Gait Control of Lower Body Exoskeleton

B. Tech Final Year Project Review

Project Members

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Project Guides

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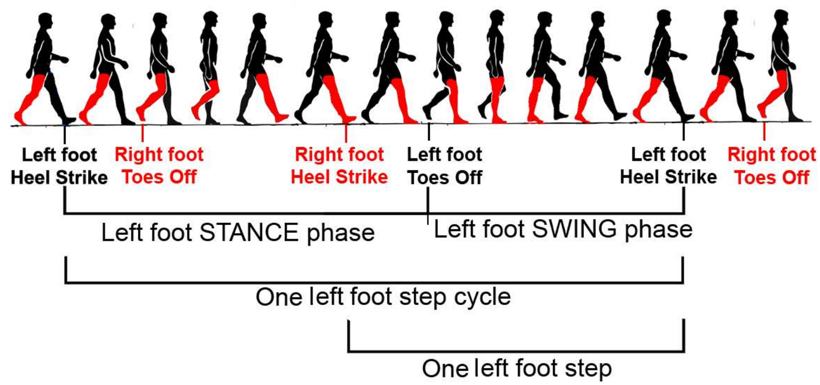
Introduction

What is Gait?

Gait refers to the movement pattern of the limbs during locomotion, commonly associated with walking. It involves a coordinated sequence of movements of the legs and arms to propel the body forward.

What happens to gait under load?

Adding weights alters the biomechanics of gait by increasing the load on muscles and joints. It may lead to changes in stride length, step frequency, and overall stability as the body adapts to the added load.



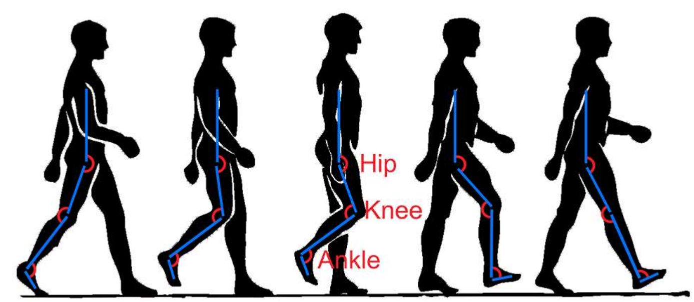


Image Source: Georgiou, T., et.al (2020)

Introduction (Continued)

What are Exoskeletons?

Exoskeletons are wearable robotic devices (over specific regions or overall, of the body) designed to enhance physical performance. They augment power by providing mechanical assistance to muscles, reducing fatigue, and increasing endurance.

How do exoskeletons help?

Exoskeletons distribute weight more evenly across the body, changing the load path and thus reducing the strain on muscles and joints during weight-bearing activities. By supporting the load, exoskeletons enable individuals to carry heavier objects with less effort, improving overall mobility and productivity.

Image Source: DRDO developing exoskeleton for the Indian soldiers posted in high altitudes, Financial Express

Literature Review

S.No	Source	Title	Inference
1	Kinoshita, H. (1985). Ergonomics, 28(9), 1347–1362.	Effects of different loads and carrying systems on selected biomechanical parameters describing walking gait	Significant change of body posture and gait pattern observed when lifting heavy weights , indicating that the risk of encountering stress-related injuries is considerably greater as the load increased in magnitude.
2	Al-Shuka, et. al (2019).International Journal of Dynamics and Control, 7(4), 1462–1488.	Biomechanics, actuation, and multi-level control strategies of power-augmentation lower extremity exoskeletons: an overview	Factors such as interaction force wrench for control purpose, among others required for force augmentation to be considered for design of a control strategy for power augmentation in exoskeletons were discussed.
3	Grimmer, et. al. (2020). Frontiers in Robotics and AI, 7.	Human Lower Limb Joint Biomechanics in Daily Life Activities: A Literature Based Requirement Analysis for Anthropomorphic Robot Design.	A study of the range of motion and joint parameters (velocity, acceleration, torque, and power)exhibited by healthy subjects alongside a motion study of actions (such as walking, jogging, running, climbing, and sitting to standing) was presented.

Literature Review

S.No	Source	Title	Inference
4	Zoss, A, et. al. (2006). IEEE-ASME Transactions on Mechatronics, 11(2), 128–138.	Biomechanical Design of the Berkeley Lower Extremity Exoskeleton (BLEEX)	Introduces the 14 DOF (7 DOF per leg) lower extremity exoskeleton for power augmentation that anthropomorphic in design.
5	Amiri, M. S, et. al. (2019). IEEE Access, 7, 167210–167220.	Initialized Model Reference Adaptive Control for Lower Limb Exoskeleton	A comparative study of IMRAC and non-IMRAC rule on a closed-loop PID controller detailing the mathematical expression of the control schemes' LLE structure, transfer function, and convergence rates

Literature Gap

- Augmentative exoskeletons are not available in the market, and the research sector covers the entire leg with hip, knee, and ankle actuators (at least 6 DOF). The under-actuated exoskeletons (4 DOF, hip, and knee) in literature are still in the research phase, with their dynamic models either being treated as ones with single-point contact at the foot between the unit and the ground or having no contact with the ground (model, ends at above the ankle joint).
- A gap exists in the literature where the exoskeleton is underactuated, having a complete metallic sole unit in contact with the ground (multi-point contact).
- The approach for designing controller for exoskeletons and its implementation is not available in literature.

Aim

- Our work involves designing a controller for an underactuated Lower Limb Exoskeleton (4 DOF, only hip and knee joint control) that enhances the user's load-bearing capacity and testing the unit's efficacy on a flat plane. Thus, the feasibility of an underactuated system to provide power augmentation like traditional higher DOF exoskeletal systems is determined.
- We aim to work on an approach that strikes a balance between extensive modelling and model free PID approaches. Studying kinematics and dynamics to design compensators for over/undershoots on top of a PID architecture.

