POSTURAL STABILITY OF BIOMECHANICAL MODEL USING PASSIVITY BASED NONLINEAR MODEL PREDICTIVE CONTROL

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Dedication

This thesis is devoted to my dear parents and my endearing wife, whose boundless support and encouragement have meant invaluable, to my friends, and to all my teachers for their guidance, support, and faith in my perseverance.

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I am deeply thankful to Almighty Allah for His endless blessings and for granting me the strength and potential to complete my thesis. Hard work and trusting in Allah Almighty's plan are the keys to success. As mentioned in the Holy Quran:

"With difficulty, there is ease"

Qur'an (5:94)

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Abstract

Maintaining postural stability is crucial in human biomechanics, particularly for activities like standing and walking. This thesis explores a novel control strategy combining Nonlinear Model Predictive Control (NMPC) with Passivity-Based Control (PBC) to enhance the stability of a single-link biomechanical model representing the human ankle joint. The model, resembling an inverted pendulum, captures the dynamics of balance, including gravitational forces and inertia. Traditional control methods, such as Proportional-Integral-Derivative (PID) and $H\infty$, often struggle with the nonlinearities inherent in human biomechanics, which can significantly impact stability and pose challenges in managing postural sway. In this work, PBC is employed to impose passive behavior on the system, enhancing its natural stability. The passivity property ensures energy dissipation and stability, even in the presence of nonlinearities. NMPC is integrated with PBC to optimize control performance, solving an online optimization problem at each sampling instant, thereby ensuring effective and physiologically safe control actions. Simulation results demonstrate that the combined NMPC-PBC strategy effectively stabilizes the ankle joint model, quickly returning the system to equilibrium after disturbances. This study offers a robust control approach with significant implications for rehabilitation, fall prevention, and assistive technologies, advancing our understanding of human postural stability.

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ACRONYMS AND ABBREVIATIONS

NMPC	Nonlinear Model Predictive Control
PBC	Passivity-Based Control
COM	Center of Mass
CNS	Central Nervous System
PID	Proportional-Integral-Derivative
PDA	Proportional-Derivative-Acceleration
BOS	Base of Support
COP	Center of Pressure
SQP	Sequential Quadratic Programming
LQR	Linear Quadratic Regulator
PBT	Perturbation based training

CHAPTER 1

INTRODUCTION

1.1 Overview

Retaining postural stability in human being is essential meanwhile it is challenging. In daily life when some movement actions take place by the humans which is crucial that their upright position should be maintained and the balance of standing at upright posture or while moving from one point to another the postural sway must be controlled [1].The study of posture movement in humans is crucial for several applications, such as the diagnosis and rehabilitation of patients, fall prevention in older adults, control and design of an artificial body part, ensuring stability when there is motion, and the interaction analysis of neuro-muscular. The maintenance of the upright position and balance in humans can be achieved by a sophisticated neuromusculoskeletal system [2]. The inputs to human body received from visual, vestibular and proprioceptive sensors are quite important for every muscle in the body to get properly managed and helping the posture stabilization to be achieved [3]. Through the combination of three different types of sensory input signals, the central nervous system (CNS) manages proper postural adjustment by activating appropriate muscular responses, for postural control if only one sensory signal is used then the CNS reacts based on that individual signal. However more sensory signals are utilized then the efficiency will be increased and the balance can be maintained sufficiently. Theoretically, if perceptual precision is decreased by some external perturbation, the CNS undergoes a rectification process, which will decrease the inaccurate gain in reverse enhancing the influence of precise gain. That is necessary to mention during rectification process, control of stable balance can be disturbed, where in absence of visual input the body sway will be increased [4] [5] [6]. Researchers employ various strategies to regain balance after experiencing perturbations. In elderly age the fall is major cause of injuries, where the studies show that wearing lower extremity in simple terms using thigh support enhance stability in the frontal plane and ankle support increase stability in sagittal plane. Thus, it can be summarized which utilizing the benefits of thighs and ankle support could serve as efficient intermediation to avoid falls and lower the associate risks [7].

The sagittal plane can be considered for smaller perturbations while combination of both sagittal and frontal planes utilized in larger disturbances, even dealing with greater perturbations motion at the knee joint including with other two (hips and ankle) joints, is activated. The ankle strategy entails stabilization with the movement of ankle joint that is resulting for entire body to behave as a single-link inverted pendulum [8].The essential objective of postural stability framework in a static position is to control the vertical

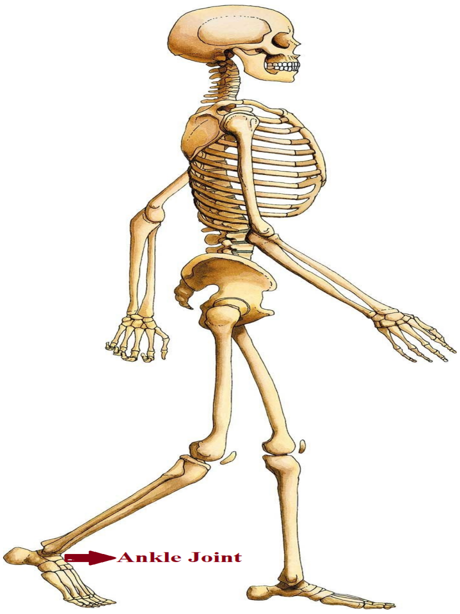

Figure 1.1: Human Lower Body Joints

posture of a human's center of mass (COM) inside the base of support (BOS), that can be determined by the length of immobile foot, further stability bounded by the height of the COM, weight of the individual's body, and BOS domain. Additionally, the boundary of the stability can be influenced by the position and velocity of COM [9].According to Kuo, researchers aimed to better understand the postural analysis and enhance its stability they have employed mathematical model of musculoskeletal system for locomotion mechanisms [10].

1.2 Motivation

The increasing prevalence of balance disorders, especially among the elderly and individuals with musculoskeletal impairments, has underscored the need for advanced control strategies in biomechanical systems. Maintaining postural stability is a fundamental requirement for daily activities, and disruptions in balance can lead to severe consequences such as falls and injuries. This growing concern has driven research toward the development of reliable and adaptive control methods that can manage the complexities of human movement.

In this context, the ankle joint plays a crucial role in maintaining postural balance, particularly in response to sudden perturbations. Effective control of this joint is essential not only for fall prevention but also for improving rehabilitation processes for those recovering from joint-related injuries. Given the nonlinear and dynamic nature of the human body, traditional control techniques often fall short of providing the required precision and adaptability.

Motivated by these challenges, this research aims to explore the potential of advanced control strategies, specifically Nonlinear Model Predictive Control (NMPC) and Passivity-Based Control (PBC), in addressing the inherent complexities of the biomechanical system. The integration of these two control methods provides a robust framework capable of predicting future states while maintaining energy balance within the system. This hybrid approach offers a promising solution to enhance postural stability and contribute to the broader field of biomechanics, particularly in clinical applications focused on joint health and rehabilitation.

