Worcester Polytechnic Institute Robotics Engineering Program

Bioinspired Exosuit

A Major Qualifying Project Report
submitted to the Faculty of
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfillment of the requirements for the
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Abstract

The Bioinspired Exosuit utilizes pneumatically-actuated artificial muscle ("Hydro Muscles") to provide assistive forces while walking. This project continues on a multi-year effort to utilize Hydro Muscles for this purpose. The exosuit uses neural network-based control, informed by a comprehensive suite of sensors that determines the state of the suit and pose of the user. Neural network-based control allows for the adaption to the user's specific gait cycle and provides optimized support to decrease the energy consumed while walking.

Acknowledgments

We would like to acknowledge the immense support that Professor Marko Popovic provided to us throughout the process of our MQP.

This project would not be possible without our advisor Professor Popovic and co-advisor Professor Ziming Zhang.

We also want to give a big thanks to the team that came before us. Both Ellen Clarrissimeaux and Julia D'Agostino have given us endless support, advice, and guidance in our continuation of their project.

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Introduction

Conventional artificial limbs, braces, and related technologies, designed to assist the movements of users. This project, the Bioinspired Exosuit, is a multi-year effort to redefine traditional assistive technologies This soft-robotic exosuit specifically aims to ease the process of walking. The exosuit consists of a soft, flexible undersuit made of straps, and a hard, flat board housing all electrical components. By utilizing soft, pneumatically-actuated artificial muscles, called "Hydro Muscles", the exosuit can provide assistive forces to the legs. These artificial muscles employ compressed air to expand and contract very quickly, providing the assistive forces by pulling the user's legs in specified directions. The Hydro Muscles are placed on three major muscle or muscle groups instrumental in walking, those being the gluteus maximus, the quadriceps femoris, and the gastrocnemius (Physiopedia, n.d.).

Additionally, the introduction of neural network-based control enables this Bioinspired Exosuit to adapt to the user's gait cycle. A comprehensive suite of orientation, position, and force sensors are employed by the neural network-based control in order to provide feedback and direct support. Ideally, neural network-based control would be able to optimize firing times of the Hydro Muscles to maximize the forces on the legs during the individual's gait cycle. In addition to finding the optimal gait cycle, neural network-based control is also able to continually update firing timing as the user walks, ensuring that benefits are not lost, even if users change their gait cycle while walking.

Overall, the Bioinspired Exosuit has a vast variety of applications that it could be applied to, the largest of which being physical therapy. With the Bioinspired Exosuit, those who have weakened functioning in their legs could greatly benefit in using this exosuit. Examples may be a person who has broken their leg, an astronaut returning from extended time in space, or even an elderly person who has trouble walking long distances. Many instances of needing to strengthen the muscles in a person's legs are viable conditions for the Bioinspired Exosuit to perform at optimal conditions. Additionally, this exosuit can also be used for athletic training, or daily indoor activities. The lightweight nature of the exosuit and the flexibility of the undersuit, or strap system, allows for easy and comfortable use, and challenges many existing solutions to assisting those who cannot produce a normal gait cycle.

Background

Gait Cycle

The gait cycle represents the movements of the legs that happen during normal human walking. This gait cycle can be broken down into two different stances: the stance phase, which accounts for about 60% of the cycle, and the swing phase, which accounts for about the other 40%. The stance phase can be broken down even further into about five phases: initial contact, loading response, mid-stance, terminal stance, and the pre-swing. The swing phase can be broken down into the last 3 phases: initial swing, mid-swing, and terminal swing. These phases can be seen in Figure 1 (Gait and Balance Academy, 2020; Themes, 2016; Tidy, 2013; TeachMeAnatomy, n.d.).

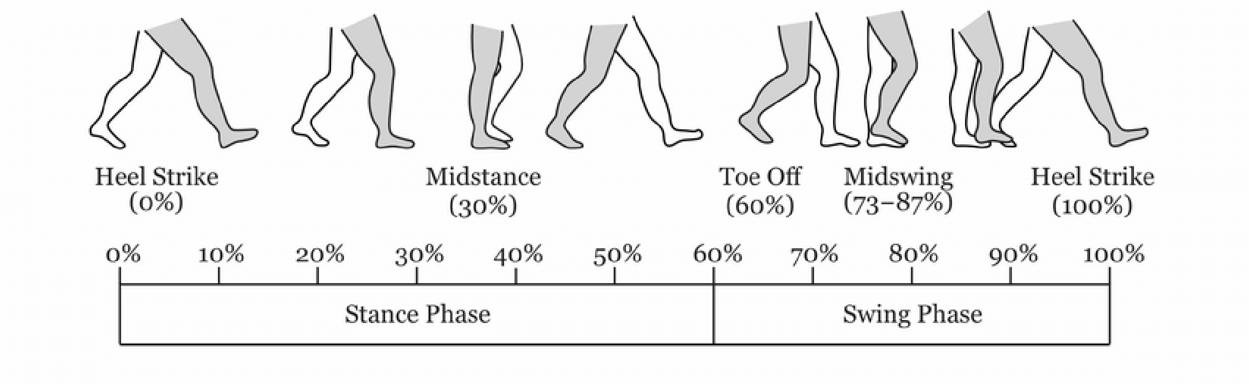


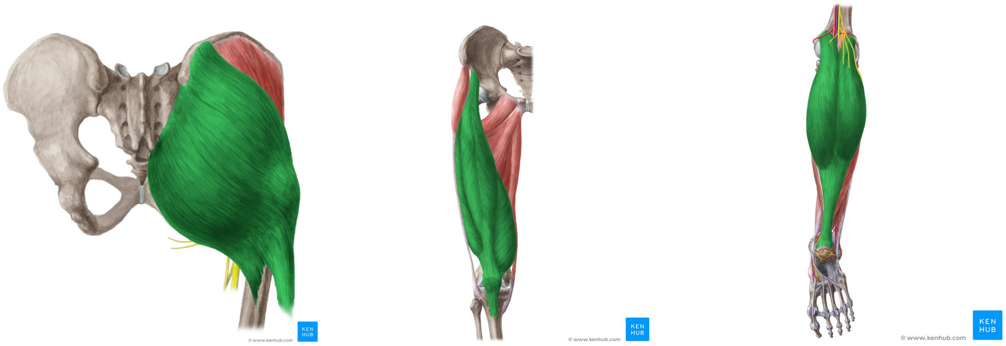
Figure 1: Human Gait Cycle during level walking. The percentage timings of the gait events are approximate, they vary depending on the individual and environment (Sherratt et al., 2021).

Lower Limb Anatomy

There are many individual muscles located in the human legs that contribute to the process of walking. After reviewing the major muscles in the legs, three were chosen as the most beneficial to the act of walking: the gluteus maximus, the quadriceps femoris, and the gastrocnemius.

The gluteus maximus muscle is located across the buttocks and the thighs (Figure 2). This muscle's primary function is to control movement of the leg at the hip. When the leg is extended or rotated, this muscle is being utilized to control these movements (Physiopedia, n.d.).

The quadriceps femoris muscle group which is located between the hip and the knee (Figure 3). This muscle group is made up of four muscles which control the movement of the thigh and knee. Specifically, it assists in extending and rotating the leg, as well as bending the knee (Physiopedia, n.d.).



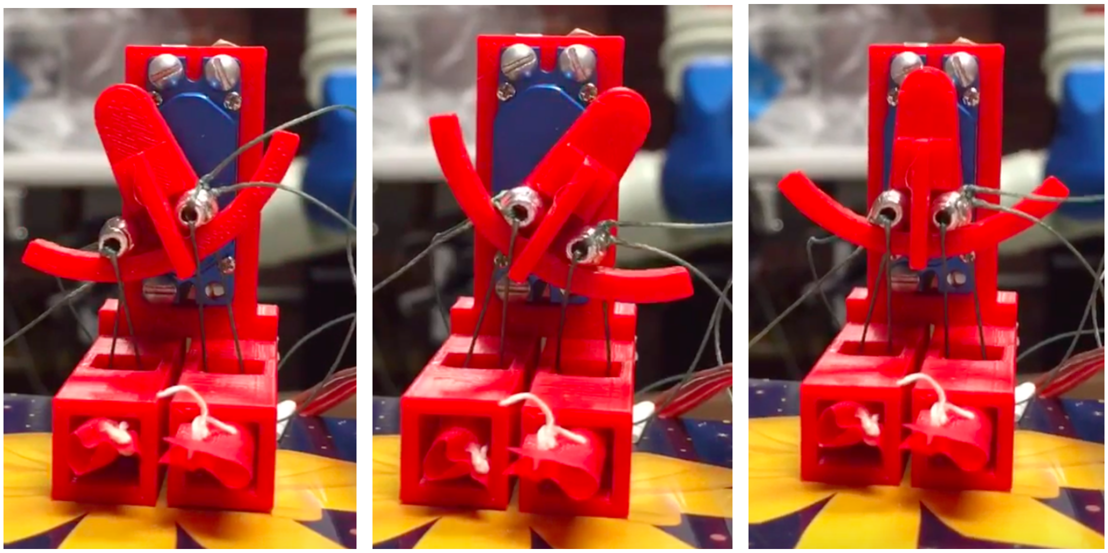
Figures 2, 3, and 4: Each muscle or muscle group is highlighted in green. From left to right: Gluteus Maximus, Quadriceps Femoris, and the Gastrocnemius (Physiopedia, n.d.).

Finally, the gastrocnemius is located between the knee and foot, which can be seen in Figure 4. This muscle primarily acts to bend the foot as well as acting as a powerful flexer for the knee, along with the quadriceps femoris muscle group. This muscle also acts to provide propulsion forces while walking, running, or jumping (Physiopedia, n.d.).

CRFC Valves

The Compact Robotic Flow Control (CRFC) valves were designed in previous years and are integrated into this version of the Bioinspired Exosuit. The function of the valve is to control the airflow to each of the Hydro Muscles.

There are three major components to the CRFC valves: the servo and case, the tubes, and the KastKing. The servos are KST X10 Micro Servos which are rated for a torque of 4.85 kg*cm and 0.12/60deg at 7.4V (Amazon, n.d.). The KastKing takes a limited tangent force of about 50 pounds (Kastking, 2018). Since the servos from the previous iteration were replaced by these new servos, the servo casings needed to be redesigned to fit the new servo measurements. This redesign included resizing the hole that fits the servo and shifting the holes where the string is thread through the base. Additionally, the 3D printed servo horns were slightly redesigned so that there is more than one fixture point to the purchased servo horns. Neither the tubes nor the string and tying measures were redesigned and were implemented into the CRFC valves as is.



Figures 5, 6, and 7: The CRFC Valve shown in its three key positions. The left valve shows airflow only entering through the left tube. The middle valve shows airflow only entering through the right tube. The right valve shows airflow not being able to enter either tube (Clarrissimeaux, 2021).

The primary function of the CRFC valve is to control the airflow through the Hydro Muscles. This is a patent-pending design that operates using a cam mechanism. The 3D printed servo horn fits over the servo horn and is looped around by the string, which has been tied before the base. The legs of the string pass through the base of the servo case via two small holes, keeping the string vertical to hold the maximum tension. After passing through, each side is tied so that each tube has an air-tight seal. As a result, when the servo is in its resting position, which is straight up, both tubes are completely choked and no air may pass. This allows the Hydro Muscles to retain pressure while the valves remain at the neutral position (Clarrissimeaux, 2021; Curran et al., 2018; Moffat, 2019).