Objectives

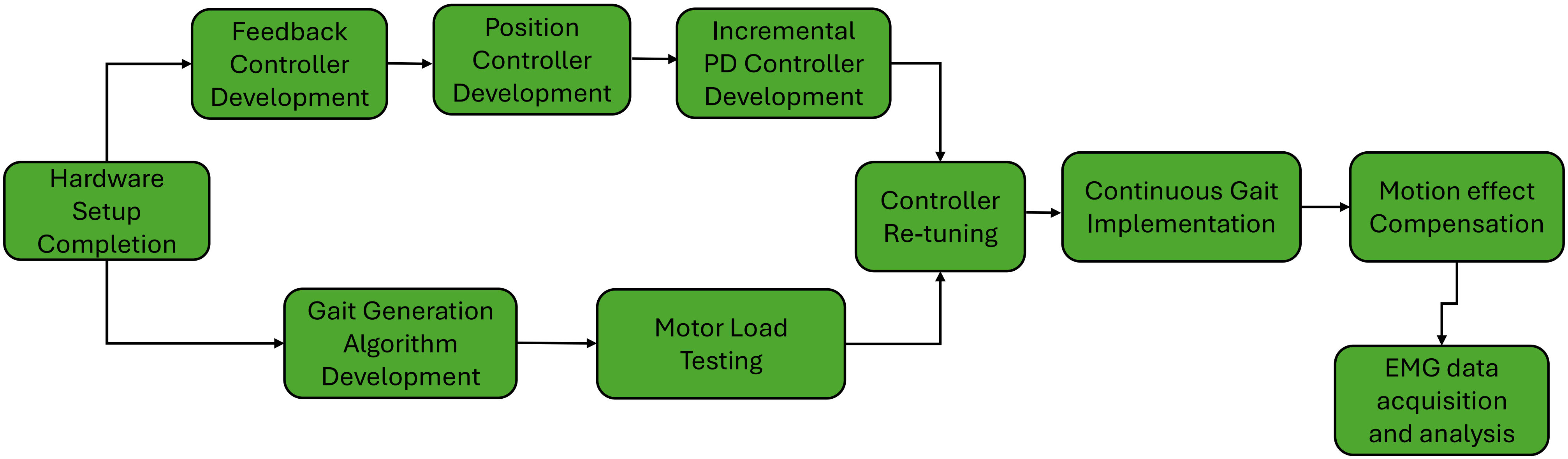
To configure torque controller and design position controller for a BLDC motor to reach and hold the position.

To analyze the differences in gait patterns and study contact forces at foot with and without load when using an exoskeleton and when not using an exoskeleton.

To deploy an PD + Bang Bang controller to trace a desired gait pattern on both external weight-loaded and without external weight-loaded conditions.

To test the developed controller's efficacy in augmenting the user's strength by studying the spikes in forces at the foot when using the exoskeleton.

