many different flow control applications, such as soft robotics, agriculture, medicine, and/or housing utilities. The CRFC Valve is a more cost-effective, versatile, compact, and lighter alternative to the current valves within the industry.

Table 2.2: Design Specifications

Parameter	Original Solenoid Valve	Specification for CRFC Valve
Mass	280 grams	Less than 280 grams
Size	240 cm^2	No more than 240 cm^2
Cost	\$20	No more than \$20
Control	On/Off Control	On/Off Control and Proportional Control

2.2.2 Design Elements

The CRFC Valve began as a rudimentary design with an entry port, an exit port, and a merged port to be connected to the fluidic actuator. The elements of the design were developed to utilize a choking mechanism controlled by a simple micro servo motor.

Micro Servo

The micro servo was to be used as the main actuator for the valve, as it is lightweight, can supply relatively large amounts of torque, and can be finely controlled. Several different servo motors were tested, with stall torques ranging from 1.6 kg-cm to 5.8 kg-cm, weights ranging from 9 g to 20 g, and required voltages ranging from 3 V to 7.4 V. All motors were shown to be effective in providing enough torque for the choking mechanism.

Tube Casing

Thin-walled surgical tubing was used to transport the fluid in the valve due to its elasticity and strength. Since pressurized fluid would be flowing through the tubes, they were encased in a sewn fabric sheath made of smooth kite material. This material would prevent the latex tube from ballooning and reduce friction against the tube for the choking mechanism.

The choking mechanism involved a string looped around each of the tubes. After testing with air pressurized to 0.69 MPa (100 psi), it was found that a single crossed loop around the tube required the least amount of force to completely close the orifice.

Another element that was adjusted to optimize the required forces was the surface against which the string pulled the tubing. Many different profiles were tested, from flat, to dome-shaped, to pointed, to indented. It was determined that a slightly curved indented profile required the least amount of force to completely seal the tubing, since it created a more gradual decline in the angle of choking.

Curved Component

The main element for the choking mechanism was the curved component to be attached to the servo horn. On the sides of the curved component were two "wings", around which the string would be looped so that it could pull the tubes closed. As the servo horn would rotate, the distance between this loop and the tubing would change, allowing the tension to increase or decrease to change the size of the tube's orifice. Small metal beads were used on the loop to prevent friction against the curved component. The curved "wings" provided a track for the grooved beads to roll along without risk of falling off.

2.2.3 Final Prototype

The current model of the CRFC Valve can handle over 100 psi of pressure, increasing with the torque of the servo being used. The 3D printed casing holds the servo motor, which operates as the main actuator of the device, and two tubes, which allow for bi-directional fluid flow (Fig. 2.4). One tube is the entry port, where fluid can be pumped in to an attached device, and the other is the release tube, where the fluid can be pumped out. For one-directional flow operations, only one of these tubes would be necessary. On the anterior side of the valve, the two tubes merge with a Y-connector to attach to the device. On the posterior side of the valve, the tubes are separate, allowing one to be connected to a pressurizing device, while the other is able to release the fluid when the tube is opened.

String looped around each tube is pulled by the rotating servo to open and close the ports. When tension is added to the string, it pulls the tubing upwards against the proximal portion of the casing, which has a slightly curved profile. Pulling the tube around this element seals the tube and prevents fluid from escaping. The semi-circle element also creates a more gradual decline in the angle of choking, taking some pressure off of the tube component. Each tube is made of 5mm wide, 1mm thick surgical tubing encased in kite fabric. The kite fabric prevents the ballooning and possible bursting of the tube, as well as adding additional protection against friction from the string.

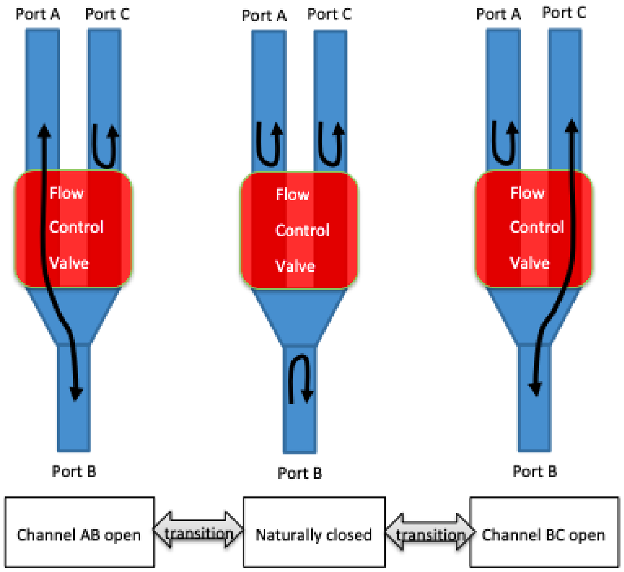

Figure 2.4: CRFC Valve states.