Hydro Muscles

Hydro Muscles serve as artificial, pneumatically-actuated muscles to provide assistive forces during normal human walking. Each Hydro Muscle is made of an inner tube, a fabric sleeve, two collars on either end, and barbed plugs. Each Hydro Muscle has only one entrance for airflow and the other side is blocked, and each side is choked with a collar so that no air may escape around the plugs. The purpose of the fabric sleeve is to restrict the Hydro Muscle from expanding radially, and forcing the muscle to only expand longitudinally.

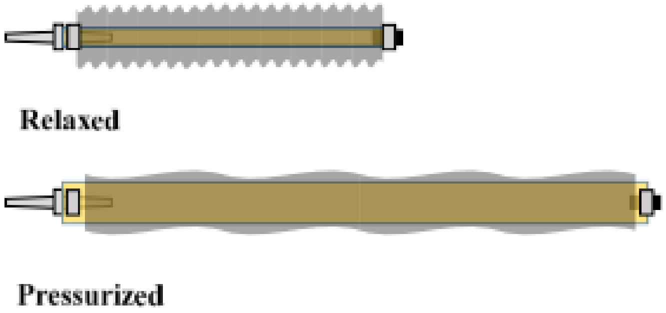
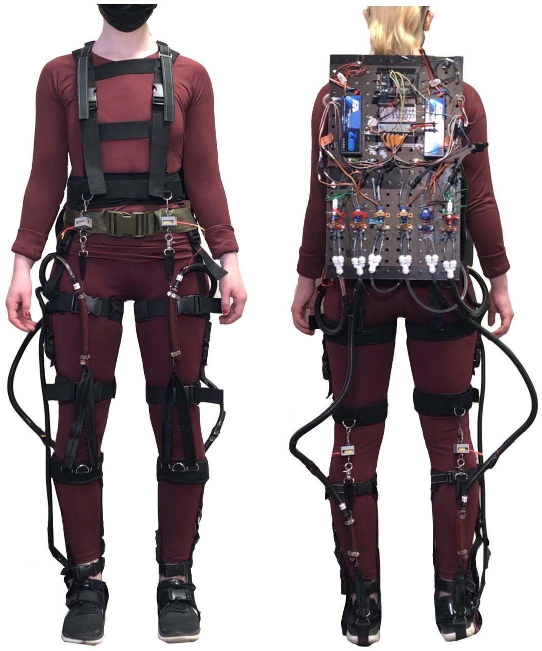


Figure 8: A visual diagram of a Hydro Muscle both relaxed and pressurized (Clarrissimeaux, 2021).

When compressed air is forced into the Hydro Muscle, the muscle expands in length about twice as large as it had been contracted. When the compressed air is no longer being supplied, the Hydro Muscles shrink back to their contracted state immediately. This contracting action of the Hydro Muscles is what generates the assistive force on the user's joint. Three major muscles, and/or muscle groups, on each leg were identified to aid significantly in the walking process: the gluteus maximus, the gastrocnemius, and the quadriceps femoris. Hydro Muscles are then placed at these muscles to aid their movements (Clarrissimeaux, 2021; Curran et al., 2018; Sorrells et al., 2015; Sridar et al., 2016).

Previous Bioinspired Exosuit



Figures 9 and 10: A front and back view of the previous iteration of the Bioinspired Exosuit (Clarrissimeaux, 2021).

This project is a continuation of the previous year's Bioinspired Exosuit project. The previous project goals were to create the exosuit to lower the metabolic cost of walking with speeds ranging from 2.5 mph to 3.4 mph. Additionally, all electrical and power components were to be included on the exosuit and the whole suit should not exceed 15 lbs. The previous year's Bioinspired Exosuit utilized a strap system with tri-length adjustable silk straps. They also utilized single Hydro Muscles on each major muscle group, those being the gluteus maximus, quadriceps femoris, and the gastrocnemius, to provide the assistive forces while walking. The board which housed all electrical components was constructed out of an aluminum frame and a heavy wooden board. The force sensors attached to the Hydro Muscles were constructed in house using a 3D printed casing, a 3D printed plate, sponge, and a force-sensitive resistor (FSR). Finally, the metabolic cost of walking was measured using the PNOE device (Clarrissimeaux, 2021).

Project Goals

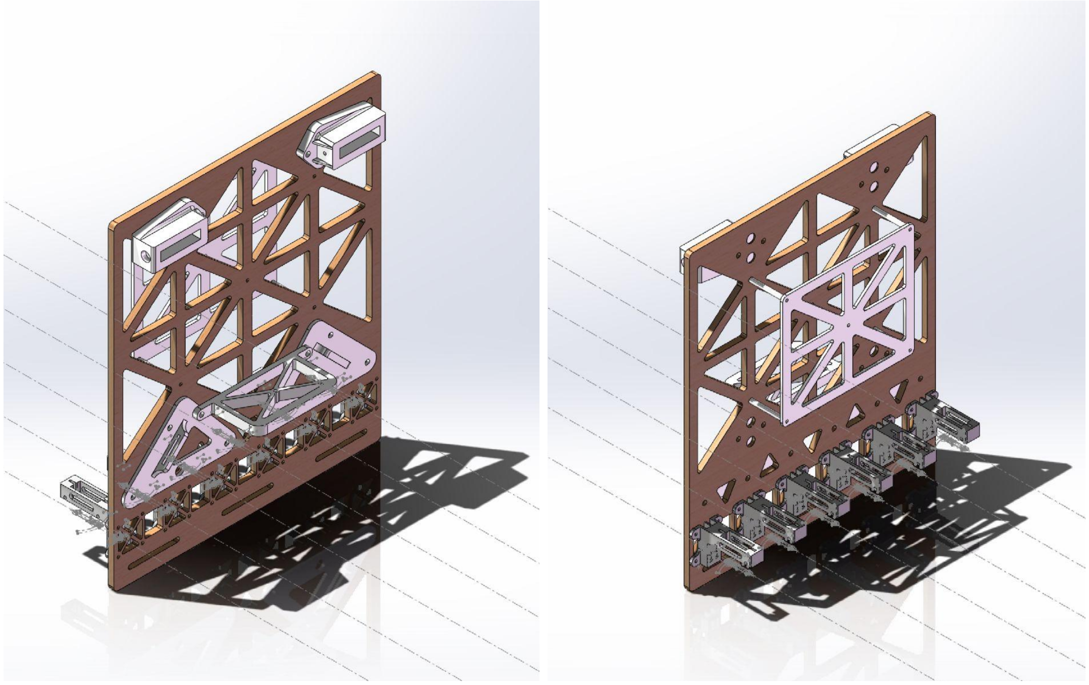
The main objective of this project is to develop the Bioinspired Exosuit to lower the heart rate of most people walking with assistance. This will be obtained through a series of goals for this year's Bioinspired Exosuit. These objectives include:

- To develop a novel method of controlling Hydro Muscles with CRFC Valves using five IMUs and six force sensors.
- Upgrade the hardware comprising the CRFC Valve assemblies to include a new servo motor, enabling the valve to handle a larger range of movement speeds with more accurate control.
- Create new Hydro Muscles for the triceps muscle group, increasing the dynamic range of the segment to apply greater forces when necessary.
- Develop a closed-loop feedback control system for the Hydro Muscles to ensure that the appropriate tension scaled from body weight is applied to each subject across the experiment.
- Adapt the exosuit to utilize muscle firing timing on a single leg in order to adapt to different gait cycles through sensor-driven machine learning, which is then applied symmetrically.
- Make a comparison between the muscle firing cycle when the force sensor reaches its peak value, and the novel method utilizing a neural network.
- To design an exosuit that, compared to unassisted performance, lowers the average heart rate across all subjects walking on flat ground between 2 and 4.5 mph.
- To create an exosuit that packages all electronic components within a footprint that will remain under 8 lbs and reduce the overall size by 25%.

Methodology

Materials and Build

Redesign of the Backpack



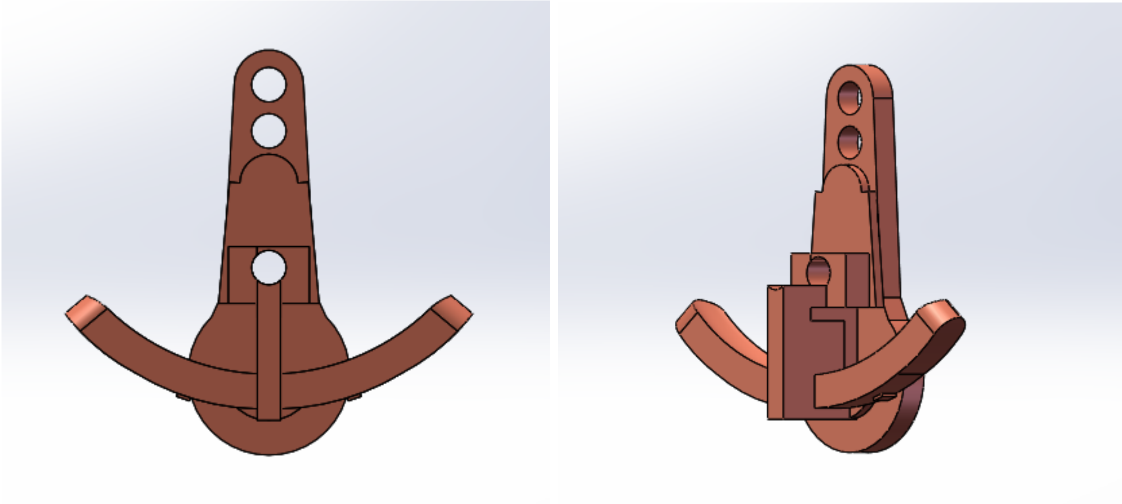
Figures 11 and 12: A front and back view of the CAD model from the redesign of the backpack.

In order to decrease the burden on the candidate, we decided to decrease the weight of the whole backpack. The previous backpack was around 10 pounds, including straps on the body. We completely redo the backboard design so that it is more well-manufactured and lighter. By laser cutting a ¾ in wood board and replacing the large aluminum holder to a simpler 3-D printed parts, strap system, we managed to decrease the weight of the backboard under 8 pounds to make sure that all the participants of the tests would not feel any discomfort while testing to the most extent.

Construction of the CRFC Valves and the Hydro Muscles

Figures 13 and 14: A Hydro Muscle (left), and all of its components (right) (Clarrissimeaux, 2021).

To construct the Hydro Muscles, the materials needed are ½ inch outer dimension and ¼ inch inner dimension tubing with Uber Hose tubing, red fabric sleeving, barbed plugs, and collars. Each Hydro Muscle is different in length but constructed in the same manner. First, the tubing is cut to length, and covered in the red fabric sleeve. This fabric sleeving restricts the tubing from expanding radially, only allowing movement parallel to the tube. Next, each end of the tube is fitted with a barbed plug. One plug includes a nose to allow airflow while one plug is meant purely to block the exit of the Hydro Muscle. Finally, Hydro Muscles are then fitted with two collars to restrict airflow around the barbed plugs and glued with hot glue to further restrict the Hydro Muscle. The Hydro Muscle lengths are as follows: the gluteus maximus muscle measures about 5 inches unpressurized and 10 ¼ inches pressurized, the quadriceps femoris muscle measures about 4 ¾ inches unpressurized and 10 ¼ inches pressurized, and the gastrocnemius muscle measures about 2 ½ inches unpressurized and 4 ¾ inches pressurized. The individual gluteus maximus muscle is capable of producing about 22 pounds of force, the individual quadriceps femoris muscle is capable of producing about 12 pounds of force, and the gastrocnemius muscle is capable of producing about 11 pounds of force. Each muscle group is made up of two Hydro Muscles which are bound to each other via wire and string to produce more force (Clarrissimeaux, 2021; Curran et al., 2018; Sorrells et al., 2015; Sridar et al., 2016).



