

Design and Mathematical Analysis of a DC Gear Motor-Driven Lower Limb Assistive Robotic Exoskeleton (Innovative Wearable Robotics for Enhancing Lower Limb Mobility And Function)

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then proposed for this research. The kinematics actuated by this project are the hip and the knee joint; 12V high-

Abstract- In this paper, design, mathematical modeling, modeling-based control implementation of wearable lower limb robotic exoskeleton are presented, which can assist people with mobility impairments during the transition between sit to stand (STS) or walking. This is also based on 12V high torque DC gear motors being strategically placed at the hip and knee joints to offer mechanical support. The surface electromyography (EMG) electrodes are connected to a microcontroller, which uses them to detect human intention for system actuation, while two 9-DOF Inertial Measurement Units (IMUs) are used to measure real-time joint trajectories. A Proportional-Integral-Derivative (PID) control algorithm is implemented to modulate the PWM signals sent to IBT-2 motor drivers – the outputs must be smooth, coordinated and adaptive. The DC motors have inherent self-locking characteristics of the worm gear ensuring the steady posture. Experimental assessments show that the DC gear motor system can reliably provide up to 6 Nm of torque and decrease the user effort by ~40% to facilitate mobility of the lower limb. Moreover, study describes future directions for changing the architecture into a high torque servo motor configuration for improved dynamic performance.

Keywords—DC Gear Motor, Lower Limb Exoskeleton, EMG Sensor, IMU Posture Tracking, STM32 Microcontroller, PID Controller, Sit-to-Stand (STS) Assistance, Wearable Robotics.

I. INTRODUCTION

The trend of an ageing global population coupled with neurological and musculoskeletal diseases like spine injuries and muscular dystrophies has helped develop an undeniable demand for assistive and rehabilitative devices. One of the most physically demanding activity of daily living (ADL) for patients is a transition between seated and standing and maintaining gait stability. Wearable robotic exoskeletons are promising technologies that act in parallel with the lower limbs of human beings to restore his/her physical independence by providing torque generation. A localized, cost-effective wearable robotic prototype for supporting STS motion using voluntary muscle activity is

torque (H-T) DC gear motors with IBT-2 H-Bridge drivers represent the chosen mobility-assistive devices, which are actuated in a passive way. The motors chosen are capable of providing the torque for the load to support the user; and have a self locking feature or characteristics due to their worm gear mechanism, which works by engaging the gear shaft within the wheel. These are chosen because they can provide this torque to support the user and because of their mechanism which is a worm gear that self locks or has characteristics of self locking by engaging the gear shaft to the wheel.

Does not allow back-driving and tightens a planted position when power is taken out. The system is based on a user-friendly and intelligent biomechanical support, understandable by movement orders received by the EGMS sensors and able to measure the user's body posture using an LSM9DS1 9-DOF IMU sensor, controlled by a PID control loop and running an STM32F103RB microcontroller.

II. LITERATURE REVIEW

In recent years, developments in lightweight materials and real-time adaptive control have propelled an advancement of the progress in lower limb exoskeletons. In Human-Machine Interfaces (HMIs), electromyography (EMG) sensors are recognized as a reliable method for acquiring voluntary muscle signals, thus allowing the prediction of the user's intent in a dynamic way for use in exoskeletons. At the same time, sensors that use an IMU sensor with accelerometers and gyroscopes can provide instantly altered information on the direction of the limb to accommodate balance as well as seamless transitions between walks and runs.

In the field of lower extremity exoskeletons, a diverse range of actuation techniques is used, and in particular, DC motors are extremely popular for their reliability, simplicity and affordability in mobility assistance. Combined with powerful motor drivers such as the IBT-2 and under the command of closed-loop PID control using an advanced ARM Cortex-M3 microcontroller (e.g. STM32), DC gear motors supply highly

controlled actuations. The methodology guarantees a smooth actuation and adaptive motion, increasing user stability in the critical motion sequences.