Methodology



Experimental Setup

Front View

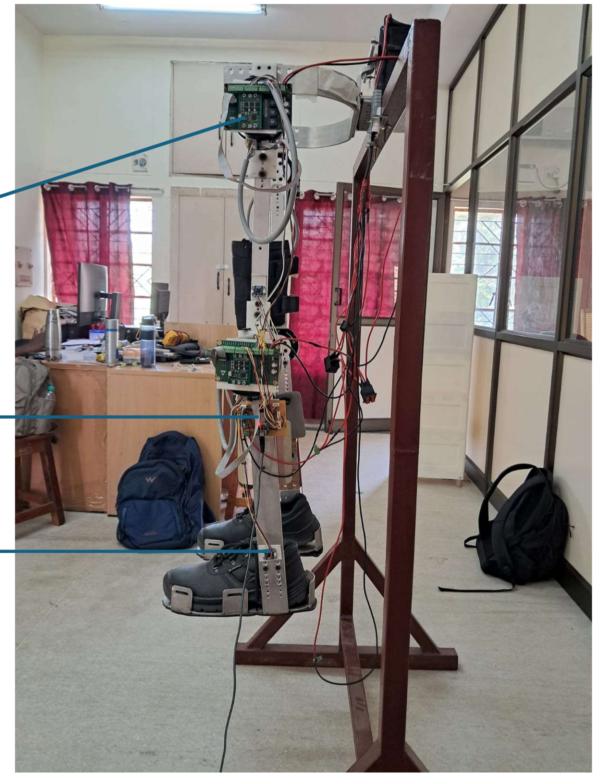
Battery

Motor

Motor Driver

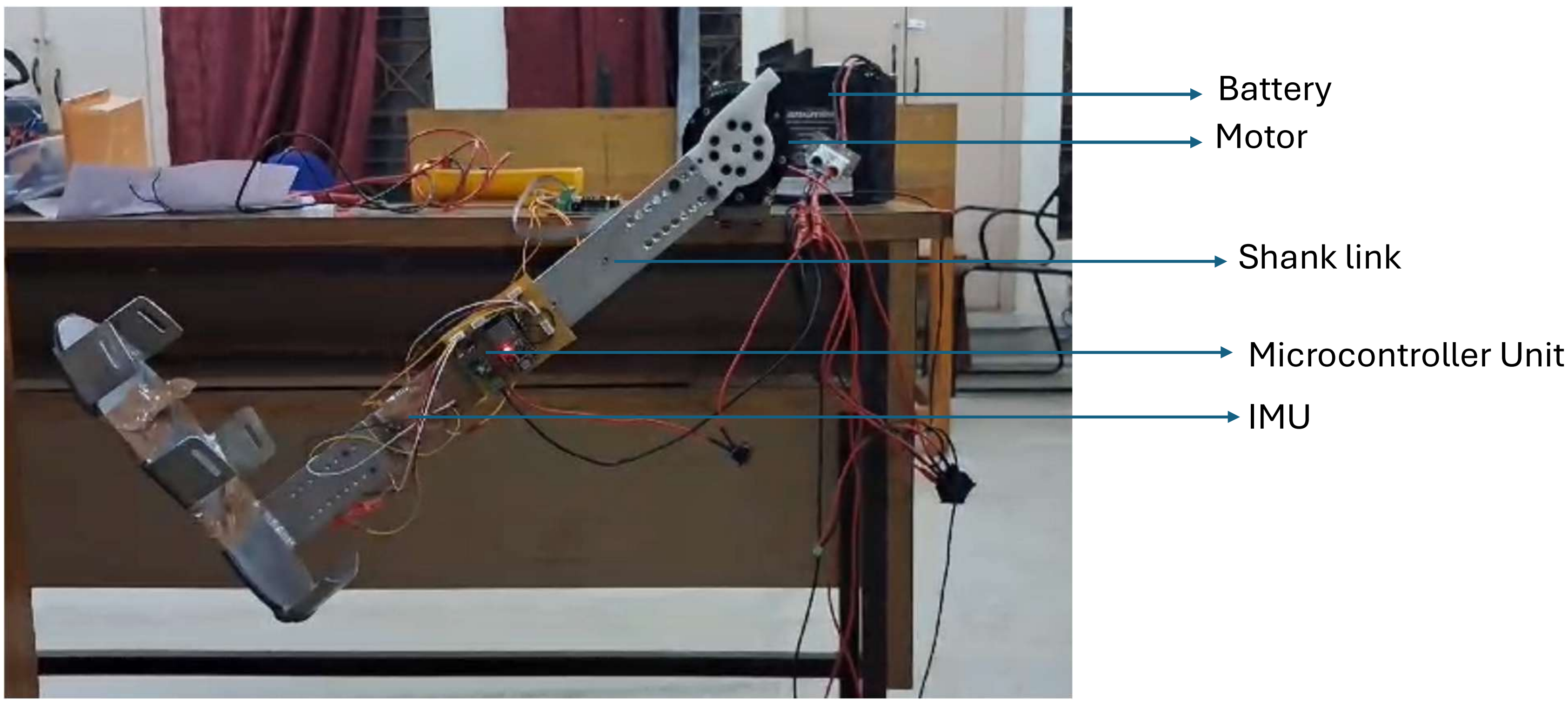
Microcontroller Unt

Inertial Measurement Unit

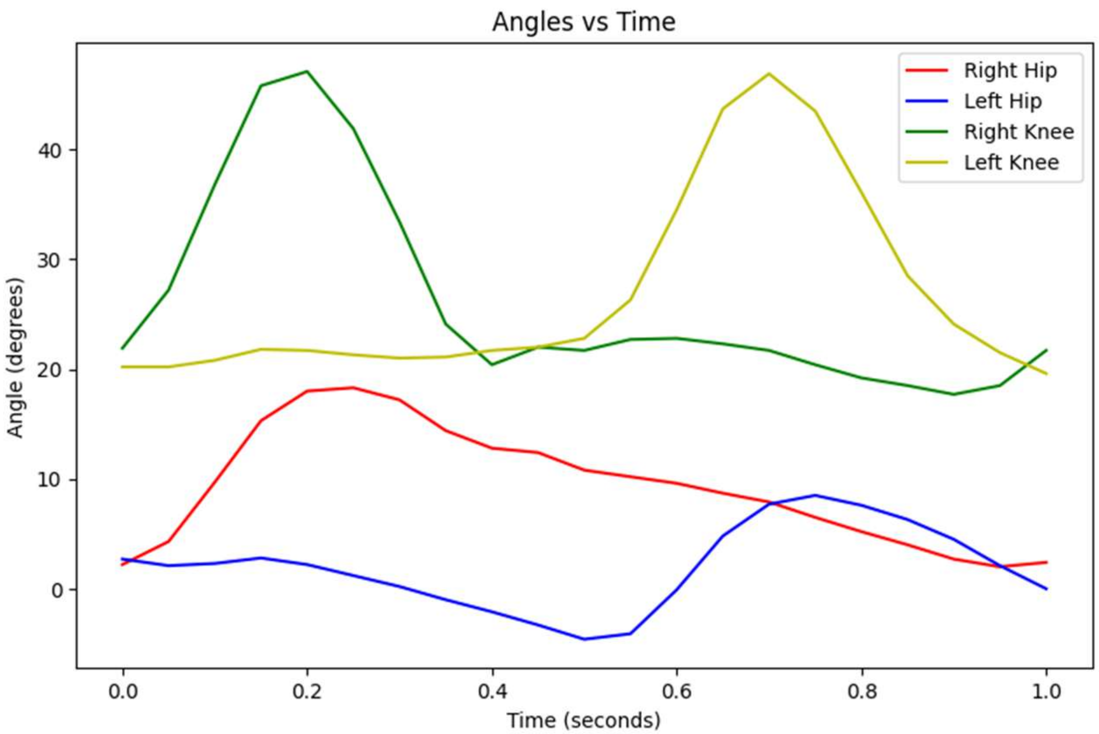


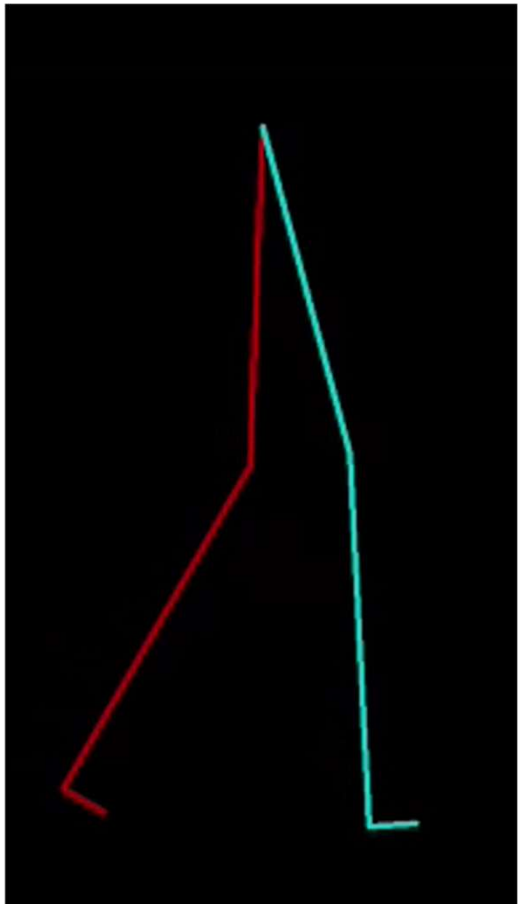
Side View

Results – Single DOF Position Controller

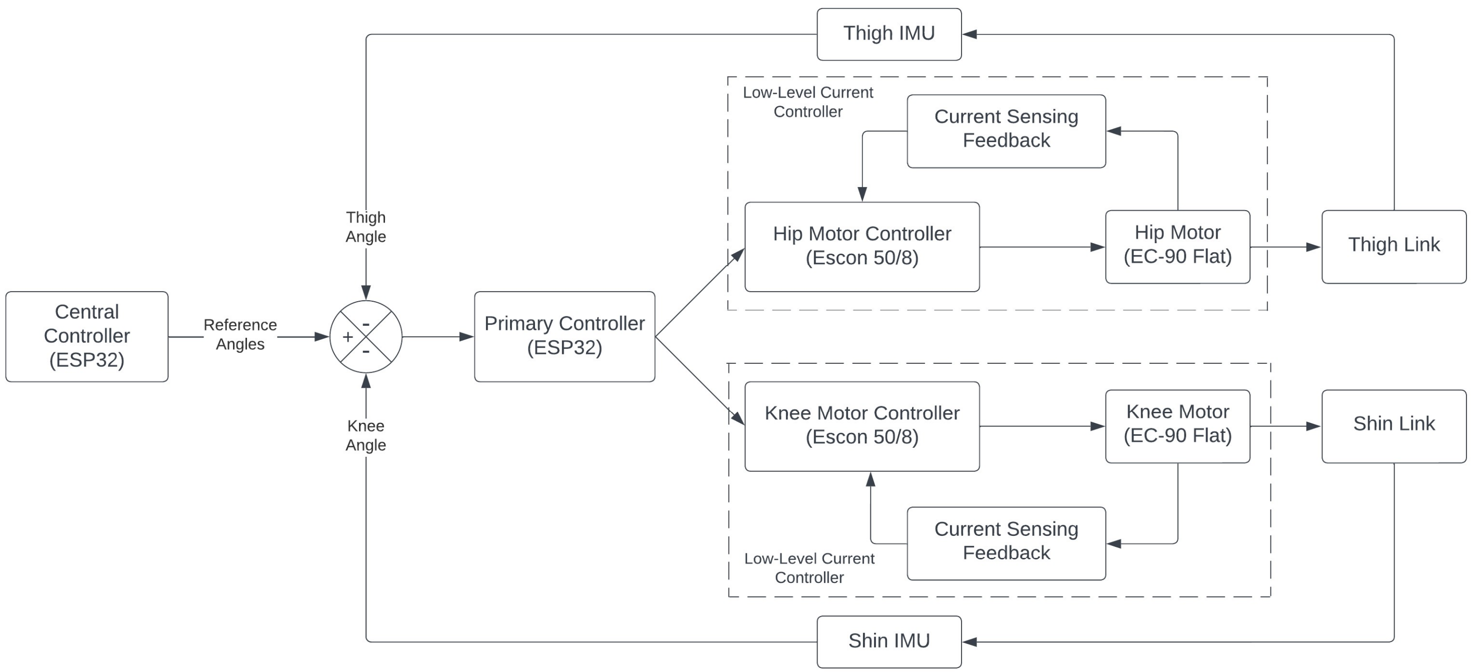


Results – Gait Data Study and Visualization



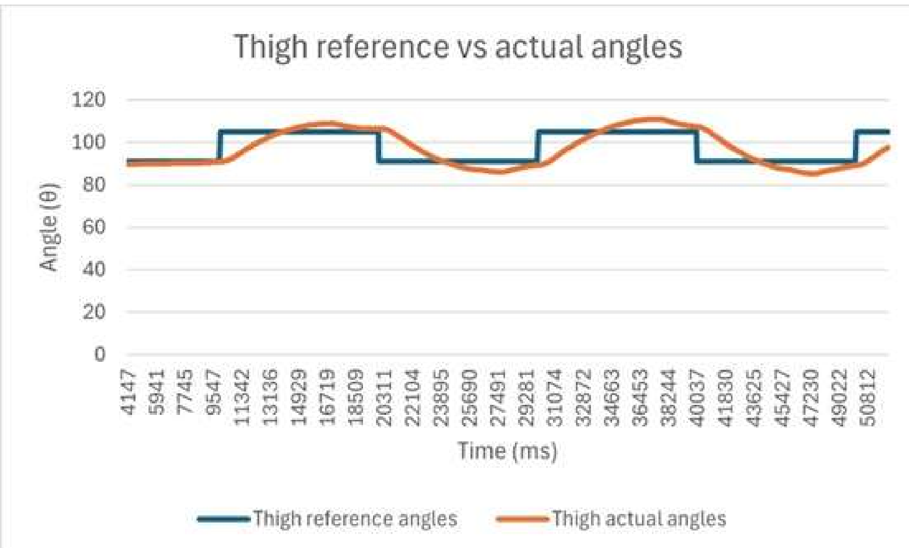


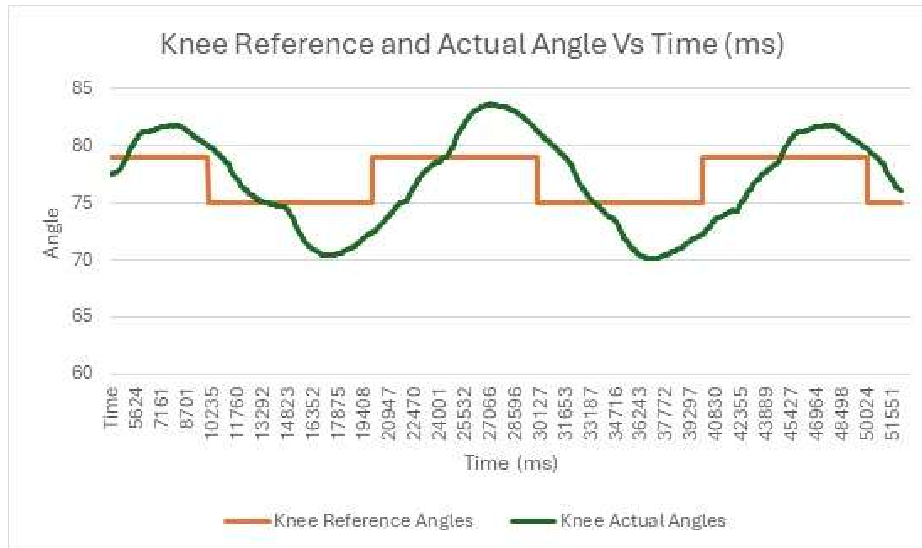
Controller Architecture



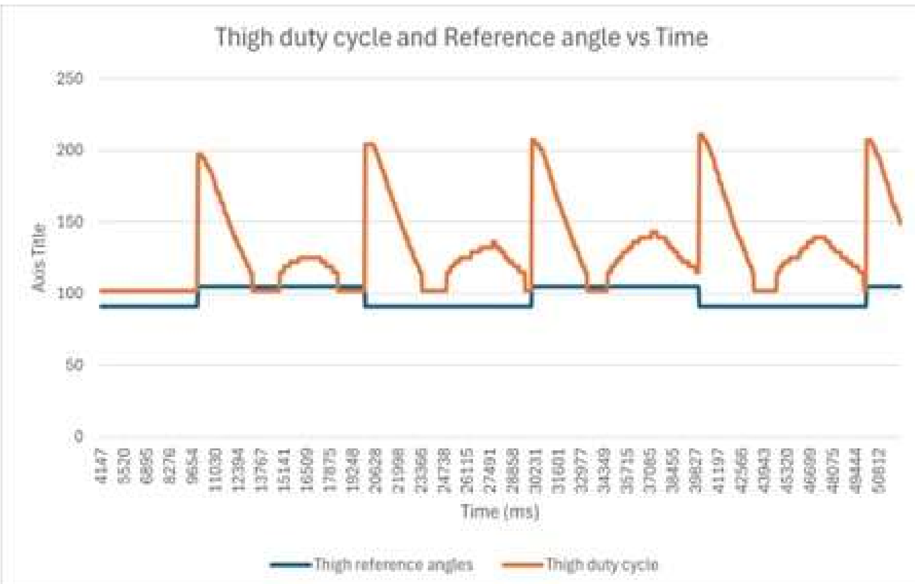
Results - Single Leg Gait Cycle