Figures 15 and 16: The 3D printed servo horn in a front (left) and isometric (right) view (Clarrissimeaux, 2021).

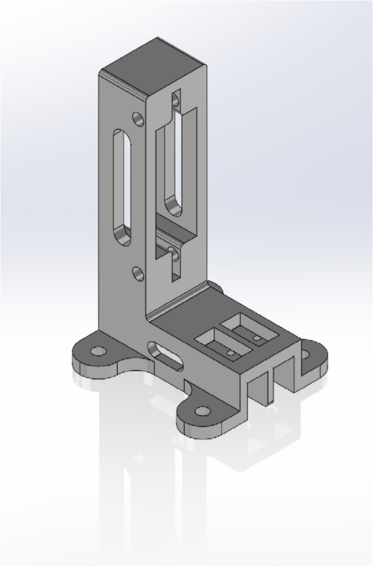
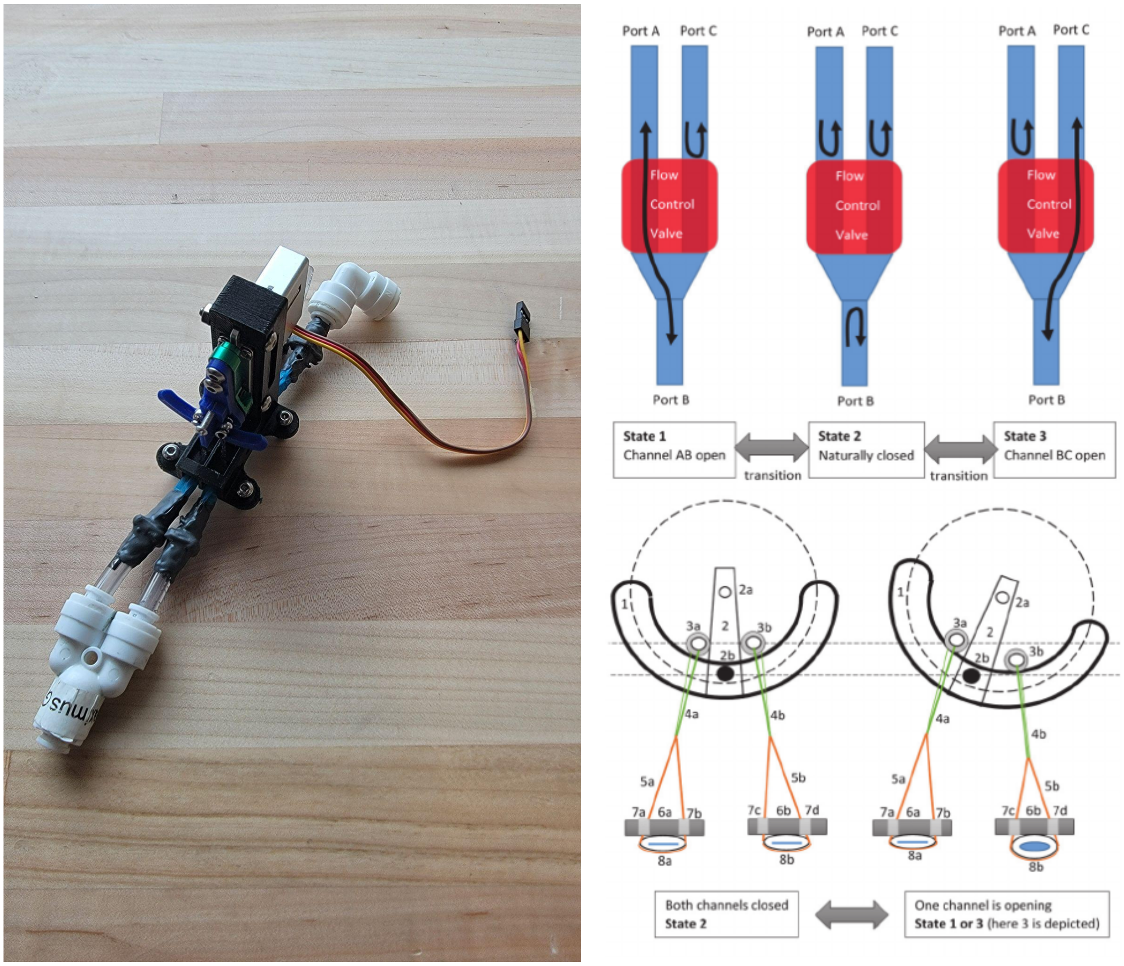


Figure 17: The 3D printed servo case in isometric view.

To construct the CRFC valves, the materials needed are 0.02 inch wide and 0.08 inch thick surgical tubing, kite fabric, spider wire string, beads, a 3D printer, JB Kwikweld, and a KST X10 Micro Servo. First, the servo casings and the custom servo horns are 3D printed for each CRFC valve. Next the tubes are constructed. Each tube is cut from 0.02 inch wide and 0.08 inch thick surgical tubing, which are cut to be approximately 2 inches in length. Next, the kite material is cut and wrapped around the tube, then it is tightly secured. It is important to secure the kite material around the tubing as tightly as possible, as this prevents the surgical tubing from expanding laterally, and consequently exploding. After the kite material is applied, the last step is to insert small airways to create only two points of entry for airflow. Once these are inserted, the area around these entryways are welded with JB Kwikweld. Once dry, the tubes are completely air-tight, aside from the two entry points, and ready for use.



Figures 18 and 19: A physical CRFC Valve is shown on the left. A diagram depicting how the valve works is on the right (Clarrissimeaux, 2021).

Finally, all parts are ready to be assembled to create the CRFC valve. First, push the servo into the 3D printed servo case, then attach both servo horns. Next, thread a bead onto two pieces of spider wire, and tie a knot about 2 centimeters from the bead. Place the looped Spider Wire around the custom servo horn, and thread the Spider Wire through the holes in the bottom of the servo case. Next, place the tubes into the slots on the bottom, and tie the tubes when the servo horns are at the mid-way so that no air may pass through the tubes while the servo is in its neutral configuration. Once completed, the CRFC valve is complete and ready for use. Six of these CRFC valves are needed to function the Bioinspired Exosuit, for each of the six groups of Hydro Muscles (Clarrissimeaux, 2021; Curran et al., 2018; Moffat, 2019).

Construction of the Straps

Figure 20: A strap showing the rigid meshing inside major straps (Clarrissimeaux, 2021).

The Bioinspired Exosuit is partially made up of a strap system. These straps are made of polyester, velcro, and a woven strap material. Straps have one long pocket in order to house the woven strap material with clip buckles. In order to retain its general shape, a semi-rigid mesh material is inserted into the polyester fabric. Finally, velcro material is glued to corresponding straps to hold the structure of the exosuit. Additionally, the rough surface for the velcro is used on each of the leg straps for more grip onto the participant's pants (Clarrissimeaux, 2021).

Exosuit Component Placement

A series of straps were constructed to support the exosuit and adhere it to the user. These straps are strategically placed along the user's feet, legs, and torso. Specifically, the foot straps wrap around the foot like a net, with buckles at the top foot and ankle. The leg straps include the upper calf, lower thigh, and upper thigh. The torso straps include two straps wrapping around the abdomen, two straps around each shoulder, and a strap between shoulder straps at the collar and mid-back. Additionally, all straps are made adjustable to conform to a wide range of people. Below is a schematic of the strap system on a user (Figures 21 and 22). The gluteus maximus Hydro Muscle connects from the upper portion of the shoulder strap to the upper thigh strap. The quadriceps femoris Hydro Muscle connects from the waist strap to the lower thigh strap. Finally, the gastrocnemius Hydro Muscle connects from the upper calf strap to the heel of the foot strap. Additionally, there is a load cell between each of the Hydro Muscles and the upper straps.

Figures 21 and 22: The entire Bioinspired Exosuit shown in a front (left) and back (right) view.

For all electrical components, a lightweight board was constructed which attaches to the straps located at the user's back, similar to a backpack. This board houses two 7.4 volt batteries, six CRFC Valves, an ELEGOO Mega 2560 R3 board, and three breadboards containing two Adafruit ItsyBitsy 32u4-5V 16MHz and six PMD Hx711 Load Cell Amplifiers. All electronic components are wired between each other to be as neat and organized as possible. Additionally, each CRFC valve is connected to each other on one end of the tube, so they all receive equal amounts of the same source of compressed air. The other end of each CRFC Valve is connected to each of their respective Hydro Muscles by Vinyl-Flex PVC 18-14 clear plastic tubing.

Tubing and Wire Connection System

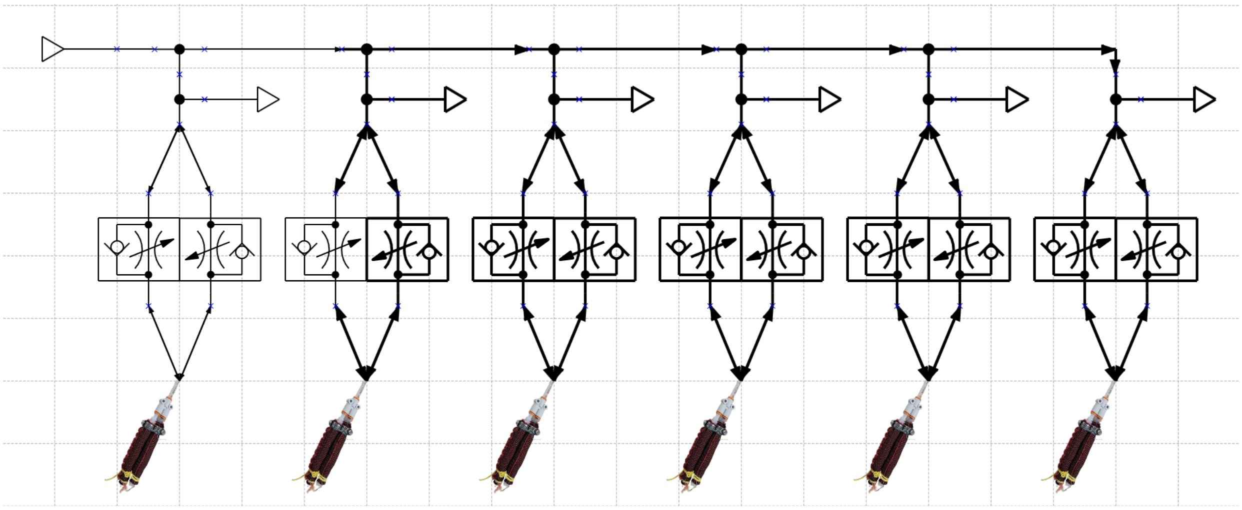


Figure 23: A schematic of the pneumatic airflow system. Each rectangle represents a CRFC Valve.