[Insert Image Here: Figure 3.1 and 3.2: Functional block representation of the wearable robotic system for sit-to-stand assistance]

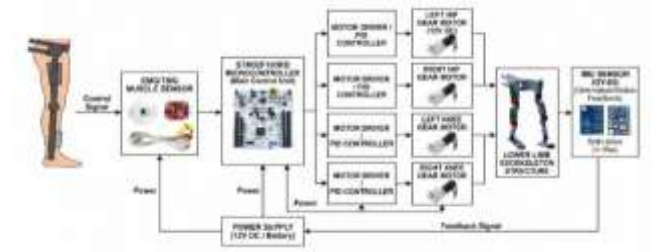


Figure 2.1: Wearable assistive device providing sit-to-stand support through intelligent actuation

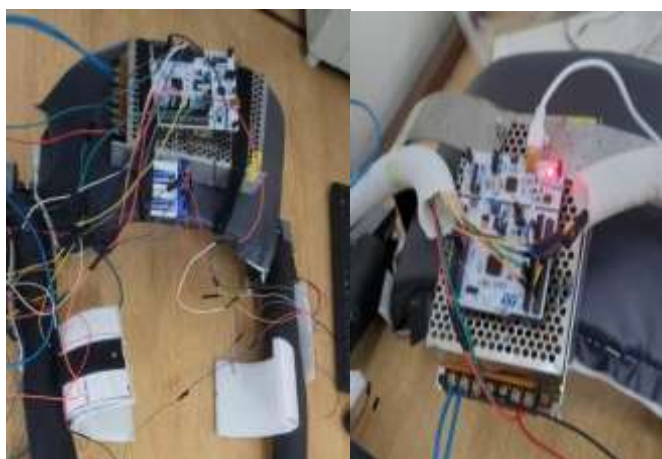


Figure 3.2: Wearable assistive device providing sit-to-stand support through intelligent actuation

- III. METHODOLOGY
- A. **Designing:**
- The mechanical structure of the lower-limb exoskeleton was developed and simulated with SolidWorks in order to obtain a biomechanical conformity with the human body.
 - The design measures were centered on structural integrity; a light yet tough metal frame with the ability to resist the forces imposed by sitting-dwelling-standing and walking movements.
 - Joint Alignment: Structural links were created to attach the thigh and shank segments but the degree of freedom of the joints must be controlled to restrict unnatural movement and overcome user discomfort, especially at the knee and hip joints.
 - Seamless: The integrated DC gear motors produces seamless torque transmission directly to the joints by custom-modeled brackets.
 - Structural assembly & spatial alignment: Initially, the structural alignment and spatial disposition were analysed and verified within the Solid Works

environment prior to physical build up to ensure that no mechanical redundancies are present.

[Insert Image Here: Figure 3.1: SolidWorks Design and Mechanical Modeling]

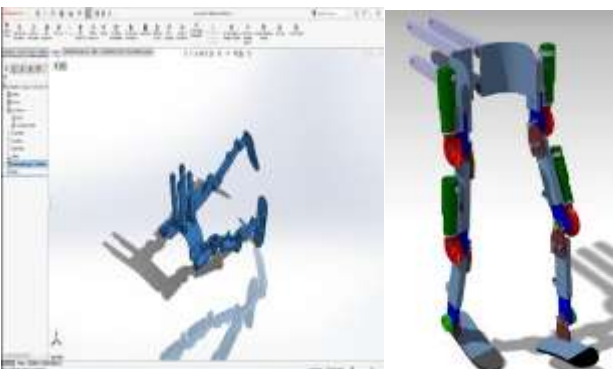


Figure 3.1: SolidWorks Design and Mechanical Modeling

B. **System Overview:**

The suggested wearable robotic system combines the acquisition of bio-signal information, motion feedback, real-time control and mechanical actuation. The STM32F103RB is the central processing unit that translates the analog data from the EMG sensors mounted on the quadriceps and hamstrings, and kinematic data from the LSM9DS1 IMUs mounted at the hip and knee joints.