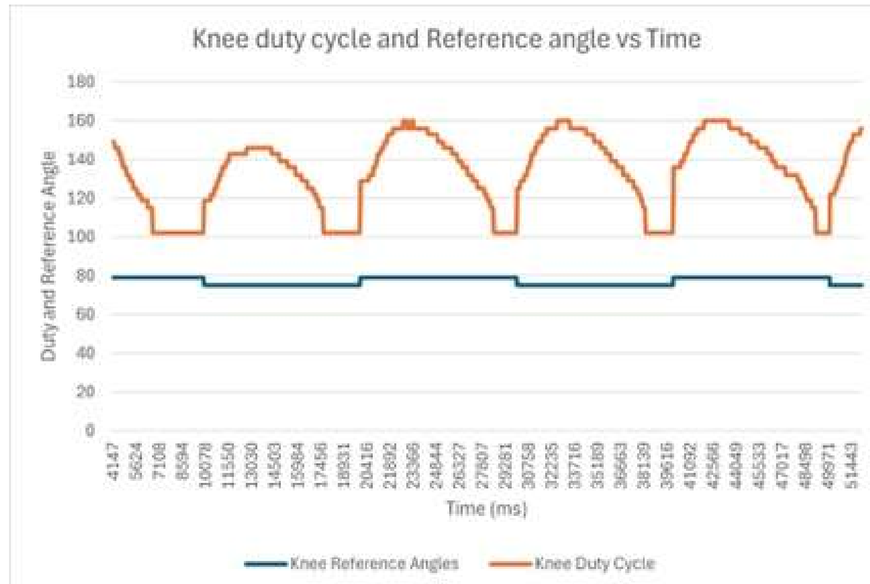
Results – Controller Response



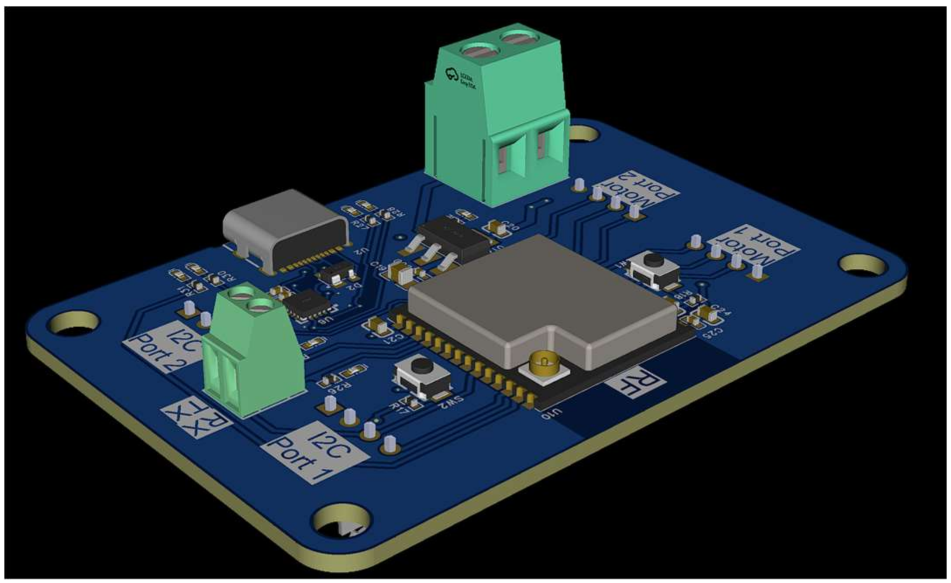


Controller Response

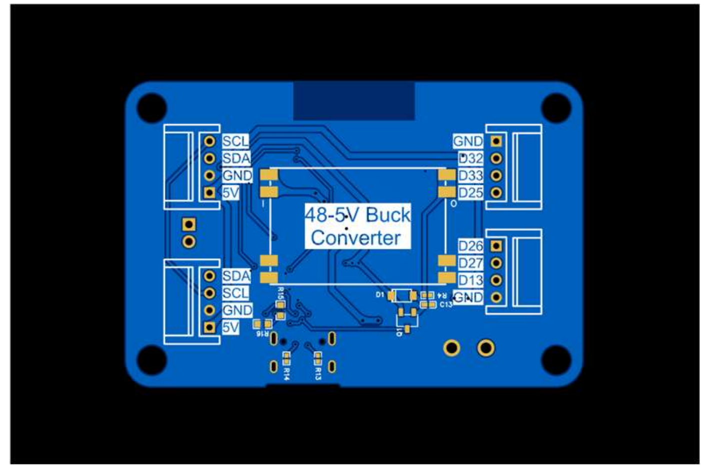




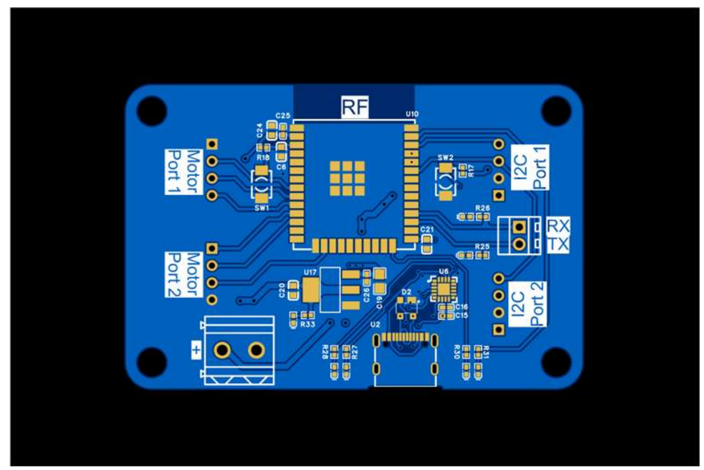
PCB Design



Motor Port 2
Motor Port 1
I2C Port 2
RX TX
I2C Port 1
RF



SCL
SDA
GND
5V
GND
D32
D33
D25
48-5V Buck Converter
D26
D27
D13
GND
SDA
SCL
GND
5V



RF
Motor Port 1
I2C Port 1
RX TX
Motor Port 2
I2C Port 2

Code Base

Angle Update

```
double thigh_points[2] = {91, 105};
double shin_points[2] = {79, 75};
int i = 0;
```

```
void update_values() {

  unsigned long current_time = millis();