Moreover, the introduction of white noise in the system represents real-world conditions where uncertainty and time lags affect sensory inputs and outputs. Incorporating these elements into the control strategy not only simulates realistic physiological processes but also provides insights into how these disturbances can be managed effectively.

1.3 Problem Statement

Maintaining postural stability is crucial for human mobility and balance, particularly during daily activities and in response to external perturbations. Traditional control methods like PID and $H\infty$ controllers struggle to address the nonlinear dynamics inherent in the human body's neuromusculoskeletal system. The complex nature of human biomechanics poses significant challenges in effectively controlling postural sway, especially in scenarios involving sudden disturbances. Existing methods often fail to provide the necessary stability and quick recovery required for practical applications such as rehabilitation, fall prevention, and assistive technology development. Therefore, there is a need for a more robust and adaptive control strategy that can effectively manage these nonlinearities to ensure reliable postural stability, leading to improved safety and performance in various real-world scenarios.

1.4 Research Gap

In the study of human lower body biomechanics and nonlinear dynamics, the system encounters significant challenges in analyzing and maintaining postural stability, particularly in regaining balance after experiencing perturbations. Traditional control methods, such as PID and H_∞, often prove inadequate for managing these complexities, resulting in suboptimal stabilization and inefficient recovery to equilibrium. Moreover, conventional control strategies typically concentrate on either control theory or biomechanical modeling, with few efforts made to integrate these fields. This highlights the need for innovative approaches that combine insights from both disciplines, fostering a deeper understanding of how to maintain and restore balance effectively.
In this study, the identified gap is presented through the following approach:

i. **Nonlinear Biomechanical Modeling and Control**: Human postural dynamics were modeled using a developed single-link biomechanical model that incorporates Nonlinear Model Predictive Control (NMPC) and Passivity-Based Control (PBC) to account for nonlinearities. This approach ensures stable management of postural stability.

ii. **Simulation and Optimization**: This research integrates the energy-based stability of PBC with the optimization capabilities of NMPC, offering a novel control strategy that outperforms traditional methods in stabilizing the system during disturbances.

The main objective is to incorporate more sophisticated nonlinear control techniques in conjunction with detailed biomechanical modeling to enhance solutions for postural stability, particularly under complex real-world disturbances. By employing these advanced methods, the aim is to better manage the nonlinearities inherent in human biomechanics and provide a more effective and robust response to disturbances, ensuring reliable stabilization and quicker recovery of equilibrium in real-life scenarios.

1.5 Research Contribution

This research will make following contributions:

i. **Advanced Nonlinear Control for Postural Stability**: This study introduces a novel control approach that combines Nonlinear Model Predictive Control (NMPC) with Passivity-Based Control (PBC) to stabilize a single-link biomechanical model of the ankle joint. By addressing the inherent nonlinearities in human postural control, this technique provides a more effective and adaptive solution compared to conventional methods. The integration of NMPC and PBC allows for precise control and stabilization, ensuring the system can efficiently maintain balance and quickly return to its equilibrium state even under complex disturbances. This approach offers a significant improvement over traditional strategies by enhancing both the stability and robustness of the postural control system.

ii. **Energy-Based Stabilization**: By leveraging the energy concepts of PBC, the proposed method ensures that the system behaves in a passive manner, enhancing overall stability and allowing for asymptotic stabilization of the system's output errors. This contributes to a more physiologically relevant and efficient control mechanism for maintaining upright posture in dynamic environments.

iii. **Optimization of control performance**: The integration of NMPC enables the online optimization of control inputs, ensuring that the system can quickly and efficiently respond to perturbations while staying within anatomical constraints. This hybrid control strategy not only improves stability but also optimizes the control performance, making it suitable for real-world applications such as rehabilitation and assistive technologies.

iv. **Framework for Postural Stability Enhancement:** : The research provides a comprehensive framework that combines advanced control theory with biomechanical modeling, offering a holistic solution for improving postural stability. This framework can be applied to various scenarios, including fall prevention in older adults, improving balance in patients with neuromuscular disorders, and enhancing the design of prosthetics and exoskeletons.

1.6 Limitations

There are some limitations to this work as well:

i. **Computational Complexity:**: The integration of Nonlinear Model Predictive Control (NMPC) with Passivity-Based Control (PBC) requires significant computational resources due to the need for real-time optimization at each sampling interval. This can limit the applicability of the proposed control strategy in scenarios where processing power is constrained or when dealing with highly complex biomechanical models.

ii. **Assumptions in Model Simplification:** The single-link biomechanical model used in this study simplifies the complex dynamics of the human body by focusing primarily on the ankle joint. While this model provides valuable insights into postural stability, it may not fully capture the interactions between multiple joints and muscles in more dynamic or multi-joint movements, potentially limiting the generalizability of the results.

1.7 Thesis Organization

The rest of the thesis is organized as follows:
In **Chapter 2**, Literature review and a comparative analysis of scholarly work conducted by various researchers is presented.
In **Chapter 3**, Outlines the design and technical details of our proposed methodology, providing an in-depth explanation of the approach.
In **Chapter 4**, Describes the experimental setup and provides a detailed discussion of both the experimental procedures and the control schemes employed, along with a thorough analysis of their results.
In **Chapter 5**, Conclusions and future work are presented.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

Numerous researchers have significantly contributed to the advancement of various controllers and control theory with the aim of developing smart and efficient systems for posture stability. Over the years, diverse methodologies have been proposed to enhance the performance of control techniques. These contributions span across different approaches and innovations, each offering unique insights and improvements. From foundational theories to cutting-edge technologies, the continuous evolution in this field highlights the ongoing efforts to refine and optimize control systems for better stability and effectiveness in practical applications. This literature review will explore these advancements, examining the key methodologies and their impacts on the development of posture stability systems.

2.2 Pose estimation techniques for lower joints

It should be noted that studying and exploring human postural control, particularly the upright standing position, is well-suited for modeling approaches. This configuration can be conveniently used to test motor control theories and assumptions. The models in question are based on the inverted pendulum due to its similarity to the human body and its intrinsic instability. Controllers designed thus far aim to replicate the functions of the central nervous system (CNS), which sends commands to muscle movements. [11] [12].

Employing Feedback controllers by researchers in standing posture for getting better insight of neural control by either steady position simulation [13] [14] [15].or exposing the postural disturbance [16] [17] [18].

In [19]] a single-link biomechanical model in the sagittal plane was employed. The study involved experiments with 32 individuals, comprising 16 young subjects and 16 older subjects. After conducting simulations and analyzing kinematic data, the researchers concluded that there were significant differences in time delay and sensory inputs in feedback loops between the two age groups.