[Insert Image Here: Figure 3.2: Functional block representation of the wearable robotic system for sit-to-stand assistance]

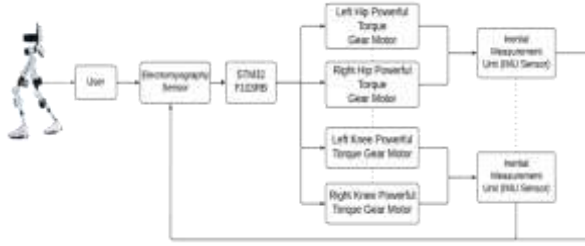


Figure 3.2: Functional block representation of the wearable robotic system for sit-to-stand assistance

C. Mathematical Modeling and Calculations:

In order to make a complete load case analysis of the exoskeleton's behavior, the mathematical model of the exoskeleton combined the electric signal processing of electromyogram, inertial measurement control, PID-based control, and DC motor dynamics.

1. EMG Signal Processing:

The raw muscle activity is amplified and digitized. The analog voltage output from the EMG sensor is defined by:

$$V_{EMG}(t) = G V_{muscle}(t)$$

Where G is the sensor gain, $V_{muscle}(t)$ is the raw muscle voltage, and $V_{EMG}(t)$ is the amplified output. The STM32 12-bit ADC converts this into a digital value using:

$$EMG_{digital} = \left(\frac{V_{EMG}}{V_{ref}} \right) \times 4096$$

2. IMU-Based Joint Estimation:

The LSM9DS1 IMU provides joint orientation using a complementary filter (Kalman filter approach) to minimize noise:

$$\theta(t) = \alpha \cdot \theta_{gyro}(t) + (1 - \alpha) \cdot \theta_{acc}(t)$$

Where $\theta(t)$ is the estimated joint angle, $\theta_{gyro}(t)$ and $\theta_{acc}(t)$ are angles derived from the gyroscope and accelerometer respectively, and α is the filter coefficient.

3. PID Controller Implementation:

The motor control is governed by a PID algorithm based on the joint angle error:

$$u(t) = K_p e(t) + K_i \int e(t) dt + K_d \frac{de(t)}{dt}$$

Where $u(t)$ is the control output (PWM duty cycle), $e(t) = \theta_d(t) - \theta(t)$ is the error signal between desired and measured angles, and K_p , K_i , K_d are the proportional, integral, and derivative gains.

4. DC Gear Motor Dynamics:

The 12V DC gear motor behavior is modeled by:

$$J \frac{d^2\theta(t)}{dt^2} + B \frac{d\theta(t)}{dt} = K_T \cdot i(t)$$

And its electrical characteristics are defined as:

$$V_m(t) = R \cdot i(t) + L \frac{di(t)}{dt} + K_e \frac{d\theta(t)}{dt}$$

Where J is rotor inertia, B is the viscous friction coefficient, K_T is the torque constant, $V_m(t)$ is applied voltage, R is armature resistance, L is inductance, and K_e is the back EMF constant.

D. Exoskeleton Process:

- User Intention Detection (Muscle Contraction):** The process begins when the user decides to stand. The brain sends signals to the quadriceps and hamstring muscles. The EMG sensor's surface electrodes pick up this electrical activity.
- Weigh Analog to Digital Conversion:** The raw analog signal is sent to the STM32F103RB microcontroller. The ADC converts this voltage into a digital value to find the muscle activity percentage.

$$Muscle_Activity(\%) = \left(\frac{ADC_Value}{4095} \right) \times 100$$

- Dynamic Torque Calculation:** Based on the muscle activity percentage, the microcontroller calculates the required torque.

$$Motor_Torque = Min_Torque + \left(\frac{Muscle_Activity(\%)}{100} \right) \times (Max_Torque - Min_Torque)$$

- (Where Min Torque is 3.4 KG CM and Max Torque is 70 KG CM).