  if (current_time - previous_time >= stabilizing_time) {
    i = 1 - i;
    previous_time = current_time;
  }
}
```

Setpoint look up table, and open loop timer based update function

Feedback

```
void feedback() {
  update_values();
  sensors_event_t theta_thigh, theta_shin;

  bno_thigh.getEvent(&theta_thigh, Adafruit_BNO055::VECTOR_GRAVITY);
  bno_shin.getEvent(&theta_shin, Adafruit_BNO055::VECTOR_GRAVITY);
  thigh_error = thigh_points[i] - get_angle(&theta_thigh);
  shin_error = shin_points[i] - get_angle(&theta_shin);
}

double get_angle(sensors_event_t* event) {
  double temp_angle, x, y, z;
  event->type == SENSOR_TYPE_GRAVITY;
  x = event->acceleration.x;
  y = event->acceleration.y;
  z = event->acceleration.z;

  if (abs(z) > 3) {
    Serial.println("Please hold the mount vertical.");
  }
  else {
    if ((x < 0) && (y < 0)) {
      temp_angle = (atan(y / x) * 57.2957795131);
    }
    else if ((x > 0) && (y < 0)) {
      temp_angle = 180 - (atan(y / x) * 57.2957795131);
    }
    else if ((x > 0) && (y > 0)) {
      temp_angle = (atan(y / x) * 57.2957795131);
    }
    else {
      temp_angle = 180 - (atan(-y / x) * 57.2957795131);
    }
  }
  if (temp_angle > 180) {
    temp_angle = temp_angle - 180;
  }
  return temp_angle;
}
```