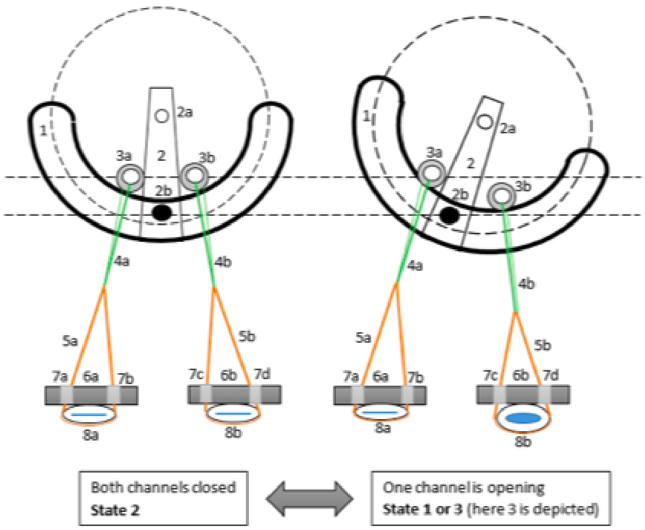

Figure 2.5: Inlet opening due to servo rotating curved component.

To prevent excessive tension in the string, a 3D printed curved attachment was made to fit over a standard servo horn for the strings to loop around (Fig. 2.5). The curved attachment includes a track for small metal beads to roll along to minimize friction in the system. When the servo angle changes, the string tension will change to alter the size of the inlet opening of the inner latex tubing.

The curved profile was approximately calculated to prevent excessive string tension when the tubing is closed, but to allow sufficient slackening of the string to allow the tubing to open fully. Equations (2.1)-(2.5) and Figure 2.6 display the parameters used and calculations performed to customize the valve. These equations yield an expression for the profile of the curved component, with an arc radius of 20 mm and a total angle span of about 50 degrees.

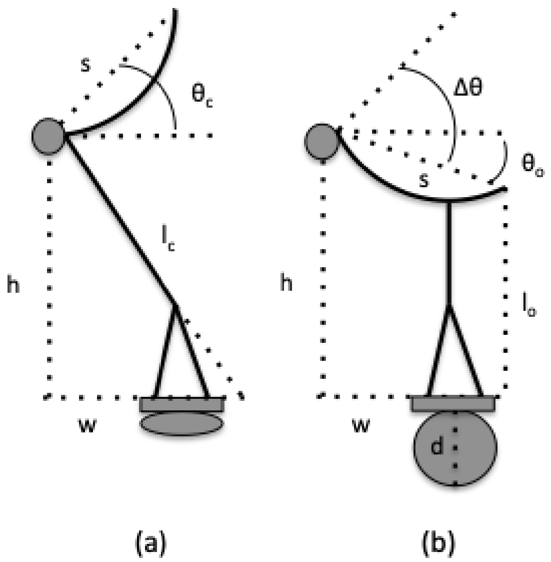

Figure 2.6: Simplified valve geometry for Curved Profile, with valve closed (a) and open (b).

$$l_o = l_c - d_t \tag{2.1}$$

$$s = \sqrt{(h - l_o)^2 + w^2} \tag{2.2}$$

$$\phi_c = 2arcsin(s/2r) \tag{2.3}$$

$$\phi_o = arcsin((h - l_o)/s) \tag{2.4}$$

$$\Delta\phi = \phi_c - \phi_o \tag{2.5}$$

In the resting state, the servo is at a neutral, symmetrical position, with Tube A and Tube B both closed, depicted as State 2 in Figure 2.5. Rotating the servo counter-clockwise will cause Tube A to open (State 1), while rotating the servo clockwise will cause Tube B to open (State 3). Different angles that the servo moves can control the size of the tube inlet/outlet, introducing intermittent, analog stages.