The tubing and wiring system throughout the Bioinspired Exosuit is designed to be compact and as streamlined as possible. Two different types of tubing are present on the exosuit: Vinyl-Flex PVC 18-14 tubing and hard plastic hose-like tubing. The Vinyl-Flex PVC 18-14 tubing allows the compressed air to travel from the CRFC Valves to their respective Hydro Muscles. The PVC tubing which connects the CFRC Valves to the gluteus maximus muscles travels along the side of the board, connecting to the Hydro Muscles behind it. The PVC tubing which connects the CRFC valves to the quadriceps femoris muscles wraps up and around the hip area. The PVC tubing which connects the CRFC Valves to the gastrocnemius by traveling along the back of the legs. Additionally, each force sensor as well as each step sensor are connected to the breadboards. To protect the wires running along the exosuit, hard plastic hose-like tubing runs from the feet to the breadboards. The wires from all sensors are fed through this hose at various entrance points and exit at the top to connect to the breadboards. One tube for each leg exists with an additional small portion of tubing running from the front quadriceps femoris Hydro Muscles to the main wire tubing (Clarrissimeaux, 2021).

Augmentation

Control System Design & Layout

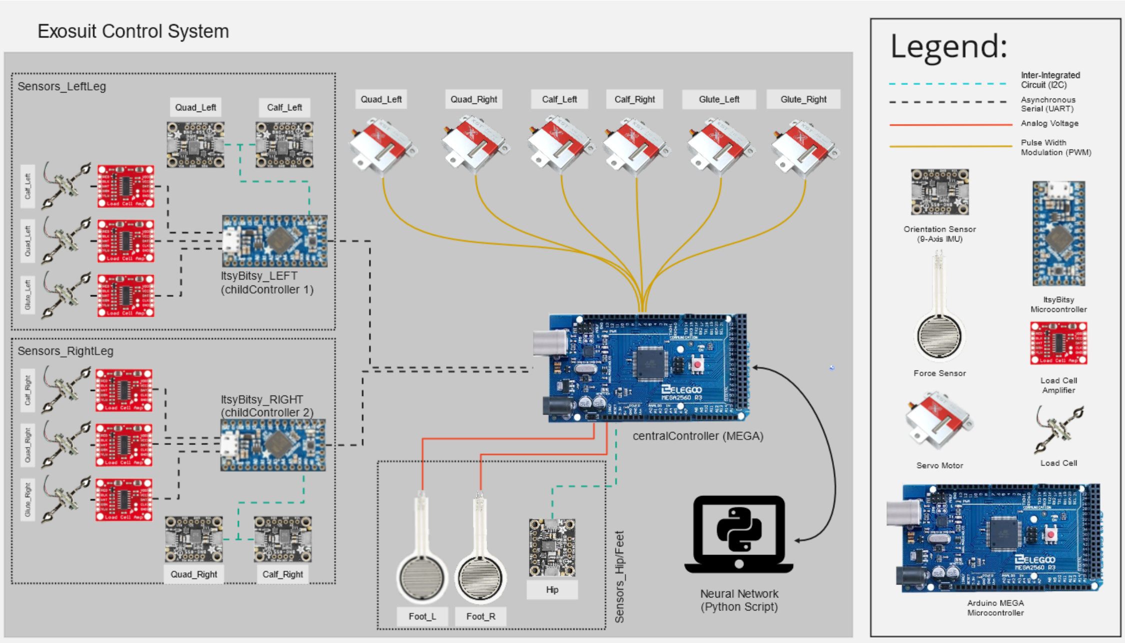


Figure 24: A new control system layout was necessitated due both to the addition of new sensors, as well as for consolidating electronics where possible to decrease used volume and weight.

One of the primary avenues initially explored was to keep the Arduino MEGA-based microcontroller board and add a servo shield, as much space was taken up purely for a simple, bulky breakout board pertaining to the CRFC valve servos. However, due to unexpected complications concerning the implementation of many BNO055 IMUs, the overall control system architecture needed to change. Communicating primarily via I2C, the Adafruit BNO055 breakout board gives developers two possible I2C device addresses to choose from: 0x28, and 0x29. As the team wished to integrate five of these sensors into the suit, by default, there would be I2C device address conflicts, which would at best prevent more than half of the sensors from operating. From here, two paths were proposed: the implementation of a multiplexer (mux) to rapidly change the

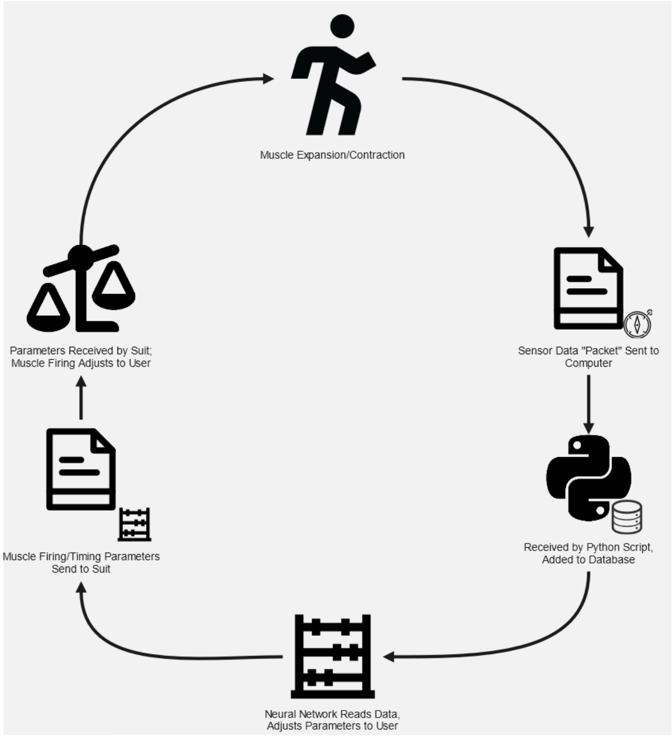


Figure 25: Control loop

address lines of each IMU at a frequency high enough to not impede communications or normal operations, or using multiple microcontroller boards to use multiple I2C buses in parallel. Given these factors a multiple microcontroller design was chosen to be most optimal.

Two Adafruit ItsyBitsy 5V microcontroller boards were added to the overall control system stack to handle all IMUs pertaining to the quad and calf muscle groups. These two boards would communicate to the Arduino MEGA, which would serve as the “head” or primary microcontroller for suit-side operations. In essence, the MEGA will have a bidirectional communications link between the tethered computer and itself. All sensor information would be received and processed by the MEGA to be sent to the computer, which in turn would send back information necessary to adjust the suit’s operation to adapt to the wearer.

Sensors

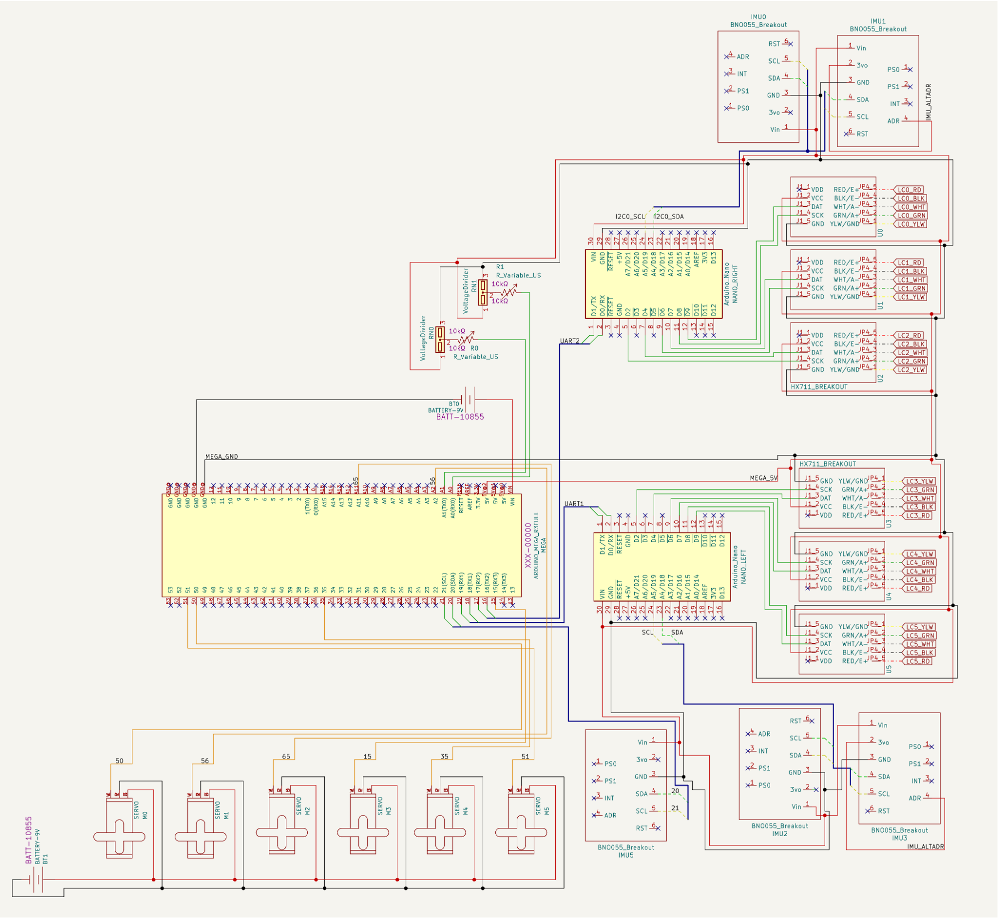


Figure 26: The electrical wiring schematic.

Thirteen sensors are used to estimate the position, orientation, supporting force, and gait cycle stage of the user. For position and orientation estimation, five nine-axis inertial measurement units (IMUs), two placed on each leg near the quadriceps and calf muscles and one near the hip, are used. The output force of each Hydro Muscle is determined through load cell stacks, which comprise a load cell amplifier and a load cell, respectively, for each muscle. Six of these stacks track the quadricep, calf and glute Hydro Muscles on each leg. Finally, two force-sensitive variable resistors connected to voltage dividers are placed on each foot, and are used to determine the amount of weight the user is applying.

By orienting several IMUs across the exo-suit, it is possible to estimate the pose (position & orientation) of each leg joint, as well as the torso. Quaternions for each IMU are received and sent from the suit-side control system stack to the tethered computer, which are then processed to adjust various parameters of the suit based on observed walking patterns.

Additional data on the approximate force applied to the user's anatomy is given through the load cells, tied to each Hydro Muscle. This information provided serves as an additional metric to not only track the amount of effort the user is putting in to walk, but also the stage of contraction/extension for each relevant Hydro Muscle. Combined with the quaternions sent by the IMU, it is possible to get more statistics on the performance of the suit, the effect on the user, and each user's unique gait cycle.

Communications of the sensor system

The unique package of sensors used on the suit meant that high-bandwidth, high-frequency communications needed to be facilitated between each device within the control system stack. Additionally, as a total of three microcontrollers are used, a robust network must be established to ensure that all data that is sent and received between the controllers will not be lost in transit.

Two-wire serial, or a Universal Asynchronous Receiver-Transmitter (UART) serial bus, was heavily favored as the primary means of communication between each microcontroller. As Serial was a design requirement for most college assignments using Arduino microcontroller boards, several team members already had experience with the bus.