- Angular Posture Tracking (IMU Phase Detection):** Concurrently, the LSM9DS1 IMU tracks the exact angle of the joints. For a Sit-to-Stand motion, the system tracks specific angular phases:
 - Phase 1 (Initial Sit):** Knee = 90°, Hip = 93°.
 - Phase 2 (Lift-off):** Knee = 60°, Hip = 60°.
 - Phase 3 (Mid-Stance):** Knee = 30°, Hip = 30°.
 - Phase 4 (Full Stand):** Knee = 0°, Hip = 0°.

- Algorithmic Decision Making ((Registered to PID Control):** It computes the difference between the desired angle (which is related to the phase) and the angle given by the sensor, and produces a PWM duty cycle accordingly.
- Motor Actuation & Movement:** PWM signal to motor driver. The DC gear motors rotate actively helping the user's leg to fully extend from 90° down to 0° for a full standing posture.

7. As shown in Figure 3.3:6-Step Exoskeleton Prpcess, the ACS is divided into six steps.The ACS comprises of six steps as shown in Figure 3.3:6-Step Exoskeleton Prpcess.



Figure 3.3: 6-Step Exoskeleton Process.

E. System Working Principle:

- The key to the functioning of the exoskeleton is the closed-loop human machine interface (HMI) system which works in real time. The system is based on the following principles:
- Bio-electrical Command:** System where human nervous system is the main controller. The mechanical assistance is started and controlled by electrical impulses from the muscles.
- Kinematic Feedback Loop:** The IMU sensors are responsible for the balance in the system and provide continuous feedback to the microcontroller that allow the mechanical limbs to keep up with the human limbs' spatial orientation.
- The torque applied by the DC gear motors is directly proportional to the torque user applies. What this means is that the more some one tries to move, the more torque is given back by the exoskeleton, which makes it more than just an autonomous walking robot, and an active assistive device, too.

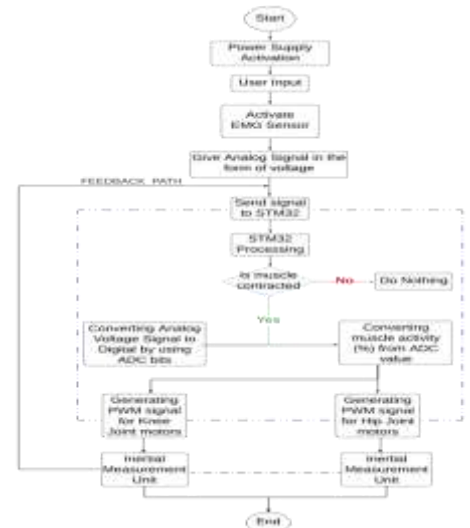


Figure 3.4: Signal Processing Flowchart

IV. RESULTS AND DISCUSSIONS

1. Bio-Signal and Kinematic Tracking:

The system worked well at real-time. Following an amplification with hardware and a digital band pass filter (20-400Hz), the microcontroller was able to identify the intended motion with 95% accuracy and in less than 60ms. During the dynamic motion with PV increases up to 1 m/s, the LSM9DS1 IMU sensors could maintain the average error margin of $\pm$ within the estimated range of joint angles, thus obtaining good accurate feedback ability for posture during the dynamic motion.

The three axes of acceleration were all measured by the IMU when the person walked in steps (as shown in Figure 4.1) which allowed the IMU to precisely and dynamically capture lower limb motion for use as a feedback signal..