The valve has dimensions of 6cm x 5cm x 2cm, though it only occupies 2/3 of that volume, and has a total mass of 28.5 grams. The power requirements and angular speed are dependent on the servo being used; in this prototype, the servo used had a speed of 13.09 rad/s (0.08 seconds per 60 degrees of rotation) when operated at 6 volts [32].

Chapter 3

Experiments

3.1 Humanoid Walking Robot Gait

The movements of a lightly tethered HWR walking on a treadmill with a belt moving at a constant pace of 0.28 m/s were recorded using IMU sensors and high speed camera (Fig. 3.1).

Figure 3.1: HWR setup.

3.2 Compact Robotic Flow Control Valve

The flow characteristics of the CRFC Valve were determined through experiments with the valve independently, and with the valve interfaced with the Hydro Muscle.

3.2.1 Flow Testing

First, a CFM/CMM Thermo-Anemometer was used to measure the speed of air flow while the servo motor moved to different positions. To keep each test consistent, the valve was kept at the same distance from the sensor in a controlled environment that would not affect the flow reading. The valve was tested with 0.69 MPa (100 psi) of air pressure, the air pressure typically used with Hydro Muscles.

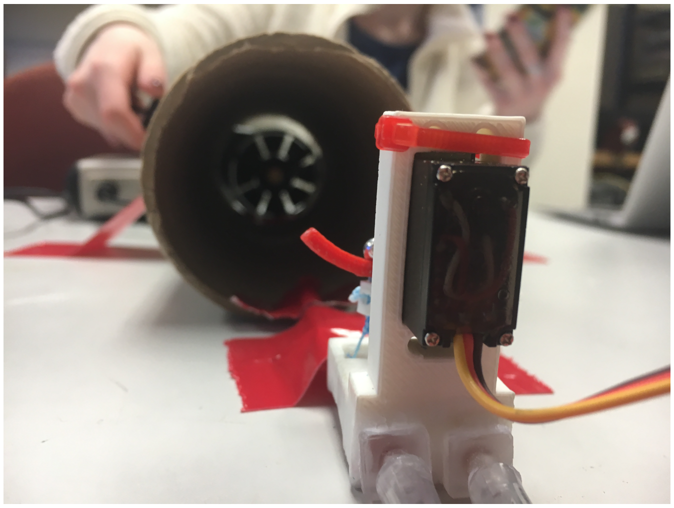

Figure 3.2: Experimental setup for CRFC Valve flow testing.

3.2.2 Muscle Elongation Rate

The CRFC Valve was originally synthesized to work in conjunction with the Hydro Muscle; therefore, an experiment was conducted to determine the relationship between the servo angle and the elongation rate of the Hydro Muscle (Fig. 3.3). This experiment was performed by turning the valves to various angles, and timing the full elongation of a Hydro Muscle with a length of 10.4 cm in its contracted state, modeled after the gastrocnemius.

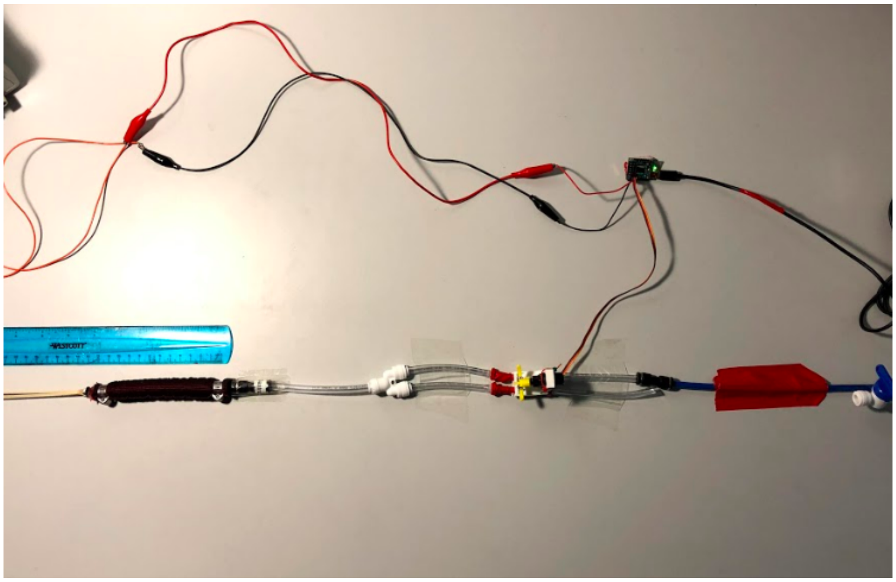

Figure 3.3: Experimental setup to analyze Hydro Muscle elongation rate.