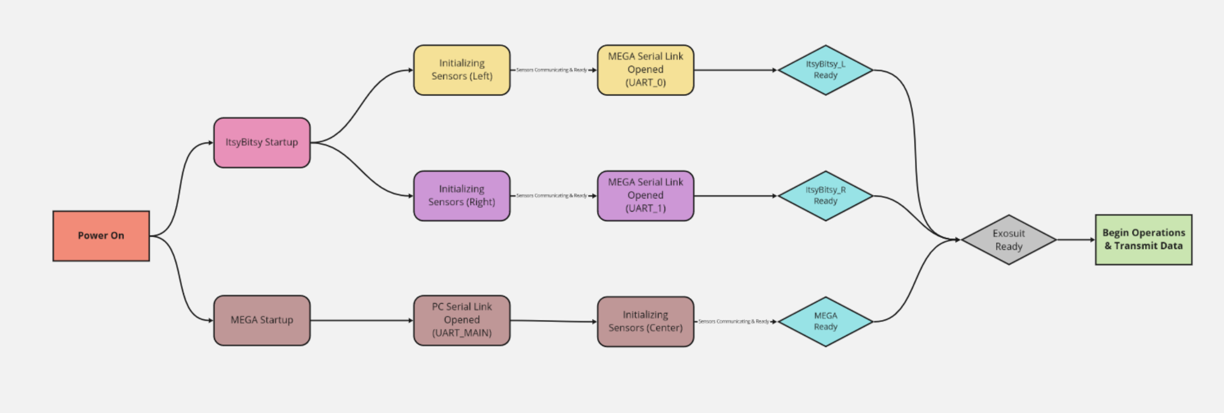


Figure 27: Exosuit Initialization Procedure

Serial Peripheral Interface, or SPI, was briefly researched as a higher-bandwidth option. As opposed to a maximum baud rate of 300k for UART, there is a theoretical upper bound of ~1 Mbps, which could make it a superior option purely from this specification.

Control Code

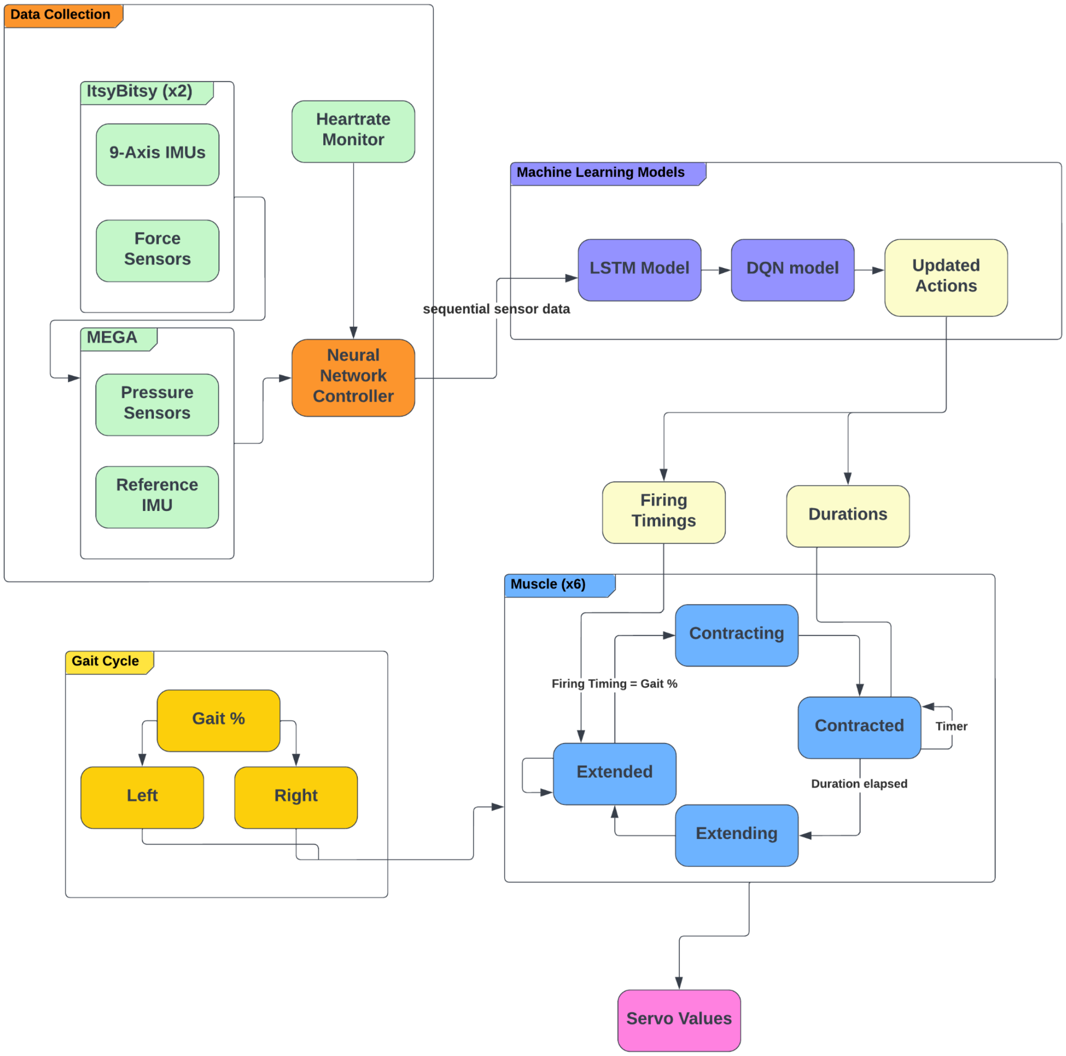


Figure 28: An overview of the system components.

The suit is able to automatically adapt to any walking speed through use of the step frequency or gait period. The gait cycle period is determined by observing the leading edge signal in the two pressure sensor circuits. Non-blocking observation of time along with the parameters received from the Neural Network is used to alter the state of the system. Depending on the state of each individual muscle, values are written to corresponding valve servos to either expand or contract the muscles.

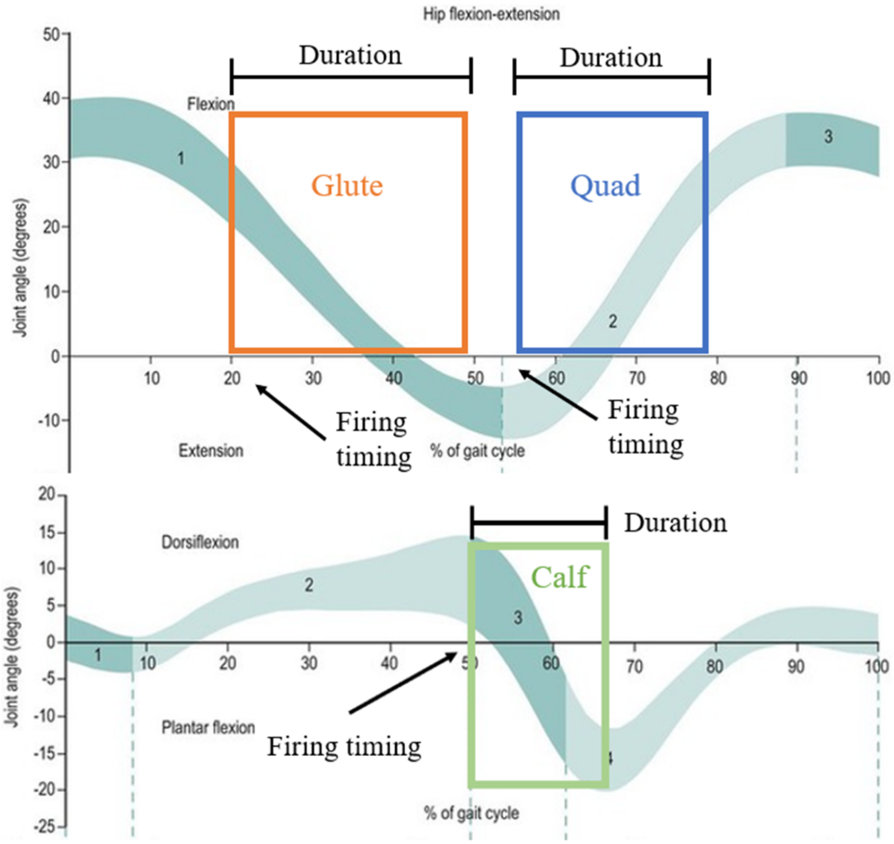


Figure 29: Diagram of firing timings and durations (Tidy et al., 2013)

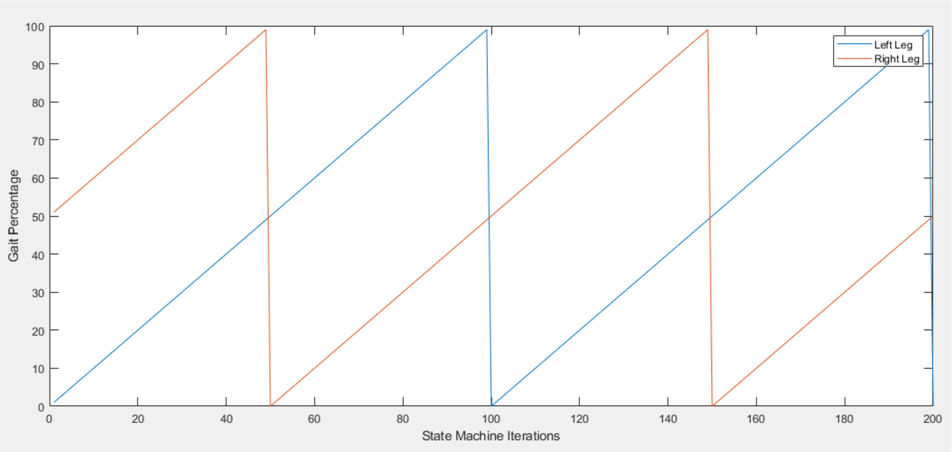


Figure 30: Gait Percentage for each throughout walking motion.

When the gait cycle of an individual leg reaches the trigger for a particular muscle, the corresponding muscle contracts for a set duration. This duration is an adjustable parameter. Each muscle has an individual duration correlated with the firing timings. Because these two types of parameters are based on gait percentage, the occurrence of the firing timing and the length of the duration dynamically adapt to change in gait through the usage of the gait cycle period.