Code Base - Controller

```
void controller() {
  feedback();
  double temp_shin;

  if ((thigh_error >= 0)) {
    digitalWrite(4, HIGH);
    digitalWrite(THIGH_CW, LOW);
    thigh_controller_output = abs(Kp_thigh * thigh_error);
    temp_shin = abs(Kp_shin * shin_error) - thigh_controller_output;
    if (shin_error >= 0) {
      if (temp_shin >= 0) {
        digitalWrite(SHIN_CW, LOW);
        digitalWrite(SHIN_CCW, HIGH);
        shin_controller_output = abs(temp_shin);
      }
      else {
        digitalWrite(SHIN_CW, HIGH);
        digitalWrite(SHIN_CCW, LOW);
        shin_controller_output = abs(temp_shin);
      }
    }
    else if (shin_error < 0) {
      digitalWrite(SHIN_CW, HIGH);
      digitalWrite(SHIN_CCW, LOW);
      shin_controller_output = abs(Kp_shin * shin_error) + thigh_controller_output;
    }
  }
```

```
  else if ((thigh_error < 0)) {
    digitalWrite(THIGH_CW, HIGH);
    digitalWrite(4, LOW);
    thigh_controller_output = abs(Kp_thigh * thigh_error);
    if (shin_error >= 0) {
      digitalWrite(SHIN_CW, LOW);
      digitalWrite(SHIN_CCW, HIGH);
      shin_controller_output = abs(Kp_shin * shin_error) + thigh_controller_output;
    }
    else if (shin_error < 0) {
      temp_shin = abs(Kp_shin * shin_error) - thigh_controller_output;
      if (temp_shin >= 0) {
        digitalWrite(SHIN_CW, HIGH);
        digitalWrite(SHIN_CCW, LOW);
        shin_controller_output = abs(temp_shin);
      }
      else {
        digitalWrite(SHIN_CW, LOW);
        digitalWrite(SHIN_CCW, HIGH);
        shin_controller_output = abs(temp_shin);
      }
    }
  }
  actuation();
}
```

Controller output to calculate speed based on error, with dynamic motion disturbance rejection

Code Based - Actuation

```
void actuation() {
  int shin_duty, thigh_duty;
  if (abs(shin_error) > 2) {
    shin_duty = int(map(shin_controller_output, 0, 240, 102, 922));
  }
  else if (abs(shin_error) <= 2) {
    shin_duty = 102;
  }

  if (abs(thigh_error) > 2) {
    thigh_duty = int(map(thigh_controller_output, 0, 240, 102, 922));
  }
  else if (abs(thigh_error) <= 2) {
    thigh_duty = 102;
  }
  Serial.println(thigh_duty);
  ledcWrite(shinChannel, shin_duty);
  ledcWrite(thighChannel, thigh_duty);
}
```

Map functions to convert speed into duty cycle, and threshold based system actuation

Conclusion of the research

i. Repeating gait cycles and achieving poses is task that should be handled in parallel for multiple DOF systems. Microcontrollers with more than one core should be employed for the task of position control, with each core monitoring one motion.

ii. The time domain response of the system on a square wave setpoint pulse has been noted. Further response-based PD tuning of the controller is now possible, since require data was obtained.

iii. A speed-based control, although easier to deploy, is not the most robust solution to the position control task. This is due to the absence of an element of impedance control or a direct torque-based input. As such, it is advisable to work on current based control approaches.

iv. The exoskeleton was worn, and EMG data output on actuation was studied to quantify that the user strength was amplified by a factor of 5. Thus, the low-cost exoskeleton prototype can augment user strength.

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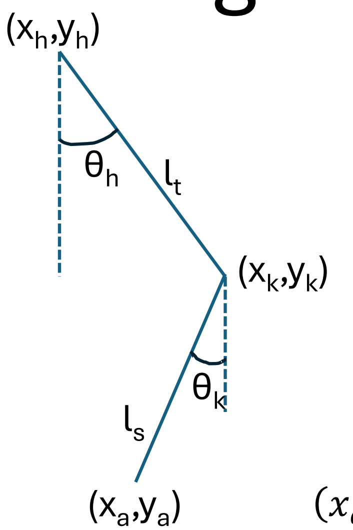
Appendix – System Modelling for Controller Design



$$(x_h, y_h) = (0, 0)$$

$$(x_k, y_k) = (l_t \sin\theta_h\,, -l_t \cos\theta_h\,)$$

$$(x_t, y_t) = \left(l_t \sin\theta_h + l_s \sin\theta_k\,, -(l_t \cos\theta_h + l_s \cos\theta_k)\right)$$

$$\left(x_k{}', y_k{}'\right) = [l_t \sin\theta_h \cos\omega_h\, dt\; + l_t \sin\omega_h dt \cos\theta_h\;\, , -l_t \cos\theta_h \cos\omega_h dt\; + l_t \sin\theta_h \sin\omega_h dt]$$

$$(x_a{}', y_a{}') = [l_t \sin\theta_h \cos\omega_h dt + l_s \sin\theta_k \cos\omega_h dt + l_t \sin\omega_h dt \cos\theta_h + l_s \sin\omega_h dt \cos\theta_k, l_t \sin\theta_h \sin\omega_h dt + l_s \sin\theta_k \sin\omega_h dt - l_t \cos\theta_h \cos\omega_h dt\; - l_s \cos\theta_k \cos\omega_h dt]$$

Nomenclature

θ_h – Hip Angle
θ_k – Knee Angle
l_t – Thigh Length
L_s – Shin Length
(x_h,y_h) – Coordinates of Hip Joint
(x_k,y_k) – Coordinates of Knee Joint
(x_a,y_a) – Coordinates of Ankle Joint
ω_h – Hip Joint Velocity
ω_k – KneeJoint Velocity

$$The\ initial\ Slope\ betwen\ the\ thigh\ link\ and\ the\ shank\ link = \;\cot\theta_k$$

Continued

$$The\ final\ slope\ (m')\ after\ simplification = -\frac{\cos(\theta_k + \ \omega_h dt)}{\sin(\theta_k + \ \omega_h dt)}$$

$$m' = -\cot(\theta_k + \ \omega_h dt)$$

$$For\ the\ shank's\ angular\ position\ to\ be\ undisturbed\ by\ the\ thigh\ motion, \frac{dm}{dt} = 0, \lim \omega_h dt \ \rightarrow 0$$