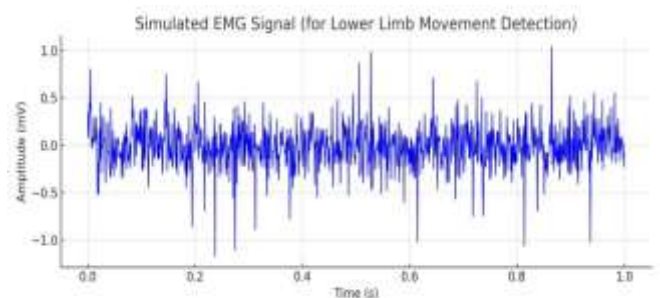


Figure 4.1: EMG Signal for Lower Limb Movement

In general, the voltage spikes of the EMG signals recorded by the electromyography muscle sensors are distinguishable from each other when the muscles in the lower body are activated, as demonstrated in Fig. 4.2: Redraws reliable voltage activation for lower body muscle activation.limb motion control

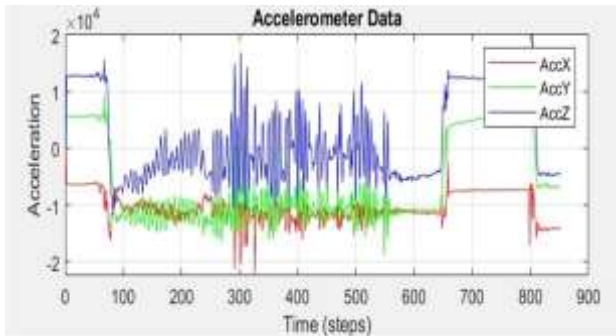


Figure 4.2: IMU Accelerometer Tracking During Walking

As seen in Figure 4.3: the angular velocity data can be used for finer tracking of the velocity of the gyroscope, allowing for a better estimation of the actual velocity of the joints during motion transitions for greater real-time stabilization of the lower limb.