A simulation analysis of loop reaction instability was conducted in [20] where it was found that increased motor neuron sensitivity and prolonged time delays can lead to instability. Additionally, a single-link inverted pendulum model for postural maintenance was proposed in [21].This study identified sensory dead zones indicated by open-loop periods and employed a proportional-derivative-acceleration (PDA) system for feedback control during closed-loop periods. The PDA system, with appropriate feedback gain, was effective in controlling and stabilizing the pendulum. It is also important to note that acceleration plays a significant role in the stabilization process.

The problem of maintaining an upright position with delays in both position and velocity feedback was addressed in [22] and [23]. In these studies, a single-link biomechanical model, considered as an inverted pendulum, was brought to an equilibrium point using a proportional-integral-derivative (PID) controller, which mimicked CNS functions. The PID controller effectively stabilized the plant; however, due to the linearization of the model in the upright posture, some oscillations in the transient state were observed.

Postural stabilization using H_∞ and PID control methods was investigated in [24] and [25] through the development of a bond graph model of the human musculoskeletal system. The simulations revealed oscillations in the transient state and indicated that the system took a longer time to settle down.

When unmodeled dynamics are present, they lead to linearization errors. Linearizing a nonlinear biomechanical model, which includes inertia and gravitational components, can result in high-amplitude joint input torques and deviations in the angular profile, potentially breaching physiological limits [26]. Consequently, linear controllers operate effectively only within a limited range where their linear approximations are valid. To address these limitations, nonlinear control techniques are employed to improve performance and overcome the drawbacks of linear controllers.

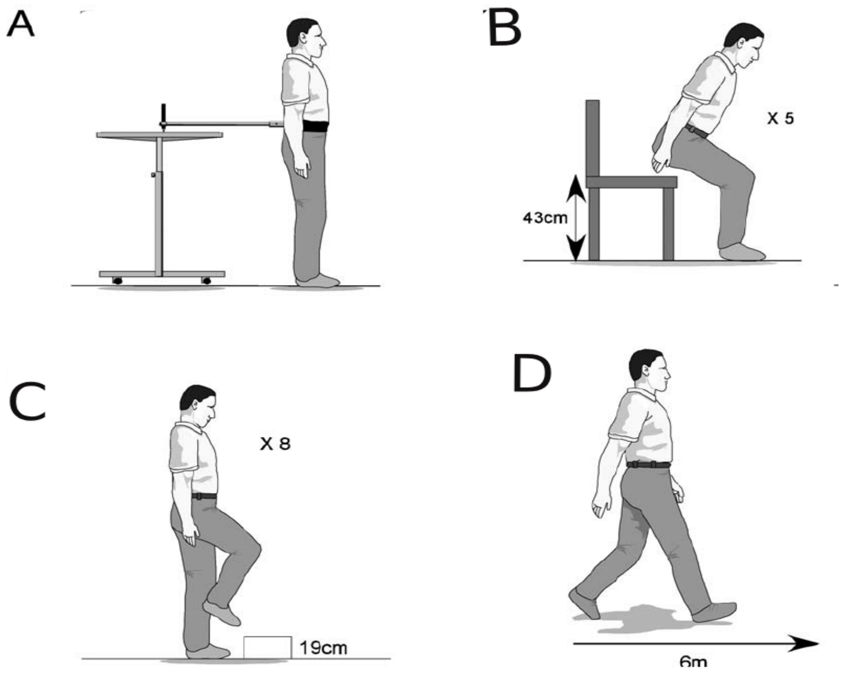

Figure 2.1: Balance and Functional Examines A) Postural Sway B) sit-to-stand C) Alternate step test D) Walking Speed.

Modified Figure Source: [27]

An experiment involving 176 individuals, with a mean age of 80.1 years living in a retirement community, was conducted to improve the control of the ankle and foot. The study assessed various characteristics including range of motion, foot posture, strength, vision, sensation, reaction time, balance while standing and leaning, sit-to-stand transitions, walking status, and stepping. Based on these assessments, researchers concluded that many of these factors are crucial for balance and functionality. The analyses consistently highlighted that ankle flexibility, toe plantar strength, and plantar tactile sensitivity are significant predictors of functionality and balance in elderly individuals. Programs aimed at enhancing foot flexibility, strength, and plantar sensation could be highly effective in improving movement and reducing the risk of falls among the elderly. [27].

2.3 Controlling Techniques for Single-Link Model

Linear controllers are known to perform optimally within a specific range, particularly when linear approximations are accurate. However, intrinsic problems with linear controllers become apparent beyond this range. This issue is especially relevant in the context of postural control systems, which are inherently nonlinear and thus require nonlinear controllers. The limitations of linear controllers highlight the need for more advanced control techniques. Nonlinear control methodologies offer a better approach to managing these systems. For example, the works described in [28] and [29] propose various simulation models aimed at enhancing postural stability, particularly in the presence of white noise and neural delays.

These models were designed to mitigate the fluctuations experienced in transient states and the slow responses reported in earlier studies [22] [23] [24] [25]. By incorporating these considerations, the models aimed to more accurately reflect the physical body's responses to perturbations. To further enhance their approach, the authors in [28] and [29] employed feedback linearization techniques in combination with H_2 compensators, as detailed in their subsequent studies described in [30]. This refinement resulted in improved postural stability, favoring asymptotic stability. Additionally, it sought to balance neural delays, thereby fine-tuning bodily movements and enabling more rapid restoration from disruptions.

The integration of feedback linearization and H_2 compensators represents a significant enhancement over previous approaches, underscoring the necessity for control techniques that accurately reflect the characteristics of human movement. These advancements highlight the importance of developing a robust control scheme capable of addressing both the nonlinearity and delay aspects inherent in human postural control. Building on the insights from these studies, we propose a new simulation approach aimed at improving postural stability in a nonlinear biomechanical model with a single link. The proposed control method involves implementing a passivity-based control (PBC) approach in conjunction with a nonlinear model predictive control (NMPC) strategy. This combined methodology represents a novel innovation in the field of nonlinear control, offering a sophisticated solution to enhance postural stability.

First and foremost, the use of energy concepts in Passivity-Based Control (PBC) makes it particularly advantageous due to its scientifically grounded and widely accepted definitions. A key principle of PBC is the incorporation of a damping component in the controller design. This damping element ensures that the closed-loop system adheres to passive characteristics, which are crucial for achieving stability. By making the system passive, the output error can be driven to zero in the limit, thereby maintaining system balance. Additionally, the introduction of damping facilitates the gradual adjustment of output and state variables toward their desired positions. Compared to other nonlinear control methods, PBC is simpler and more straightforward to implement, making it highly suitable for practical applications [31]. Its effectiveness and ease of application make PBC an excellent choice for enhancing postural stability in various settings, including rehabilitation and standing assistance.