3.2.3 Joint Actuation

The valve was also interfaced with the HWR using the gastrocnemius Hydro Muscle to demonstrate the valve's control capabilities with a robot limb. The servo was manually controlled to span the entire range of angles, while an IMU mounted to the lower limb reported the orientation of the leg throughout the motion. The servo was moved back and forth to switch between each state, and was moved at different speeds to show the effect of the inlet/outlet size on the muscle elongation rate.

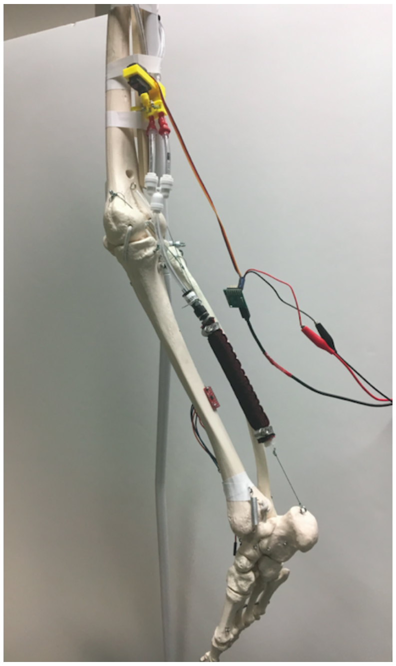

Figure 3.4: CRFC Valve actuating HWR knee joint.

Chapter 4

Results

4.1 Humanoid Walking Robot Gait

The joint angle trajectories of the lightly tethered HWR walking on a treadmill moving at a constant pace of 0.28 m/s were analyzed using IMU data and stereophotogrammetric techniques. The HWR postures are visually compared to postures based on biological data [33] (Fig. 4.1). The HWR joint angle trajectories vs. percentage gait cycle are also contrasted with biological gait data for normal [25], forward leaning [25], and toe [34] walking (Fig. 4.2). The HWR stride length was 0.78 m in average. The robot 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 HWR weight (approximately 3.3 kg) based on inverted pendulum dynamics and estimated Center of Pressure and Center of Mass locations.

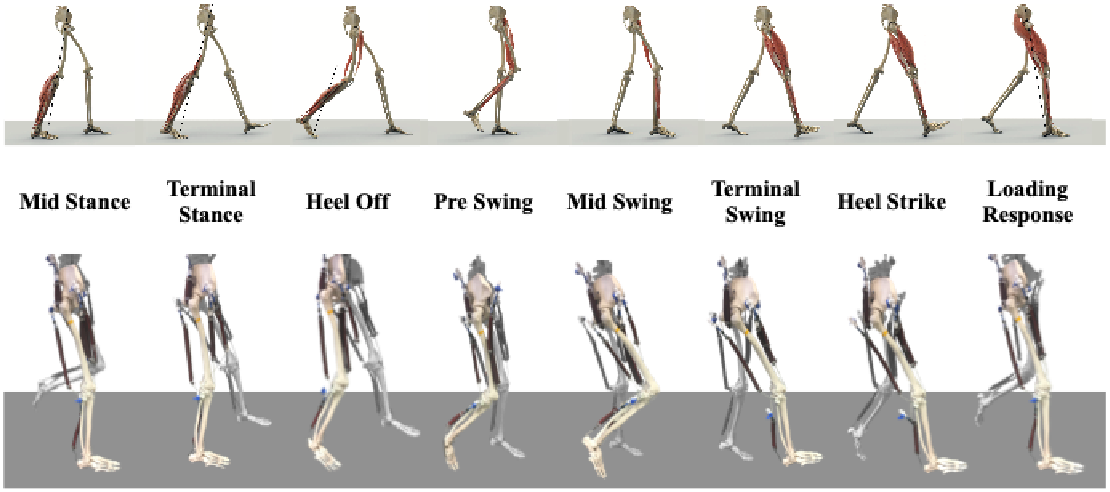

Figure 4.1: HWR driven through biologically realistic joint trajectories: computer model (top) and physical prototype (bottom).