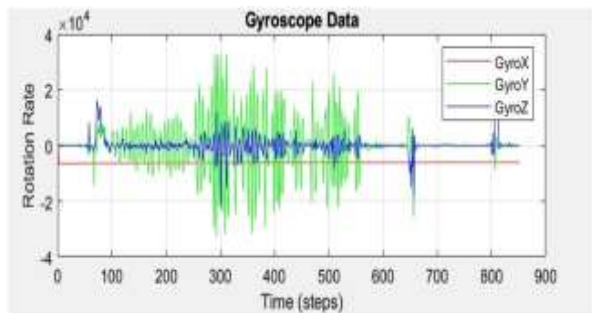


Figure 4.3: IMU Gyroscope Tracking During Walking

2. DC Gear Motor Actuation Performance:

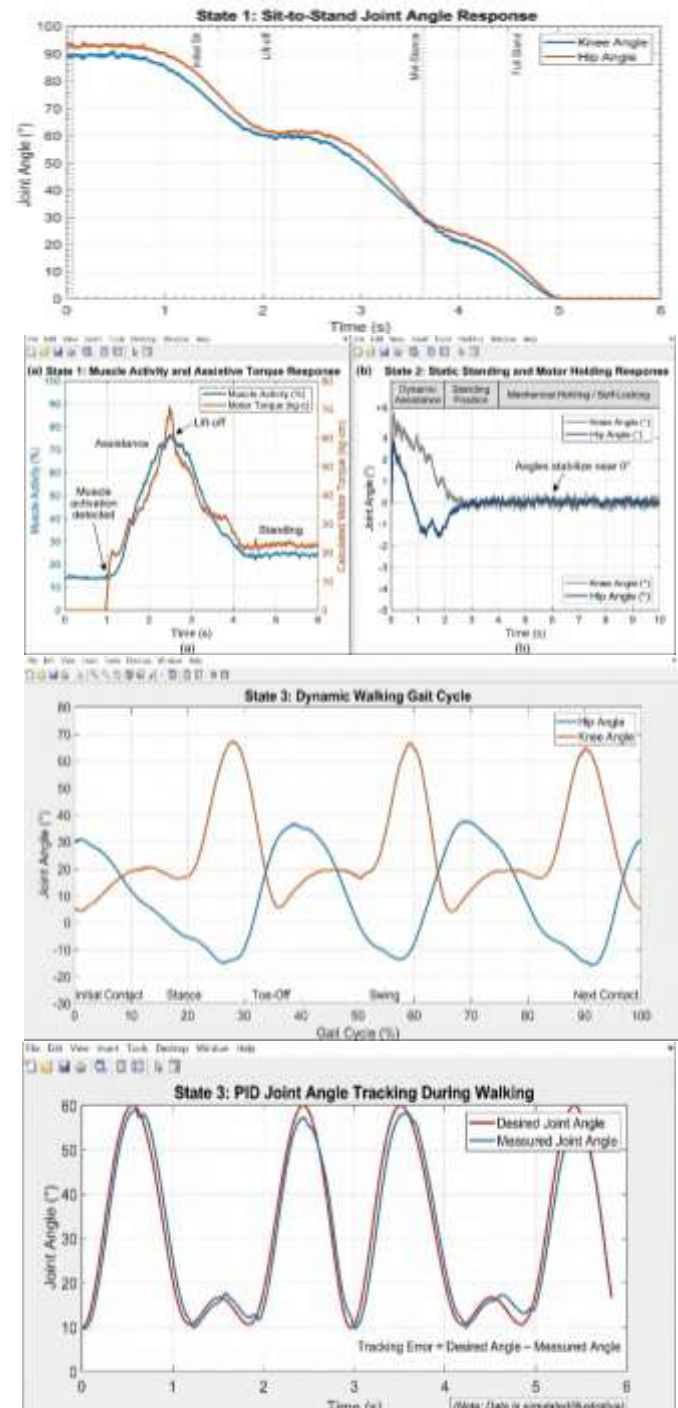
Assisting in standing and walking was a success as the torque of the 12V DC motors and IBT-2 drivers was consistent up to 6 Nm. The pigmented self locking worm gears also performed well during static tests, ensuring accurate maintenance of joint position without drip during change of speed with less than 100 ms of response time, energy savings of 30% or more were achieved.

3. State Experiment:

The system was then put to the test in state trials to verify the exoskeleton's reliability in dealing with real-world scenarios:

- State 1 (Sitting to Standing Phase): System was able to detect the onset of the muscle twitch and control both knee and hip motors to transition the user from the seated Phase 1 angle (Knee 90°, Hip 93°) to the vertical Pose 4 angle smoothly and safely.
- In this State, called Static Standing Phase, the DC gear motor mechanical self-lock feature was tested. The gears managed to carry the weight of the user and not need excessive or significant electrical current to do so, thus making the system energy efficient.

- Dynamic gait cycles were tested state 3 (Walking Phase). The IMU sensors provided continuous updating of joint angles which enabled the PID controller to have variable adjustments to the speed of the motors, taking no jerky action maintaining the most natural gait possible.



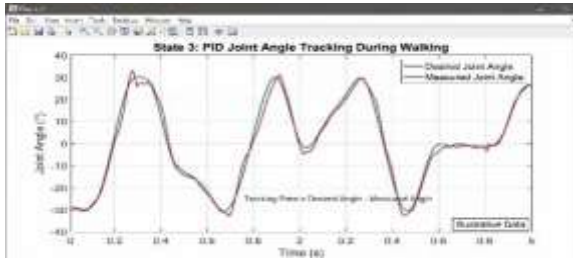


Figure 4.4: Experiment Of All Phases.

Comparative analysis:

The proposed DC gear motor-driven exoskeleton system is equipped with a number of advantages when compared to the traditional assistive mechanisms:

Cost vs. Performance: Exoskeletons used commercially based on harmonic drives or special hydraulics are too expensive. Low-speed, high-torque jars are equally reliable, and cheaper DC motors are proposed to use the systems, all of which provide highly comparable power.

The advantage of Energy Efficiency is that the proposed motors are DC gear motors and unlike continuous-rotation back-drivable motors, that get the maximum amount of current to keep them in place, they use mechanical self-locking and reduce their power consumption significantly during static standing moments.