Consequently, the proposed approach of integrating PBC with NMPC leverages the inherent stability provided by PBC while benefiting from the enhanced control performance of NMPC. NMPC is designed to address optimization problems online at each sampling instance, typically using methods such as Sequential Quadratic Programming (SQP). However, the optimization problems tackled by NMPC are nonlinear programming problems, which are often non-convex and thus entail increased computational complexity. This demand for computational resources is particularly pronounced in systems with moderate to high levels of complexity [32]. The combination of PBC and NMPC aims to balance the stability advantages of PBC with the sophisticated control capabilities of NMPC, addressing both stability and performance challenges effectively.

The extensive control capabilities offered by nonlinear controllers, combined with the close resemblance of the inverted pendulum to the human body particularly when modeled as a single-link have inspired us to develop a new simulation approach. The proposed model in this paper integrates PBC with NMPC to enhance stability recovery after disturbances within a significantly shorter time frame. This approach not only achieves rapid control performance but also ensures the quickest recovery among available methods, making it exceptionally well suited for practical applications.

By leveraging and applying advanced control methods, the potential for progress in the field of human motor control and biomechanics is vast. The proposed method is anticipated to offer enhanced accuracy in postural stability, thereby improving safety and performance in practical applications. This includes areas such as prosthesis development, rehabilitation training, and fall prevention programs. The approach, which incorporates multiple layers of postural stability enhancement, is expected to be highly valuable for advancing this concept and making a synergistic impact on the field's development.

2.4 Summary of Chapter 2: Literature Review

In this chapter, we explored the extensive body of work surrounding posture stability control, particularly in the context of human motor control. Researchers have contributed various control techniques ranging from linear to advanced nonlinear methods. Traditional linear controllers, while effective in specific ranges, have limitations when applied to nonlinear biomechanical systems. To address these challenges, nonlinear control techniques such as feedback linearization and H2 compensators have been proposed, offering better stability and response to perturbations. Additionally, the integration of advanced control systems like Passivity-Based Control (PBC) and Nonlinear Model Predictive Control (NMPC) has shown promise in improving stability and performance. By incorporating energy-based concepts, PBC ensures system stability, while NMPC provides sophisticated control for rapid recovery from disturbances. Together, these methods aim to enhance postural stability, making them highly suitable for practical applications in rehabilitation, fall prevention, and prosthetic development.

2.4.1 Insight for the Next Chapter: Methodology

The next chapter will present the methodology used in this research, detailing the modeling and control strategies applied to the single-link biomechanical model. We will delve into the integration of PBC and NMPC, explaining the simulation setup, parameter selection, and the implementation of these control techniques to achieve optimal stability and performance.

CHAPTER 3

METHODOLOGY

3.1 Overview

This chapter aims to detail the comprehensive research methodology employed to achieve the study's objectives, focusing on control methods and biomechanical modeling to enhance postural stability. It outlines the experimental process, the control algorithms used, and the analysis techniques applied to evaluate the proposed solutions. The chapter is systematically organized to describe the methods adopted in a sequential manner, ensuring a clear understanding of each segment's role in meeting the research objectives.

The first section of the chapter discusses the control strategy applied to the single-link biomechanical model of the ankle joint, which is crucial for postural control. Specifically, it provides detailed information on the Nonlinear Model Predictive Control (NMPC) and Passivity-Based Control (PBC) architectures. The discussion highlights their specific applications within the overall control system design and demonstrates how their integration enhances system stability.

Figure 3.1 illustrates the control structure through a flowchart diagram, which is composed of various sections with different shapes, sizes, and colors. This flowchart offers a schematic representation of the control structure, clarifying the connections between control inputs, the biomechanical model, and the feedback systems used to achieve optimal postural stability.

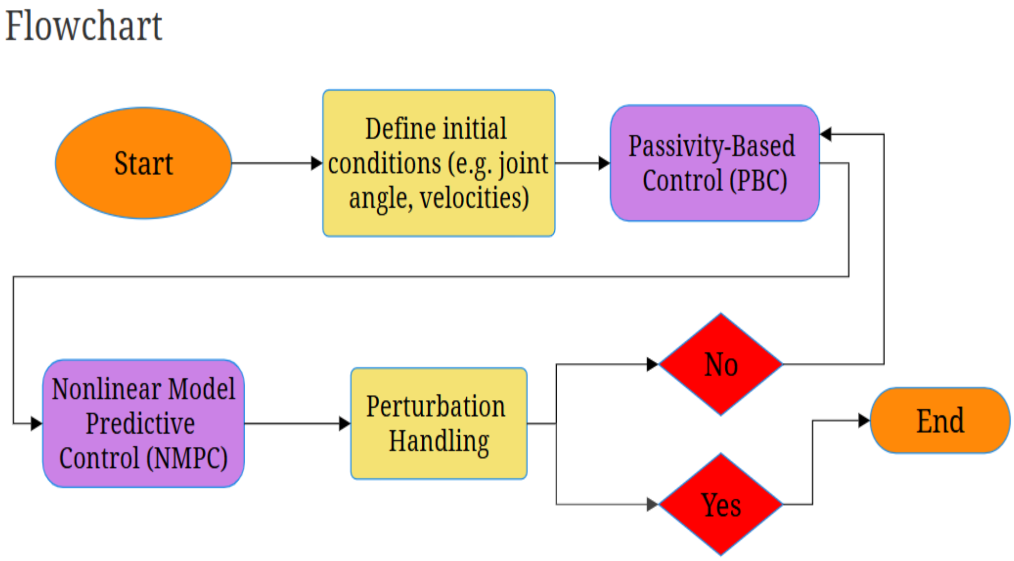

Figure 3.1: Flowchart for the Proposed Model

3.2 Procedure

This section includes a data table for the single-link model, details on the configuration of the Nonlinear Model Predictive Control (NMPC), and simulations of perturbations. It also covers the role of the controllers, system stability, and the results. Here, we demonstrate how the MATLAB and Simulink setups were conducted, and discuss the different settling times observed in the simulations.

3.2.1 Single-link biomechanical model parametric values

The simulation of postural stability was performed using a single-link biomechanical model in MATLAB Simulink. The model was developed to represent the dynamics of the human ankle joint during postural control activities and the following table is taken from [30].

The Parameters of single linke biomechanical model given for research below is used in equation (3.1).

Table 3.1: Parameters of single linke biomechanical model

Element	Symbol	Quantity
Mass of body	m	75.5 KG
Length of body segment	l	1.56m
Distance from COM to joint	k	0.78m
Inertia of body	I	2.633Nm2/Kg2
Acceleration due to gravity	g	9.8m/s2

3.2.2 Simulink Model

The central component of the model is the NMPC block, which performs the main control function by executing online optimization to determine the optimal values within the time horizon. The MATLAB Function block is used to integrate the single-link biomechanical model code with the NMPC block. This integration allows the NMPC block to interface with the model, and the results are subsequently connected to the controller.