$Which\ gives\ the\ result$

$$\csc^2(\theta_k + \ \omega_h dt)\big(\dot{\theta}_k + \ \omega_h dt\big) = 0$$

$Which\ gives\ the\ result \Rightarrow \ \boldsymbol{\dot{\theta}_k = -\omega_h}, which\ the\ compensation\ velocity\ to\ be\ provided\ to\ the\ Knee\ Actuator$

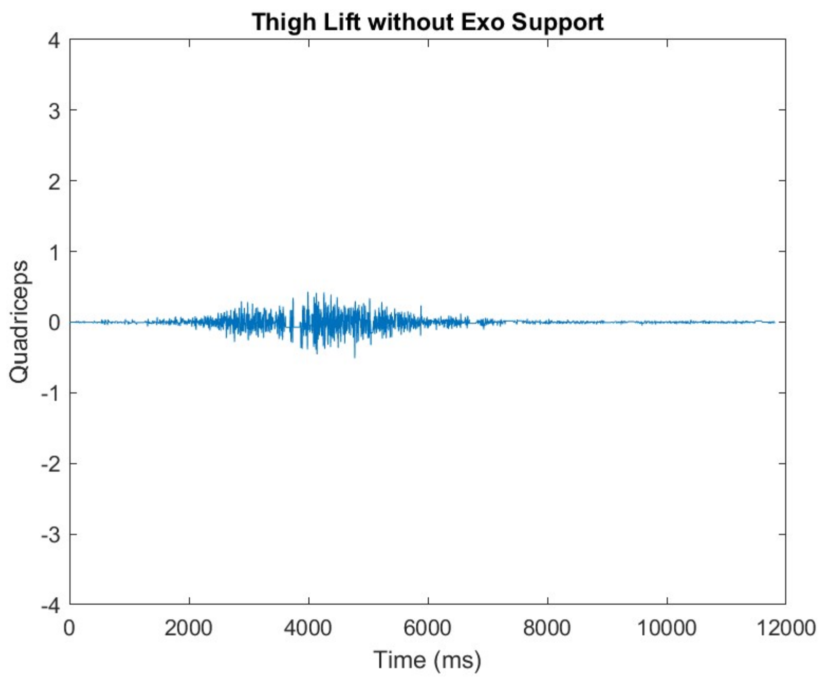
Appendix: Validation of exoskeleton strength augmentation

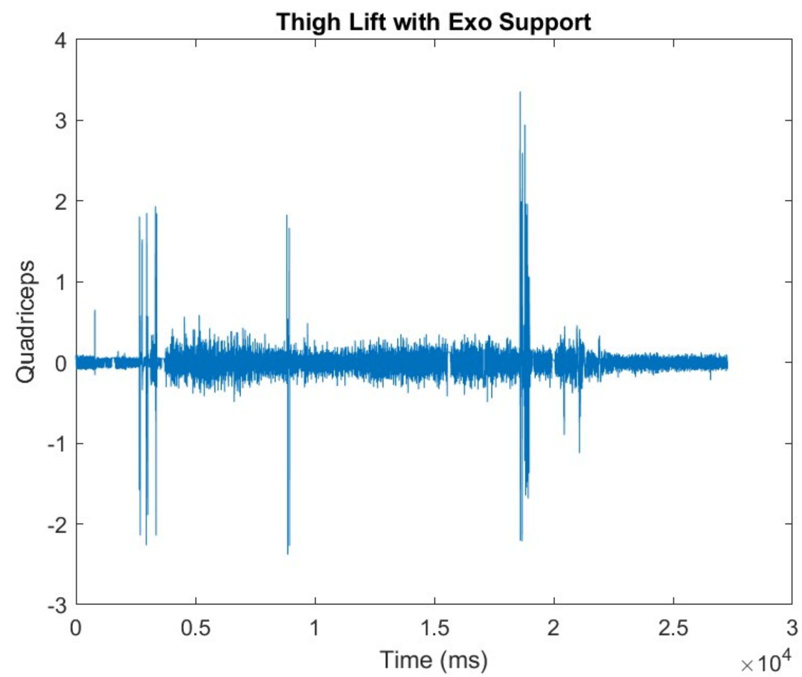
An experiment was conducted to quantify the strength and amplification capability of the exoskeleton. As such, a test subject was made to wear the exoskeleton and lift one leg with and without the support of the exoskeleton. EMG data from the quadriceps muscle group was taken as a measure of quantification of the muscle activity (the motion of the muscle, caused neural or from external support - by the exoskeleton)

Experiment Design (based on Seniam standards):

1. Target Muscle Group: The Rectus Femoris muscle is one of the dominant supporting muscles that lift the leg.
2. Sensors Used: An EMG Sensor with 3M electrodes was used, with a data sampling frequency of 2000Hz.
3. Electrode Placement: Three electrodes were placed on the target muscle, and one was placed close to the ankle joint bone as a reference. The inter-electrode separation is 20mm between the two electrodes on the muscle group. The direction of placement is in the direction of the muscle fibers.

Experiment Results





Inference:

The above EMG plots show the difference in muscle activity when the subject has no support in lifting and when the exoskeleton is functional.

- Case-1: Without support
  The EMG data shows a maximum spike with an amplitude of approximately 0.8mV, and the action on the muscle is concise. The phase during which the muscle was made to do work is short—a burst activity rather than a continuous activity. The rest of the plot shows close to no activity on the muscle.
- Case-2: With exoskeleton support
  The EMG data shows multiple maximum spikes with an amplitude of approximately 4mV, with the rest of the plot showing muscle activity close to 1mV. The continuous activity is consistent throughout the entire plot, with higher activity being in a burst form.

Conclusion:

From EMG data inferences, it can be concluded that the maximum strength exerted with support is five times that of without support. Moreover, the maximum strength with no support is the nominal strength with support. Thus, it can be concluded that the exoskeleton augments user peak strength by a margin of 400%, the nominal strength by a higher margin for higher durations.