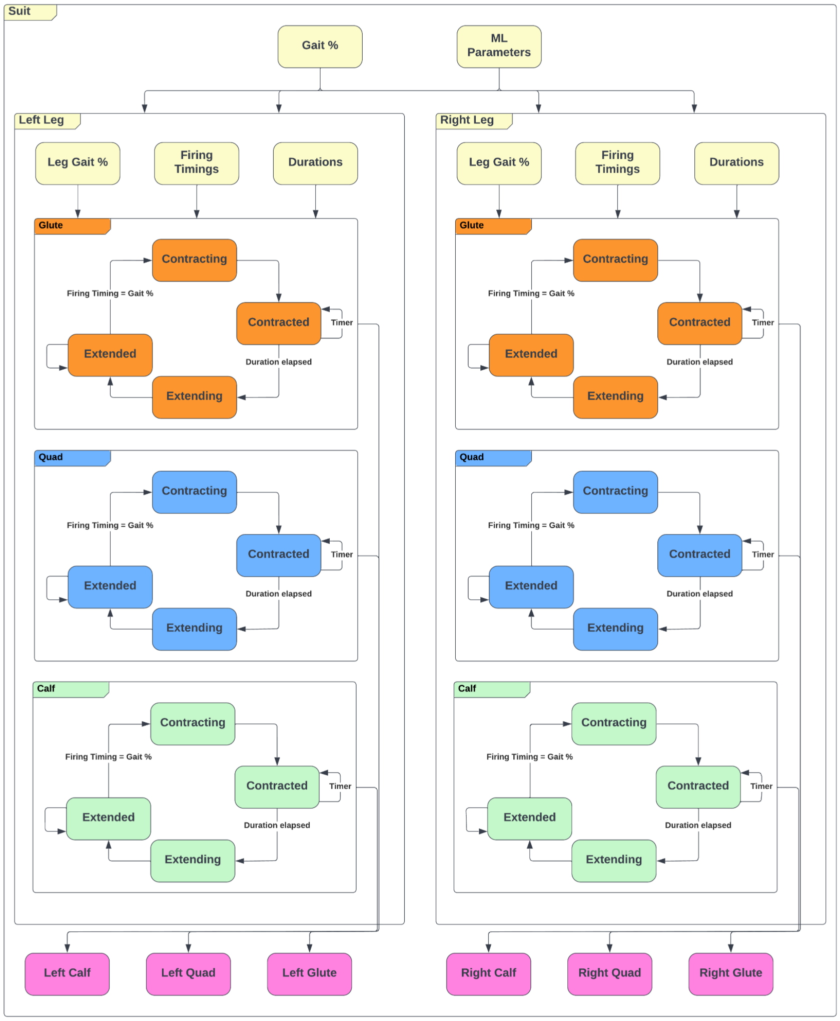


Figure 31: Diagram of lower level State Control

A hierarchical state machine is used to handle different objects which are contained inside each other in the representation of the suit. For the control system, the suit contains two legs, and each leg contains 3 muscles. At the highest level, the state is based on the current gait percentage and the current gait parameters from the Neural Network models. At the individual leg level, the gait percentage is applied to each individual leg using an appropriate offset, and when the leg is in the correct state, the muscle is triggered to fire. At the muscle level, the timing of the contraction and expansion sequence of each individual muscle is handled. This allows for each leg and muscle to operate independently of each other in a non-blocking manner.

One method used to find some initial values of our testing was to use biomechanical data and forward kinematics to predict when the muscle would be in tension. Joint angles were used to simulate motion of a 2D leg model. And through estimation of the location of hydro muscle attachment points, the change in length of each hydro muscle relative to the gait percentage can be observed. This simulation was also animated to provide a visual tool for understanding the motion of the leg and hydro muscle.

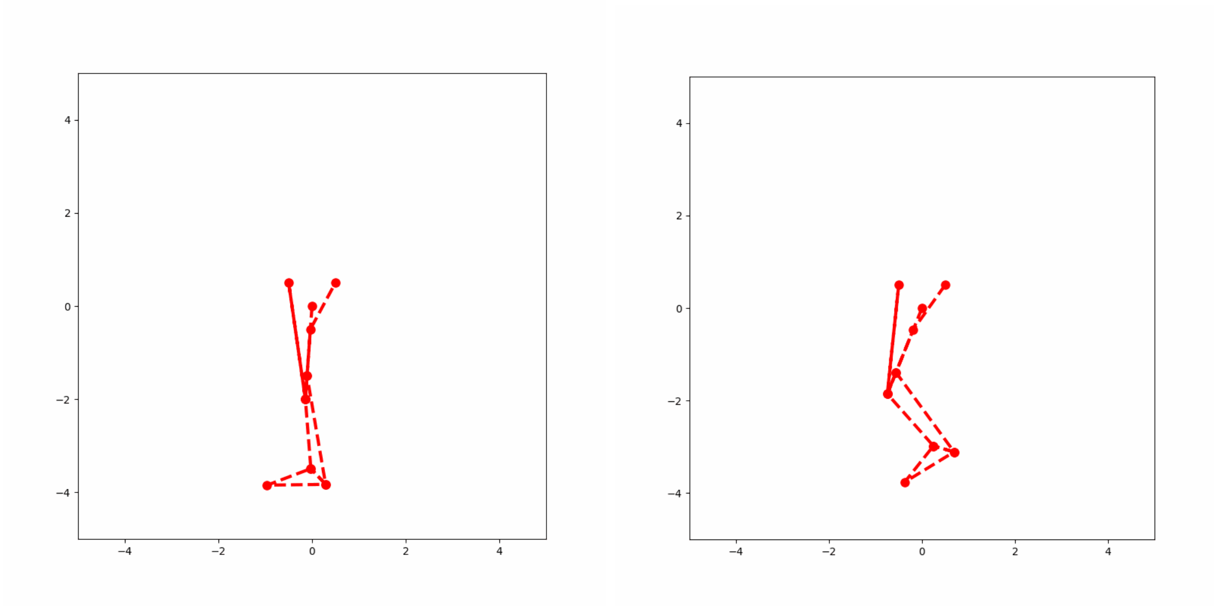


Figure 32 and 33: 2D animation

Neural Networks Architecture, Training, and Control Theory

The action is changed and updated every minute. Incrementing every minute, data from the sensors goes into the Long Short Term Memory (LSTM) network, which handles signals processing and analysis. Long Short-Term Memory (LSTM) networks are a type of recurrent neural network capable of handling long-term dependencies. The LSTM summarizes this data and puts it into a long term memory vector for the following neural network to use, which is novel compared to other methods. The fully connected neural network is implemented as a deep Q network (DQN) to perform the reinforcement learning. The DQN are neural networks that utilize deep Q learning which learn policies from high dimensional sensory input. It is receiving long-term memory as current state *St*, and using it decides what action to take. The actions generated from DQN are six values where each one is one of [-1 ,0, +1] that are going to be added to previous corresponding timings and durations to “update” them.

The model implemented is a dual neural network architecture. It consists of one LSTM first then a fully connected neural network implemented as deep Q learning.

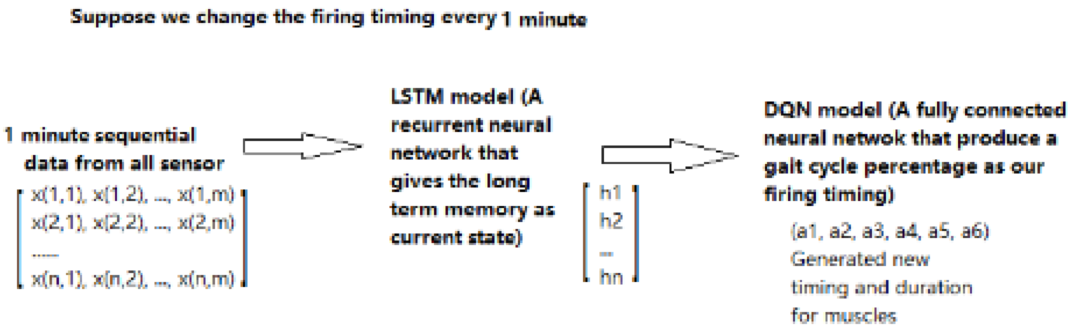


Figure 34: The dual neural network architecture and the data it processed.

By LSTM, a variety of signals (a number of n signals) from multiple sensors, which all last for m timestamps, are compressed into a vector of long term memory (h, n). The LSTM has a two recurrent layer architecture, which means stacking two LSTMs together with the second LSTM taking in outputs of the first and computing the final results. The number of features in the hidden state is 256, and the LSTM is used with n projection size. Therefore, the output long term memory vector size is $(n\ *\ 2)$. In order to generate valuable long term memory, our LSTM is trained to predict the next timestamp, which requires the neural network to learn the general aspects of a periodical signal. (Hochreiter et al., 1997) The structure of the LSTM cell and equations that describe how a long term memory is derived from a LSTM cell, where $i_t = \sigma(x_t U^i + h_{t-1} W^i)$, $f_t = \sigma(x_t U^f + h_{t-1} W^f)$, $o_t = \sigma(x_t U^o + h_{t-1} W^o)$, $\hat{C}_t = tanh(x_t U^g + h_{t-1} W^g)$, $C_t = \sigma(f_t * C_{t-1} + i_t * \hat{C}_t)$, $h_t = tanh(C_t) * o_t$. (Varsamopoulos et al., 2017)

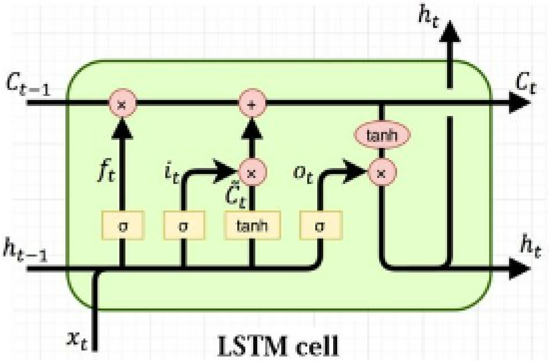


Figure 35: The structure of the LSTM cell that describes how a long term memory is derived from a LSTM cell. (Varsamopoulos et al., 2017)

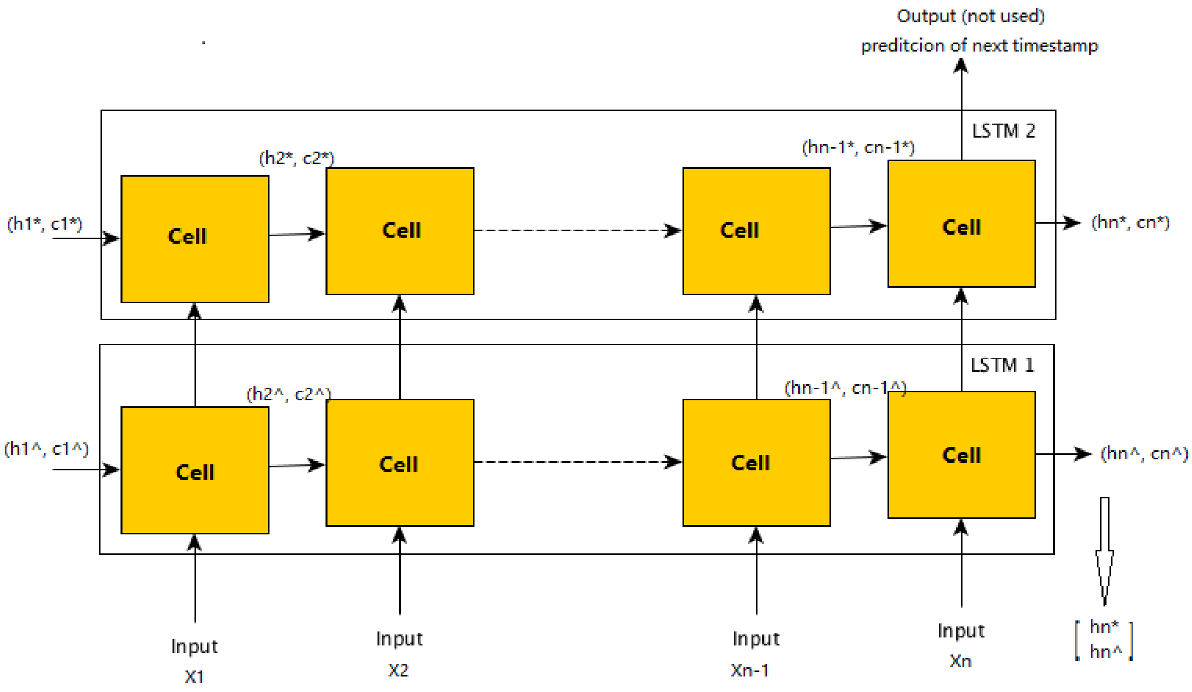


Figure 36: LSTM architecture and. The two layer LSTM generate $(n\ *\ 2)$ sized long term memory vector.