3.2.3 System and Process explanation

In our system, we first defined the parameter values for the single-link biomechanical model. We then developed the code for the main controller, which is the Nonlinear Model Predictive Control (NMPC). This involved specifying the function in MATLAB and defining the control law using Passivity-Based Control (PBC). Following this, we created a Simulink model incorporating the NMPC main block. This block performs online optimization across different time horizons to determine the optimal values for regaining stability, preventing falls, and addressing perturbations. It is also important to explain the configuration of the NMPC in Simulink, detailing how it is implemented and integrated into the system.

- Reference Port: A constant block with a reference value of $(\pi/2, 0)$ was connected to this port to define the desired target position and velocity.
- X Terminal: This terminal was connected to the output of a subsystem comprising a function block, integration blocks, and other supporting components, representing the system's current state.
- MV Terminal: The manipulated variable (MV) terminal of the NMPC block was connected to its MV output terminal, incorporating a z^{-1} delay to simulate real-time control.

After configuring the main controller block in Simulink, we incorporated two additional MATLAB Function blocks. One block was linked to the main single-link biomechanical model, and the other contained the passivity-based control (PBC) code for regulating the input torque. Both blocks were connected to the main controller. In our system, PBC functions as an observer to the NMPC block, ensuring that the system operates passively and only dissipates energy. We then tested the system with various perturbation values to assess its response to disturbances. We applied perturbation values of 1.47, 1.37, and 1.27 to the single-link biomechanical (ankle joint) model. These perturbations simulated external forces that could impact postural stability in real-world scenarios. The settling time, a critical performance metric, was recorded for each perturbation value:

- Perturbation Value 1.47 rad: The system's settling time was measured at 1.047 seconds.
- Perturbation Value 1.37 rad: The settling time was recorded at 2 seconds.
- Perturbation Value 1.27 rad: The settling time increased to 2.375 seconds.

Figure 3.2: Perturbation based trained and motor response for stability
Modified Figure Source: [33]

3.2.4 Role of Controller and System Stability

In addition, the system's stability was ensured by the NMPC, as it predicted future states of the ankle joint model and generated appropriate control actions. This control strategy enabled the model to regain balance after disturbances, thereby achieving postural stability. The NMPC's ability to predict system behavior and adjust control inputs effectively contributed to achieving an optimal balance between stability and control energy.

Figure 3.2, which illustrates perturbation-based training, relates to our model. When a person, particularly an older adult, encounters perturbations while walking, they may struggle to regain their balance quickly, leading to falls. The controller is designed to respond swiftly in such moments, preventing falls and helping the individual regain stability quickly [33].

The results obtained from the simulation demonstrated the effectiveness of the NMPC in maintaining postural stability under varying levels of perturbation. The recorded settling times provided insights into the system's response and the success of the control strategy. The simulation validated the NMPC's capability to manage the nonlinear dynamics of the ankle joint, offering valuable information for evaluating postural stability.

3.2.5 Pose Estimation

In this research, pose estimation is utilized as a critical tool for assessing and understanding the biomechanical behavior of the ankle joint, particularly in the context of postural stability. The primary focus is on tracking and analyzing the ankle joint's movements during various activities to ensure stability and health. Pose estimation involves the accurate measurement and analysis of joint angles, positions, and velocities, which are essential for evaluating the stability of the lower limb, especially in response to perturbations. This approach leverages established biomechanical models and control strategies to monitor joint behavior without relying on traditional AI-driven methods.

By integrating pose estimation with the Nonlinear Model Predictive Control (NMPC) and Passivity-Based Control (PBC) strategies, the research aims to enhance the understanding of how the ankle joint regains stability and returns to equilibrium after experiencing perturbations. The NMPC provides a framework for predicting future states of the system and optimizing control inputs in real-time, while PBC ensures that the system behaves in a stable and passive manner.

In this study, pose estimation is achieved by tracking the ankle joint's movement, which is then used to inform the control strategies applied. This method allows for the real-time adjustment of control inputs, ensuring that the joint remains stable even in the presence of external disturbances. This approach contributes to the overall goal of improving postural stability by providing a detailed understanding of joint mechanics and enabling the implementation of advanced control techniques that can compensate for the dynamic challenges faced by the lower limb during movement.

3.3 Controllers Design

3.3.1 Bio-Mechanical Modeling

For relatively small disturbances, stabilizing movements are produced around the ankle joint. To address the stabilization problem for such small disturbances, the mechanics of the human body during postural movement are approximated as a two-segment system with torque applied to the ankle joint. Each of the head, arms, trunk, thighs, and legs is represented as a single segment above the stationary feet, while the feet can rotate around the ankle joint. The length of the foot is used to measure the base of support (BOS) in the anterior-posterior direction. The biomechanical model used for calculating ground reaction forces conforms to a mirror image of the feet and body segments in the sagittal plane, as shown in Figure 3.3.

To guarantee static postural stability, it is necessary to ensure that the center of mass (COM) remains within BOS. For dynamic stability, the center of pressure (COP) must also lie within this base of support. In this model, m represents the mass of the segment, l is the segment length, and I is the moment of inertia. The distance from the COM to the joint, measured from the flexor surface of the limb, is denoted by k. The angle of the ankle, measured from the horizontal, is represented by u, which gives the position of the segment. Torque actuation τ occurs at the ankle joint due to central nervous system (CNS) command signals and the force produced by the muscles. Two main forces act on this biomechanical model: the gravitational force mg and the net torque generated by the muscle-tendon units around the ankle joint.

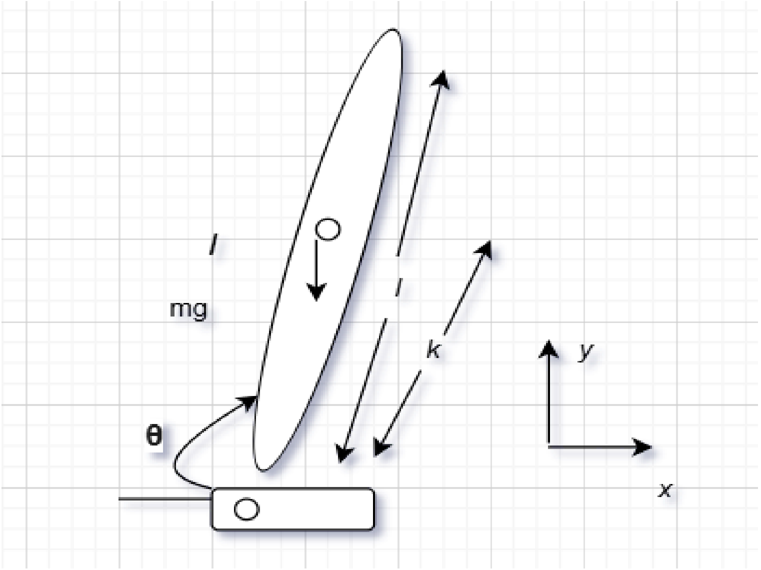

Figure 3.3: Single-Link Biomechanical Model

In our model, m represents the mass of body, g is the gravitational force, k is the length of segment from COM to a joint, θ is the joint angle between single segment and BOS which represents the position of body with respect to ground, I is the inertia of body, k represents the length of segment from COM to a joint and τ is the joint input torque. The nonlinear inverted pendulum system can be described by the following equation:

$$\ddot{\theta} = \frac{\tau + mgk\sin\theta}{I + mk^2} \tag{3.1}$$

Nonlinear plant model can be written in state space form as:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} x_2 \\ \frac{mgk\sin x1}{I+mk^2} \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{I+mk^2} \end{bmatrix} \tau \tag{3.2}$$