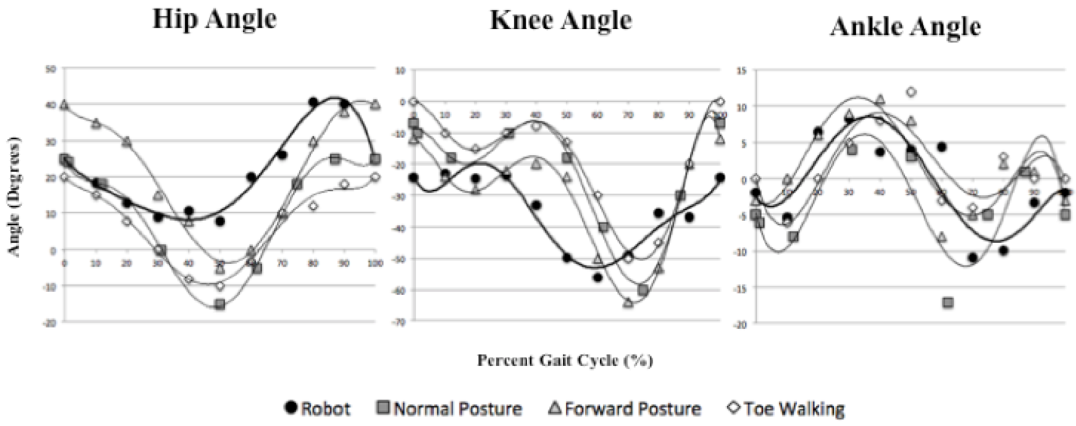

Figure 4.2: Joint angles throughout gait cycle for prototype and biological data for normal posture, forward posture, and toe walking.

4.2 Compact Robotic Flow Control Valve

4.2.1 Flow Testing

At a neutral position, with the servo pointing vertically, no air flow was detected, as was expected given the closed state of both the inlet and outlet tubes. Rotating the servo in a positive direction created a linear trend of flow release, with an R^2-value of 0.969 (Fig. 4.3). The data obtained in this test can be used to control the flow rate based on the angle of the lever component on the servo. From the results, each degree of movement corresponds to an approximate increase of 0.186 m/s of flow velocity.

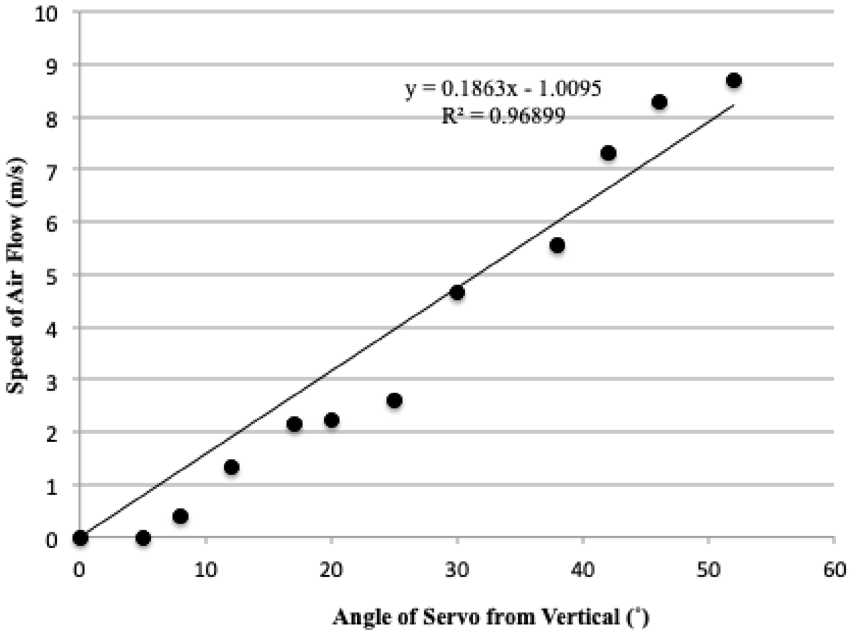

Figure 4.3: Servo Angle vs. Air Flow Velocity.

4.2.2 Muscle Elongation Rate

To test the flow velocity in relation to the Hydro Muscle elongation, the rate of elongation was collected with the curved valve attachment being rotated at various degrees, from 0 to 35 degrees in increments of about 5 degrees. There was no air flow at the neutral angle. From this test and the data above concerning servo position and flow velocity, the relationship between flow velocity and Hydro Muscle elongation velocity appears to be linear, with an R^2-value of 0.967 (Fig. 4.4).