The fully connected neural network is implemented as a deep Q network to perform the reinforcement learning. It is receiving a long-term memory vector previously generated from LSTM as the current state *St.* Using *St* combined with each possible action, the model will generate a corresponding Q-value. Then the action which is able to generate the largest Q-value will be chosen as estimated current action *At*.

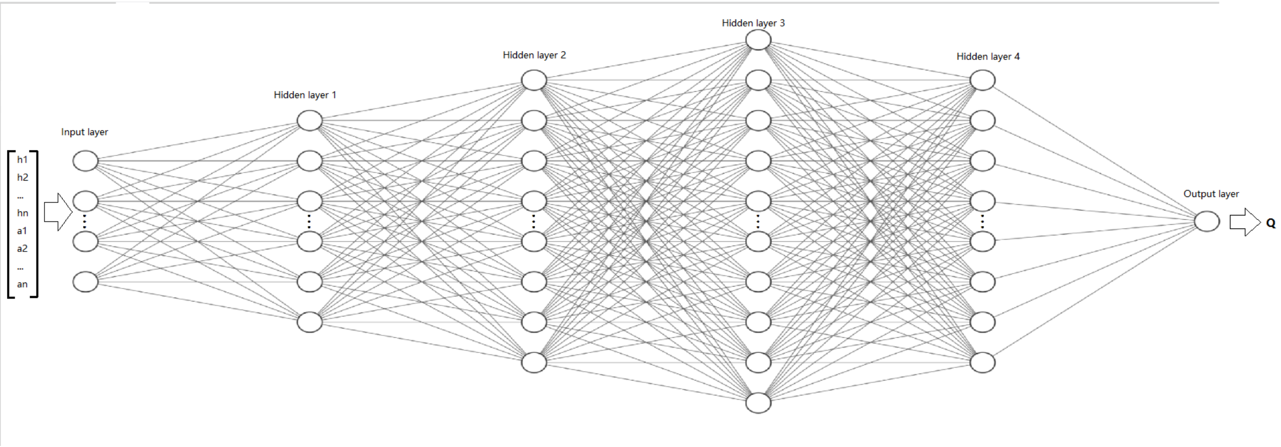


Figure 37: DQN architecture:The deep Q network consists of a 6 -layer fully connected neural network, and between each layer the element-wise activation function, Leaky ReLU, is applied. The first layer is the input layer, it takes a vector containing both *St* and *At*. The last layer is the output layer, it generates a single Q-value for this *St* and *At* combination. (NN-svg., 2018)

The deep Q network is trained using the Bellman equation $y_n = r(x_n, u_n) + \gamma Max_a Q(x_{n+1}, a : w)$, where the discounting factor γ is set to 0.99. The reward function *r(x, u)* is only using one policy: negative average heart rate reading of the corresponding state. (O'Donoghue et al., 2017) The Hubber_Loss function, $Hubberloss(y_n - Q(x_n, u_n : w))$, was used to determine the loss that updates the weights of the neural network by backpropagation. (O'Donoghue et al., 2017)

There are approximately 150 datasets collected to train the neural networks. During the data collection, every minute a random action will be generated. The sensor data and random action data are saved into a csv file every experiment for offline training. Neural networks were first trained with 90% of the dataset and tuned with 10% of the datasets. After tuning, 100% of datasets are used to train two neural networks. The LSTM was trained with 128 batch size, and NAdam optimizer with a learning rate scheduling from 0.01 to 0.0001 and 250 epoches. The deep Q network was trained with 64 batch size, and Adam optimizer with a learning rate scheduling from 0.001 to 0.00001 with 350 epoches.

Comparison Method for Reinforcement Learning

To measure the performance of neural network based control, as well as setting an initial set of timings and durations for actions generated from neural networks to update, we need to determine a gait cycle that is generally fit to most humans. Then we can use those constant gait parameters to perform the control process as a comparison to the neural network based updated gait parameters.

We attached the unextended hydro-muscles on different varieties of people and recorded the force pulling on them, when people were walking, using the force sensors attached on hydro-muscles. Then we observed the peaks of the force wave between people to people. Combining with the change of joint angles of lower limbs configuration, we concluded the timing and duration on each of three muscles which is symmetrically applied to both legs. As a result, we derived six numbers in a range of 0 - 100 that represent the timing and duration parameters of a gait cycle that is general to most people. (Tidy et al., 2013)

[47, 30, 13, 65, 58, 55] represents [Quad_timing, Calf_timing, Glut_timing, Quad_duration, Calf_duration, Glut_duration].

These constant parameters are used as gait parameters through the experiment as a comparison to the parameters that the reinforcement learning method updates every minute. By comparing the result of two methods, we can have a better understanding of the performance of reinforcement learning.

Experiments

Equipment

In order to complete this experiment, certain pieces of equipment are required. Firstly, the Bioinspired Exosuit is a necessity in order to test the functionality of the exosuit. At least one air compressor is needed in order to power the Bioinspired Exosuit. This is due to the Hydro Muscles utilizing compressed air at approximately 100 psi to actuate each of the twelve Hydro Muscles. For this experiment, we use a Husky 4 Gallon 225 PSI High Performance Crew Electric Portable Air Compressor to supply the Hydro Muscles. Additionally, since participants are tethered to the air compressor, a treadmill is required to be able to walk comfortably in place. For this purpose an XTERRA Fitness TR150 Folding Treadmill is employed for all walking portions of the test. To collect data on the participant's heart rate, the Polar H10 heart rate monitor is employed. Finally, one of the team member's laptops is connected through serial to the Bioinspired Exosuit to collect data from the exosuit and the Polar H10 device.

Procedure

Before starting the exosuit testing, a baseline heart rate and control test results must first be collected. Participants are instructed to put on the Polar Device so the heart rate at rest can be collected for a baseline. Then, participants are instructed to walk at three different speeds for a total time of 1 minute per speed. These speeds are arbitrarily chosen between a range of 2 and 4.5 miles per hour, however, most speeds are chosen between 2 and 3.5 miles per hour for optimal results.

Figure 38: An image of a subject testing the Bioinspired Exosuit.

Next, preparations needed to be followed are listed below. Firstly, the exosuit must be fitted to the participant by clipping and tightening all straps. The Hydro Muscles are all inflated and secured to the participants via yellow string tied to straps of the exosuit. Before the walking test with the exosuit is performed, all mechanical and electrical components must be tested to ensure proper results. Next, participants repeat the walking test portion, this time wearing the Bioinspired Exosuit. A total of two different tests are required per participant with each test measuring at about 10 minutes per test. The first test uses constant gait parameters while the second test contains the Neural Network model to adjust gait parameters. Participants are allowed a rest between two tests while the data is being reviewed. Two average heart rates will be calculated to measure the energy consumed of the subject and saved for the result.

Experiment data

The orientation data, force waves, walking speed, gait percentage, current contracting timing and duration of each muscle, and heart rate have all been recorded into a csv file by the end of the experiment as synchronized signals. These data will help with the analysis of the assistive systems. The most important data, heart rate, is directly related to the energy expenditure during walking. (Brosh A., 2007) Since we aim to help the user walk easier, heart rate is a valid indicator for measuring the performance in our results.

Results

Figure 39 and 40: The Bioinspired Exosuit in a front (left) and back (right) view.

With only 8 lbs of weight and less larger than previous design, the suit is meant to be lightweight and wearable so that subjects will hardly feel burdens on their shoulders when having tests on the treadmill. The suit is reliable and durable enough for several hours of testing since the Machine Learning model requires a large amount of data sets.

The Neural Network enables the program to update the muscle firing timing and the duration, which was constant previously in our comparison method. According to the graph (right below), the straight blue line represents the control with constant gait parameters while the red line is the modified gait parameters by the Neural Network.

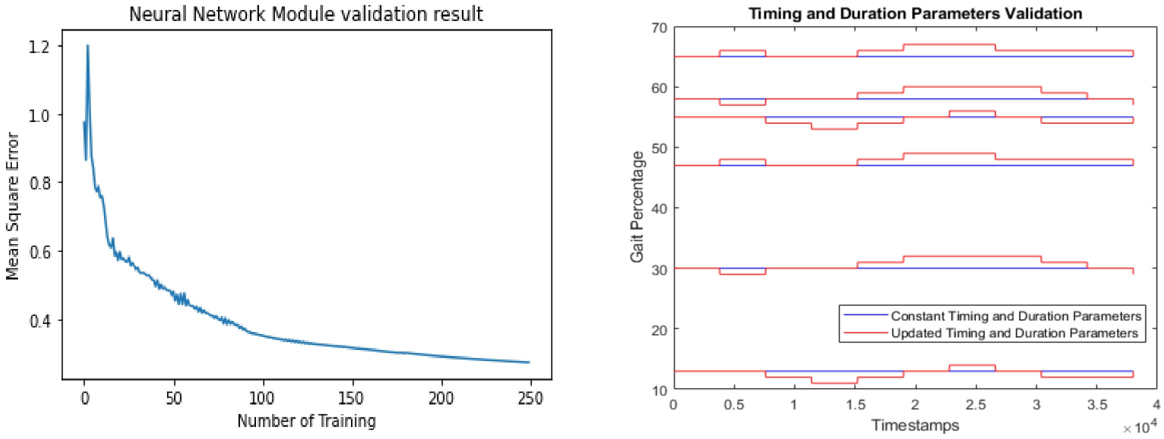


Figure 41 and 42: Neural network validation test (left) and the generated results (right).

Although there are fluctuations in the beginning, the error between the prediction from the Neural Network and test result is decreasing along with the time. The mean square error compares the predicted error and the real error and the result indicates the tendency of convergence in the model. Consequently, the model is functional to some extent.

The polar device detects the heart rate of the subject. Four subjects participated in the candidate pool and based on the table shown, all of the four tests show the validity of the suit, with or without Neural Network. For subject 1, the heart rate decreased to a great amount, but the average heart rate changed with the Neural Network is slightly higher. For the rest of the three results, our Neural Network shows a great adaptation to various subjects. And the second subject showed a less significant change in heart rate when wearing the suit.

Effect of the Bioinspired Exosuit on average heart rate (BPM)			
Subject	Speed (MPH)	Average change in heart rate (Constant Parameters)	Average change in heart rate (Neural Network Updated Parameters)
1	2.3, 3.1, 2.7	-16.65%	-14.26%
2	2.9, 3.5, 2.1	+0.56%	-4.66%
3	2.2, 3.4, 2.6	-8.59%	-15.15%
4	2.1, 3.6, 2.4	-4.71%	-11.62%

Table 1: The effect of the Bioinspired Exosuit on the subjects' heart rates.