This nonlinear plant is of the form

$$\dot{x} = \mathrm{f(x) + J(x)u} \tag{3.3}$$

$$\mathrm{y = h(x)} \tag{3.4}$$

We assume that

$$\mathrm{f(0) = 0 \text{ and } J(0) = 0} \tag{3.5}$$

The joint-angular position θ and the angular-velocity $\dot{\theta}$ are state variables. The input torque τ hence the muscle force ultimately produces the joint torque. The joint position, and its rate which are the outputs of this system; equate to the fascicle length and fascicle velocity as inputs to the muscle-spindle assembly.

3.3.2 Design of Passivity-Based Control (PBC)

In this work, Passivity-Based Control (PBC) is employed as a core method for ensuring the closed-loop stability of the single-link biomechanical model, which represents the ankle joint. The primary objective of using PBC is to design a control law for the torque input τ that guarantees the system behaves as a passive system, thereby ensuring that the actual joint angle θ closely tracks the desired angleθ_d.

Defining the Error in Angular Displacement: To track the desired angle θ_d, we define the error in angular displacement as:

$$\mathrm{Err} = \theta - \theta_d \tag{3.6}$$

The above error formula used to frame the control law which stabilizes the system.

Control Law Derivation: The PBC approach begins with the definition of the control law for the torque τ as:

$$\tau = g(\theta) - K_p \cdot \mathrm{Err} + u \tag{3.7}$$

Where:

- K_p is a positive gain that dictates the responsiveness of the control system.
- u is an additional control input.
- $g(\theta)$ is the gravitational term, defined as $m \cdot g \cdot k \cdot \sin(\theta)$, where m is the mass, g is the gravitational constant, and k is the distance from the pivot to the center of mass.

Substituting the Control Law into the System Dynamics: The dynamic equation for the single-link model is given by:

$$\ddot{\theta} = \frac{\tau + m \cdot g \cdot k \cdot \sin(\theta)}{I + m \cdot k^2} \tag{3.8}$$

where I is the moment of inertia. Substituting the control law into this dynamic equation yields:

$$(I + m \cdot k^2)\ddot{\theta} = \tau + m \cdot g \cdot k \cdot \sin(\theta) \tag{3.9}$$

By substituting τ from the control law into the above equation, we have:

$$g(\theta) - K_p \cdot \mathrm{Err} + u = (I + m \cdot k^2)\ddot{\theta} - m \cdot g \cdot k \cdot \sin(\theta) \tag{3.10}$$

Rearranging this equation to solve for u gives:

$$u = (I + m \cdot k^2)\ddot{\theta} - m \cdot g \cdot k \cdot \sin(\theta) - g(\theta) + K_p \cdot \mathrm{Err} \tag{3.11}$$

This equation represents the additional control input required to maintain system stability. **Energy-Based Stability Analysis:**To analyze the stability of the system, we define storage function which indicates the total (Potential and Kinetic) energy of the system:

$$E(\theta, \dot{\theta}) = \frac{1}{2} I \dot{\theta}^2 - m \cdot g \cdot k \cdot \cos(\theta) \tag{3.12}$$

Taking the time derivative of the storage function gives:

$$\frac{dE}{dt} = I \cdot \dot{\theta} \cdot \ddot{\theta} + m \cdot g \cdot k \cdot \sin(\theta) \cdot \dot{\theta} \tag{3.13}$$

Substituting the dynamic equation into this expression, we obtain:

$$\frac{dE}{dt} = u \cdot \dot{\theta} \tag{3.14}$$

For stability, we require $\frac{dE}{dt} \leq 0$, which is achieved if u is chosen such that $\frac{dE}{dt} = 0$. This condition leads to the following passivity-based control law:

$$u = -K \cdot \dot{\theta} + K \cdot \dot{\theta}_d \tag{3.15}$$

where K is a constant gain. This control law ensures that the total energy of the system remains constant, indicating stability.

Application to the Single-Link Biomechanical Model: In the setup of the single-link biomechanical model, determining the appropriate storage function and applying it to derive the control law are critical for restoring system stability. Essentially, by regulating the energy within the system, the Passivity-Based Control (PBC) method ensures that the pendulum remains balanced, even in the presence of disturbances or modeling inaccuracies. This PBC framework not only stabilizes the joint but also provides a robust analytical solution for the nonlinear terms in the biomechanical model, making it an ideal choice for maintaining postural stability.

3.3.3 Nonlinear Model Predictive Control (NMPC)

Nonlinear Model Predictive Control (NMPC) is a complicated control strategy employed to predict and optimize the behavior of nonlinear systems over a finite time horizon. The key objective of NMPC is to minimize a cost function that balances the trade-off between tracking performance and control effort, ensuring that the system follows a desired trajectory while respecting dynamic constraints.

NMPC Cost Function Formulation: The NMPC framework relies on the optimization of cost function J over a prediction horizon N.The general form of the NMPC cost function is expressed as:

$$J = \sum_{k=0}^{N-1} L(x_k, u_k) + \Phi(x_N) \tag{3.16}$$

Where:

- N is the prediction horizon, representing the number of future time steps considered in the optimization.
- x_k is the state vector at time step k.
- u_k is the control input at time step k.

- $L(x_k, u_k)$ is the stage cost at time step k, which penalizes deviations from desired states and control efforts.
- $\Phi(x_N)$ is the terminal cost, penalizing the state deviation at the end of the prediction horizon.

Stage Cost and Terminal Cost: The stage cost $L(x_k, u_k)$ is typically formulated to include penalties for both the tracking error and the control effort:

$$L(x_k, u_k) = \left(x_k - x_{\text{ref},k}\right)^T Q \left(x_k - x_{\text{ref},k}\right) + \left(u_k - u_{\text{ref},k}\right)^T R \left(u_k - u_{\text{ref},k}\right) \tag{3.17}$$

Where:

- Q is a positive definite weighting matrix for the state error, governing the importance of tracking accuracy.
- R is a positive definite weighting matrix for the control input error, balancing the magnitude of control efforts.
- $x_{\text{ref},k}$ and $u_{\text{ref},k}$ are the reference state and control input at time step k, representing the desired trajectory.