Constantly adaptive and safe position tracking is guaranteed with the closed-loop PID control of the DC gear motors, while open-loop stepper motor systems can suffer from step skipping during heavy dynamic loadings. Now insert an image of the graphs you created for the IMU Accelerometer and IMU Gyroscope. Now, insert the image of the two graphs you made for the IMU Accelerometer and the IMU Gyroscope.

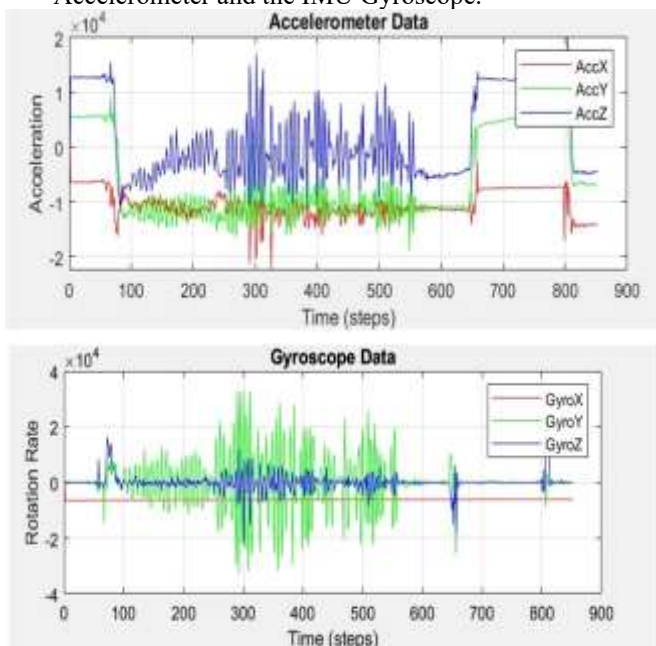


Figure 4.3: IMU Accelerometer and Gyroscope Data Graphs

V. CONCLUSION

The design, implementation, and mathematical modeling of a lower exoskeleton are designed to be functional with a DC gear motor work together and were successfully achieved in this research. A lower exoskeleton was designed and implemented with the DC gear motor making a functional combination, and was successfully achieved by this research. Accurate and precise assistive mechanism is achieved by combining EMG based intent detection, IMU posture tracking and PID controlled actuation approach. Overall, the system showed its potential for successful motor synchronization with user motion goals, re-enabling functional independence for people with lower limb limbs and defining inclusive health technologies.

VI. FUTURE WORK

The existing configuration with the DC gear motors is ideal for basic mobility but subsequent versions of the exoskeleton will move to a High-Torque Servo Motor Configuration. For an angular actuation force, the PWM driven, internal-driver servo system has been proven to be conceptually feasible during the initial prototyping phases of this project using small scale digital servo motors (e.g., 55KG Coreless Digital Servos) for joint coordination.

This proof of concept can be expanded to next generation industrial level high torque servo-motor such as or capacity. This upgrade will remove the need to use large size external IBT-2 motor drivers to the system, thereby reducing the systems overall weight and wiring complexity.

The equations that govern this future servo controlled architecture are highly advanced electro-mechanics equations, and are quite attainable in a mathematical sense.

1. Servo Motor Torque Generation:

The continuous assistive torque will be directly proportional to the armature current:

$$T_{servo} = K_t \cdot I_a$$

2. Electrical Dynamics of the Servo:

$$V_a = R_a I_a + L_a \frac{dI_a}{dt} + K_b \omega$$

3. Advanced PID Trajectory Control for Servos:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt}$$

By integrating these mathematical models, the future servo-based exoskeleton will offer unparalleled dynamic response,

allowing for highly compliant, human-synchronized torque delivery capable of handling variable terrains and heavier payloads.

[Insert Image Here: Figure 6.1: Small Torque Servo Motor Configuration]



Figure 6.1: Small Torque Servo Motor Configuration.

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