Discussion

Bioinspired Exosuit

The results gathered from the experimentation confirm the Bioinspired Exosuit is successfully meeting its goals. As expressed in Table, subjects experienced an average decrease in heart rate of about 7.35% using constant parameters. Furthermore, the average decrease in heart rate for the neural network parameters is about 11.33%. Although results per subject varied, all subjects were able to walk easier than with no assistance. Although sufficient data was collected to determine the effectiveness of the Bioinspired Exosuit, the same cannot be said for the neural network model. Although it suggests a positive tendency, there was not enough information collected to conclude if the neural network model is completely functional.

In our previous tests, the exo-suit performance also indicates that its effect on the human body is weaker under higher speed than lower speed. This may be because when the walking speed is fast, the bio-muscles move faster than the limit of hydro-muscles, thus the exo-suit starts to lose track of subjects as well as the speed chosen with respect to his/her height.

Additional Remarks

Considering the Bioinspired Exosuit is in its prototyping phase, this device is very fragile. All components have been placed on the suit for testing purposes, so components under more stress than anticipated will loosen or break. Moreover, plans were initially made to work with the Massachusetts Institute of Technology by accessing their PNOE device, which measures metabolic cost. However, when these plans fell through due to unforeseen circumstances, a new measuring standard needed to be decided on. The heart rate was chosen as the measuring standard because of its direct correlation to a person's energy consumption. Although heart rate displays a direct correlation, it is undeniably more sensitive than the metabolic cost. A person's heart rate is prone to many factors outside the scope of control. In example, disease, sleep, stress, and even the weather are just a few factors that may affect a given person's heart rate.

Conclusion

In advance to previous development, we successfully upgraded the mechanical parts and constructed the control method for the suit. The newly made hydro muscles and CRFC valves are capable of exerting large assistance forces during the gait cycle while the lightweight backboard and strap systems reduce the burden for subjects to a great extent. Based on the four control group results, the Neural Network model is observed to be able to provide a solid and smooth help in addition to the calculated value of the gait cycle to pressurize the hydro muscles in our tests.

All of the four test subjects, who participated in both data collection and test, were satisfied with the comfort of the back pack, especially after we moved the air compressor to another room to lower the noise. Even though the heart rate is dependent on many factors, it still shows a decrease for both of our control methods.

Subjects 1 and 3 had worn the suit the longest time among the four, the results were especially good for them. The average heart rate decreased for subject 1 are 16.65% and 14.26% with constant parameters and Neural Network updated parameters, respecting the speed of 2.3, 3.1 and 2.7 MPH. As for subject 3, the average heart rate decreased for subject 1 are 8.59% and 15.15% with constant parameters and Neural Network updated parameters, respecting the speed of 2.2, 3.4 and 2.6 MPH.

Subjects 2 and 4 had relatively smaller heart rate decreases, but the difference in heart rate changed between using the constant parameter and the Neural Network updated parameters are noticeable further decreased, indicating the effectiveness of our Neural Network model. 5.22% and 6.91% improvements are given by the model with respect to 2.9 - 3.5 - 2.1 MPH and 2.1 - 3.6 - 2.4 MPH speed chosen.

The Bioinspired Exosuit has a significant number of potential uses in various fields including the assistance in physical therapy, rehabilitation and heavy duties, athletic training and even daily uses. It could also be a prototype and inspiration for future developments. As for current status, it can help people to walk faster and more comfortably with the help of the lightweight design and adaptiveness of Neural Network, which marks the progress of existing wearable devices.

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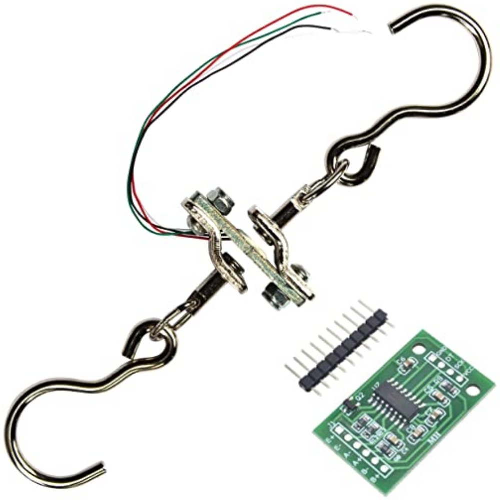
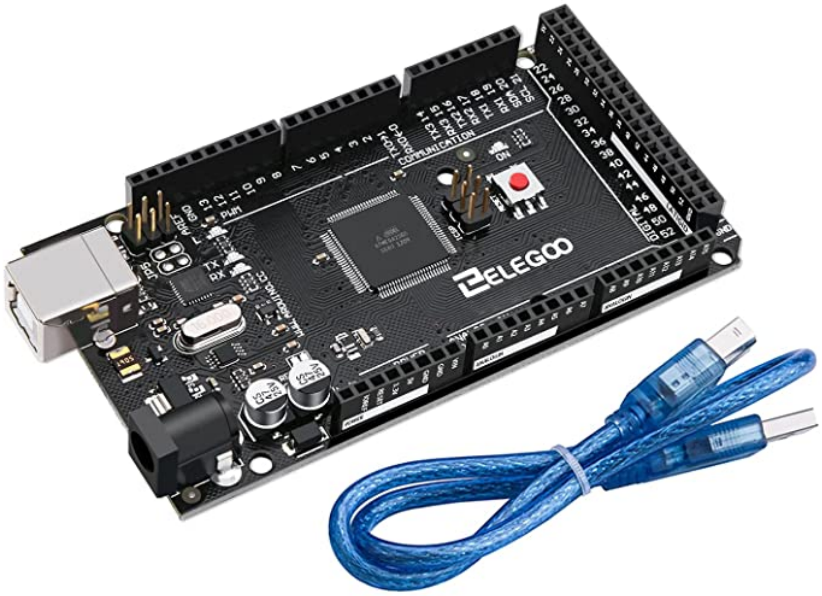
Appendix

Test (LB)	10	12	15	20	25	30	40	50	65	80
Test (KG)	4.6	5.5	6.8	9.1	11.4	14.1	18.2	22.7	29.6	36.4
Diameter (mm)	0.09	0.10	0.14	0.18	0.22	0.25	0.30	0.40	0.45	0.50

String type we use to construct the CRFC valve.

Servo selection: KST X10 High speed, High torque servo

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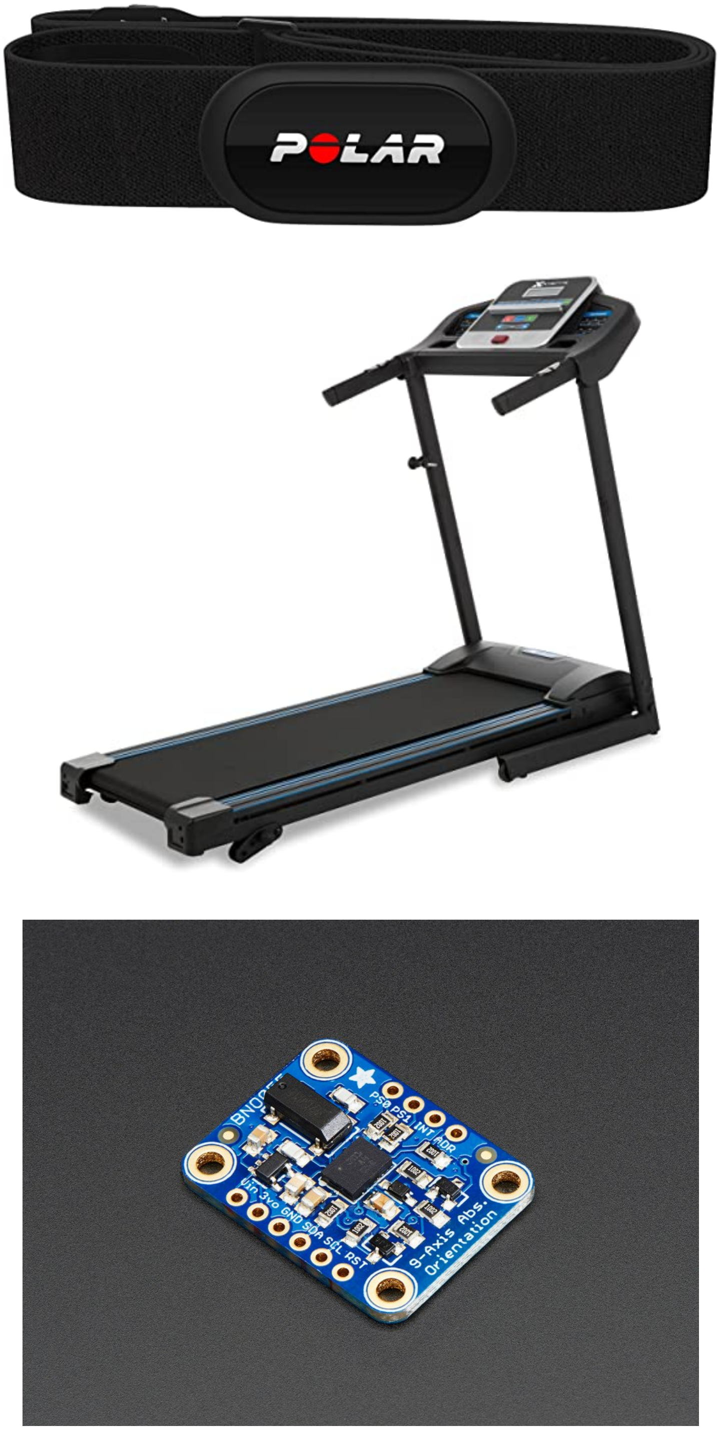

Electronics selections

$$x_2 = x_1 + L_1 * cos(\theta_{hip})$$
$$x_3 = x_2 - L_2 * cos(\pi - \theta_{knee})$$
$$x_4 = x_3 - L_3 * cos(\theta_{ankle})$$

$$y_2 = y_1 - L_1 * sin(\theta_{hip})$$
$$y_3 = y_2 + L_2 * sin(\pi - \theta_{knee})$$
$$y_4 = y_3 + L_3 * sin(\theta_{ankle})$$

$$x_{heel} = x_4 + L_4 * cos(\theta_{ankle})$$
$$y_{heel} = y_4 - L_4 * sin(\theta_{ankle})$$

$$x_{upper} = 0.25 * x_2$$
$$y_{upper} = 0.25 * y_2$$
$$x_{lower} = 0.75 * x_2$$
$$y_{lower} = 0.75 * y_2$$

$$x_{glute} = G_x - x_{upper}$$
$$y_{glute} = G_y - y_{upper}$$
$$x_{quad} = Q_x - x_{upper}$$
$$y_{quad} = Q_y - y_{upper}$$
$$x_{calf} = x_{heel} - x_{lower}$$
$$y_{calf} = y_{heel} - y_{lower}$$

$$L_{glute} = \sqrt{x_{glute}^2 + y_{glute}^2}$$
$$L_{quad} = \sqrt{x_{quad}^2 + y_{quad}^2}$$
$$L_{calf} = \sqrt{x_{calf}^2 + y_{calf}^2}$$

The forward kinematics of the 2D Leg Model.

Legend for equations:

x1, y1	X2, y2	X3, y3	x4, y4
Hip Joint	Knee Joint	Ankle Joint	Foot

Gx, Gy	Qx, Qy	LGlute, LQuad, Calf
Suit Glute Attachment Point	Suit Quad Attachment Point	Muscle Lengths