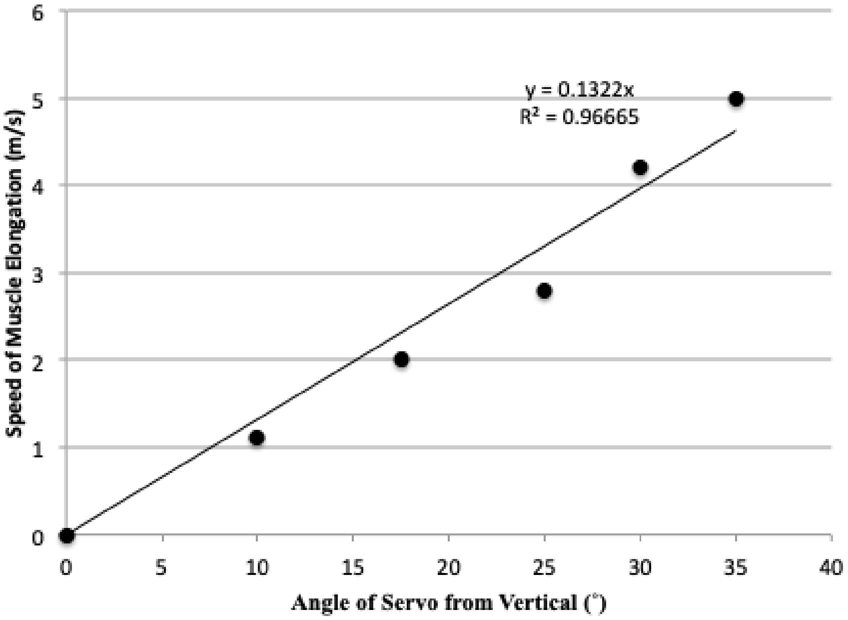

Figure 4.4: Servo Angle vs. Average Elongation Rate for Gastrocnemius Hydro Muscle.

4.2.3 Joint Actuation

The knee and ankle were actuated by the gastrocnemius Hydro Muscle connected to the CRFC valve (Fig. 6). The servo was moved to span the entire angle range in one second, then left for 3-5 seconds to allow the lower limb to stabilize, before repeating several times. The change in knee angle over a 28 second period of this cyclical servo motion is shown in Figure 4.5.

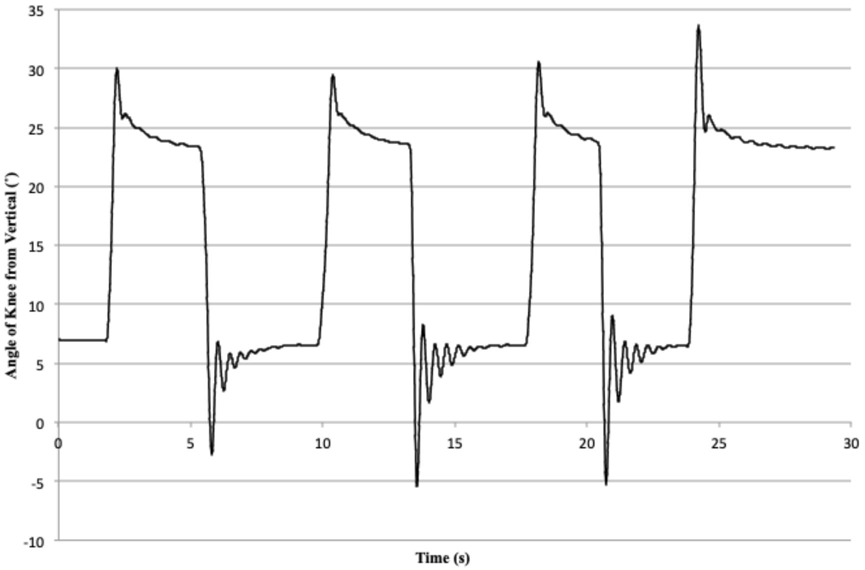

Figure 4.5: Knee Angle over Time with Cyclical Servo Motion.

Chapter 5

Discussion

The lightly tethered 12 Hydro Muscle actuated HWR, exhibiting several highly biomimetic features, was able to execute multiple steps at a slow, steady pace and emulate close to human-like walking trajectories.

The tethering was necessary to keep the robot balanced given the missing upper body causing a lack of counteracting torque along the vertical direction, for example introduced by the swinging arms [35, 36], and resulting here in a more pronounced pelvic rotation in the transverse plane during the single support phase. The passively stabilizing tethering also resolved other instabilities due to lack of more advanced control; the orifices of flow control valves were fine-tuned and set in advance and only on-off solenoid valves were actively controlled as part of the state control feedback loop based on IMU sensory data. Hence, the fixed orifice affected the smoothness and biological accuracy of the joint trajectories.

The robot 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 (Fig. 7-8).

The described HWR was not designed to carry entire weight of the pneumatic system. This, however, should not concern Lokomat-like applications in physical therapy with patients exercising on a treadmill while wearing a Hydro Muscle based exomusculature at a hospital or at home. In comparison to conventional Lokomat, which can resolve joint level body movements, the proposed Hydro Muscle actuated exomusculature can even resolve the individual muscle level actuation. Still further, due to cost effectiveness, the proposed Hydro Muscle actuated exomusculature can also be affordable for at-home use.

However, for stand-alone humanoid robot applications and for more mobile wearable assistive devices with humans in the loop, it appears critical that weight, size, and controllability of the fluid circulation system be improved. Likely, a market ready product will utilize a closed (most probably incompressible) fluid circulation system with lightweight, small, and cost-effective flow control valves. The described HWR pneumatic system uses 12 cm by 10 cm by 2 cm, 276.2g, on-off flow control modules operating individual Hydro Muscles and a heavy air compressor. To address these deficiencies and address humanoid robot and wearable assistive device applications, the new lightweight, small, cost-effective fine flow control valve, i.e. CRFC Valve, that could operate both air and liquid was designed, built, and proof-of-concept tested. In comparison, the new valve system takes up less than a volume of 6cm by 5cm by 2cm and has a mass of just 28.5g.

The Humanoid Walking Robot exhibits biological gait characteristics through pneumatic valve control that could be improved with the use of the fine control CRFC Valve. Measuring the flow rate in relation to the elongation rate will allow the HWR components to be controlled more precisely, as well as create a more natural looking gait. The CRFC Valves will be mounted on the HWR, so it can function without a plate mounted above it and walk independently.

The compact and lightweight design of the valve allows for more wearable applications. There is potential to expand Hydro Muscles and soft robotics within a variety of fields, and the CRFC Valve enables these technologies to be more compact and comfortable for the user. The CRFC system is $1/10^{\text{th}}$ of the weight and takes up $1/6^{\text{th}}$ of the volume of the original HWR pneumatic system. In addition, the CRFC Valve is also incredibly easy and cost-effective to manufacture. The cost of the valve with a standard high-torque servo is around $14 USD.

The CRFC Valve is lighter, more compact, more controllable, and more inexpensive than any other valve currently on the market. It is incredibly versatile, and because of its ability to control both liquid and gas, the CRFC Valve has potential applications in soft robotics, the medical field, agriculture, construction, and many other areas. Because it is more inexpensive than other valves, products or services could be available to people at a much more affordable price.

When coupled with the HWR, the CRFC Valve also exhibits promising control characteristics, and it serves as a proof of concept for potential wearable robotic applications in the future.

Chapter 6

Conclusion

The musculoskeletal approach to the Humanoid Walking Robot and the innovative design of the Compact Robotic Flow Control Valve, when combined, show potential to inspire a new class of wearable robotics, in particular prosthetic limbs and assistive devices for ADL or augmentations of human physical capabilities. The biologically similar trajectories show that this approach could be effectively used in gait training, and could even be customized to target specific muscle functions. In addition, this system would be affordable, lightweight, and comfortable, making them ideal for interfacing with the human body; the system has the potential for commercial, technological, and social value due to its accessibility and innovation. The CRFC Valve can have numerous applications in a wide variety of fields that all require fine control of fluid flow and that clearly may benefit from this type of valve; e.g. medical and pharmaceutical industry, military, automotive, aerospace, agriculture, civil engineering, oil and gas, etc. The synergy of the CRFC Valve with the cost-effective, energy efficient, and excellent strain properties Hydro Muscle opens a door into a new age of very interesting, useful, and accessible/affordable fluid operated robotics solutions.

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