The terminal cost $\Phi(x_N)$ is formulated to penalize the deviation of the final state from its desired value at the end of the prediction horizon:

$$\Phi(x_N) = \left(x_N - x_{\text{ref},N}\right)^T P \left(x_N - x_{\text{ref},N}\right) \tag{3.18}$$

Where:

- P is a positive definite weighting matrix for the terminal state error, emphasizing the importance of achieving the desired state by the end of the prediction horizon.

State Vector and Control Input: For the specific application of NMPC to the control of the ankle joint, the state vector x and control input τ are defined as follows:

- State vector: $x = \left[\theta, \dot{\theta}\right]^T$, where θ is the ankle joint angle, and $\dot{\theta}$ is the angular velocity.
- τ, representing the torque applied to the ankle joint.

NMPC Cost Function Specific to This Study: The cost function for this NMPC application is defined to quantify the control performance over the finite time horizon N. The tracking error at each time step k is defined as:

$$\text{err}_k = x_k - x_{\text{ref},k} \tag{3.19}$$

The cost function J to be minimized is expressed as:

$$J = \sum_{k=0}^{N-1} \left(\text{err}_k^T Q \text{err}_k + (\tau_k - \tau_{\text{ref},k})^T R (\tau_k - \tau_{\text{ref},k})\right) + \text{err}_N^T P \text{err}_N \tag{3.20}$$

Where:

- Q is the weighting matrix for the state error, ensuring accurate tracking.
- R is the weighting matrix for the control input error, ensuring control efforts are kept within reasonable limits.
- P is the weighting matrix for the terminal state error, emphasizing final state accuracy.

Optimization Problem Formulation: The main reason for formulation of optimization problem of NMPC is to minimize the cost function J related to the system dynamics and constraints. The system dynamics are described by the discrete-time nonlinear model:

$$x_{k+1} = f(x_k, \tau_k) \tag{3.21}$$

This optimization problem is solved at each time step over the prediction horizon N to determine the optimal sequence of control inputs τ_k^* that minimizes the cost function. The final NMPC cost function can thus be written as:

$$J = \sum_{k=0}^{N-1} \left((x_k - x_{\text{ref},k})^T Q (x_k - x_{\text{ref},k}) + (\tau_k - \tau_{\text{ref},k})^T R (\tau_k - \tau_{\text{ref},k}) \right) + (x_N - x_{\text{ref},N})^T P (x_N - x_{\text{ref},N}) \tag{3.22}$$

This cost function plays the role of the system to track the trajectory which is set by minimizing tracking error and control effort within the number of predicted time steps N as well as accuracy of the final state.

3.3.4 Integration with Nonlinear Equation

The integration of Nonlinear Model Predictive Control (NMPC) with the nonlinear dynamics of the system is a critical component of our control strategy. The NMPC approach predicts the future behavior of the system over a defined prediction horizon and optimizes the control inputs to minimize a specific cost function. This process involves directly incorporating the nonlinear equations governing the system's dynamics into the NMPC formulation, which allows for a more accurate and robust prediction of system behavior The nonlinear system dynamics are represented by the state equation:

$$x_{k+1} = x_k + \int_{t_k}^{t_{k+1}} f(x(t), \tau(t))\, dt \tag{3.23}$$

where:

- x_{k+1} is the predicted state of the system at the next time step.
- x_k is the current state of the system at time step k.
- $\int_{t_k}^{t_{k+1}} f(x(t), \tau(t))\, dt$ represents the integral of the nonlinear system's dynamics function $f(x(t), \tau(t))$ over the time interval from t_k to t_{k+1}.

For NMPC, this integral is used to determine the change in the state of the system under consideration when subjected to the control input τ over the predictive horizon. The function $f(x(t), \tau(t))$ describes the nonlinear dynamics of the system and its nonlinearities with respect to control signals.

The integration of the nonlinear dynamics into the NMPC framework allows the controller to make predictions that account for the system's true behavior, rather than relying on linear approximations. This is particularly important in applications involving biomechanical systems, where the dynamics are inherently nonlinear and where precision in prediction is crucial for stability and control.

In practice, the NMPC controller optimizes the control inputs τ_k over a finite horizon by solving the following optimization problem at each time step:

$$\min_{\tau_k} J = \sum_{k=0}^{N-1} \left(\|x_k - x_{\mathrm{ref},k}\|_Q^2 + \|\tau_k - \tau_{\mathrm{ref},k}\|_R^2 \right) + \|x_N - x_{\mathrm{ref},N}\|_P^2 \tag{3.24}$$

subject to the system dynamics:

$$x_{k+1} = x_k + \int_{t_k}^{t_{k+1}} f(x(t), \tau(t))\, dt \tag{3.25}$$

This approach helps ensure that the system follows a desired path by using optimal control inputs determined through the application of a nonlinear model of the system. By accurately modeling the system's behavior and predicting future states, NMPC can apply the most effective control actions to enhance both the stability and performance of the system simultaneously. This method not only improves the system's ability to maintain postural stability but also optimizes its overall dynamic response, making it more resilient to disturbances and capable of adapting to varying conditions.

The extended formulation also emphasizes the importance of accurately identifying the state and control variables within the nonlinear dynamics, as these factors significantly impact the optimization process and the effectiveness of the control strategy. By integrating the nonlinear equations into the NMPC formulation, we achieve a more robust solution to the control problem, one that is specifically tailored to accurately represent the system under investigation. This approach ensures that the control strategy is well-suited to handle the complexities of the system, leading to improved stability and performance.

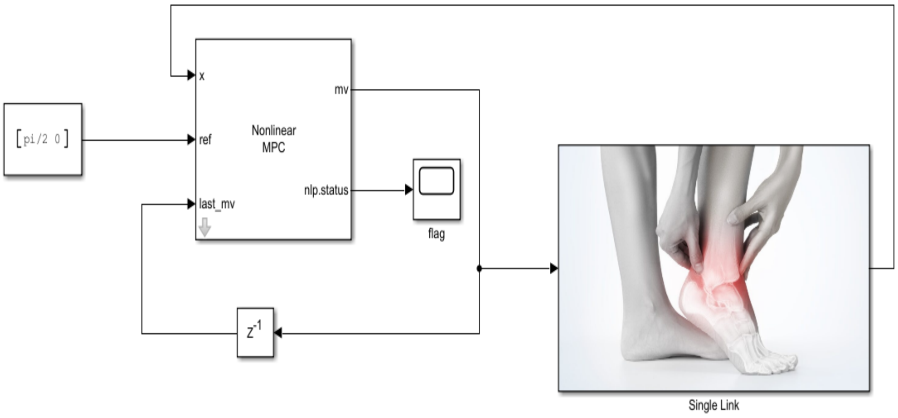

Figure 3.4: Main controller's model

The Subsystem simulink diagram is shown below:

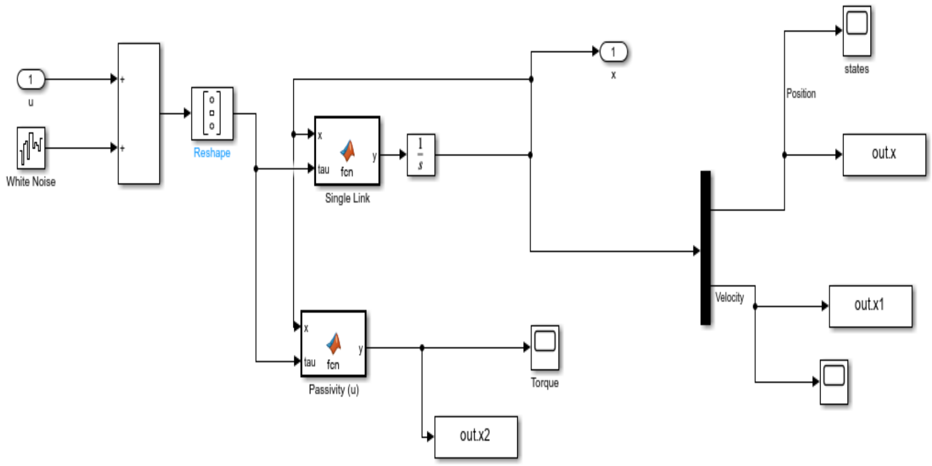

Figure 3.5: Subsystem of the simulink model

3.4 Summary of Chapter 3: Methodology

In this work, a sophisticated input strategy is developed to enhance balance control, utilizing Nonlinear Model Predictive Control (NMPC) and Passivity-Based Control (PBC) applied to a single-link biomechanical model of the ankle joint.

This approach addresses the complexities of maintaining postural stability in the presence of nonlinear dynamics and external disturbances. The PBC method ensures system stabilization by regulating energy flow and maintaining passive behavior, even under disruptive conditions. Complementarily, NMPC predicts future states and optimizes control inputs, keeping the system aligned with the desired reference path. NMPC is especially effective in handling the intricacies of the biomechanical model, ensuring precise trajectory tracking of the ankle joint, even in dynamically changing environments.

While NMPC provides predictive control and optimization, PBC stabilizes the system by dissipating energy and preventing instability. This combination allows the ankle joint to maintain its correct position relative to the applied control despite the system's inherent nonlinearities. The hybrid NMPC-PBC control strategy significantly improves the system's resilience to disturbances, successfully addressing the challenges of postural stability.

3.4.1 Insight for the Next Chapter: Discussions and Results

The next chapter will present and analyze the results obtained from the implementation of the NMPC and PBC-based control strategies. A comprehensive evaluation of the system's performance under various conditions will be provided, focusing on how effectively the combined control methods stabilize the ankle joint. The conclusions will highlight the key findings of the research, assess the practical implications of the control strategies, and suggest future directions for further improving postural stability systems.

CHAPTER 4

DISCUSSIONS AND RESULTS

4.1 Overview

In this chapter, we delve into the outcomes of experiments conducted on the single-link biomechanical model of the ankle joint, utilizing Nonlinear Model Predictive Control (NMPC) and Passivity-Based Control (PBC). These results highlight the effectiveness of these control strategies in stabilizing posture under various perturbation scenarios. Additionally, we explore the connection between these findings and biomechanical control systems, concluding with a summary of the key findings from this study. The primary objective of this chapter is to showcase the practical significance and application of the model and controllers by demonstrating how the implemented control strategies contribute to stabilizing the ankle joint. We systematically compare settling time, control effort, and the system's response to varying magnitudes of perturbation across different controllers. These comparisons are visually represented through graphs that illustrate the system's time performance, the state of stability of the model, and the effectiveness of the control mechanisms. In the conclusion, we provide a summary of the results, highlighting key insights and achievements. It is evident that the NMPC algorithm excels in reducing settling time, while the PBC method ensures system stability, even under significant perturbations. We also address the limitations of these results, offering a foundation for future studies and developments, particularly in clinical applications. Potential advancements include exploring models with more than two links or incorporating neural delays into the control system. Thus, this chapter not only provides a comprehensive presentation of the experimental results but also lays out a roadmap for future developments in postural stability and biomechanical control systems.

4.2 Simulation result of Nonlinear Model

In this part we represent the simulation result for our single-link biomechanical model of ankle joint with different initial perturbation values to see how the system responses against perturbations and at the last we also compare our result with latest work of others. The nonlinear model, which has been thoroughly detailed in Chapter 3 and is illustrated in Figure 3.3, forms the basis of our analysis in this chapter. Building upon the controllers outlined in the previous chapter, we will provide a detailed explanation of their performance and effectiveness in real-life scenarios, particularly in preventing falls in response to perturbations.

To evaluate the system's ability to trace the reference trajectory, we considered three different perturbation values. Each value and its corresponding effects will be discussed in detail, accompanied by graphical representations to illustrate the system's response. These analyses will help demonstrate the practical applications of the control strategies in enhancing postural stability and preventing falls.

In order to simulate real-world conditions and evaluate the robustness of the control strategies, a white noise disturbance with a noise power of 0.5 (W) was introduced at the input of the system. This input noise models the unpredictable fluctuations commonly encountered in physical environments. Additionally, measurement noise, also with a noise power of 0.5 (W), was added to the system's output to simulate noise that could affect the measurement signals. These noise sources allow for a realistic assessment of the Nonlinear Model Predictive Control (NMPC) and Passivity-Based Control (PBC) methods in stabilizing the ankle joint under external disturbances and noise interference.

The system's response to an initial perturbation of 1.47 rad, with a reference trajectory of 1.57 rad, is illustrated in Figure 4.1. These results reveal that the system stabilizes within approximately one second, underscoring the effectiveness and stability of the control scheme. This rapid stabilization serves as compelling evidence of the efficacy of both the Nonlinear Model Predictive Control (NMPC) and Passivity-Based Control (PBC) strategies employed in this study. Additionally, a white noise disturbance with a noise power of 0.5 (W) was introduced into the system to simulate real-world conditions, including unpredictable fluctuations in both the input and measurement signals.

In the presence of this input white noise, the system still effectively stabilizes and closely tracks the reference position. This demonstrates the robustness of the control strategies, even under noise interference. This performance is contrasted with findings from earlier studies on single-link biomechanical models, such as those reported in [28]. In that study, the system was tested with an initial perturbation of 0.1 radians, which is significantly smaller compared to the 1.47 radians used in this research. Despite this, the settling time reported in [28] was relatively low, around 3 seconds, as shown in the following comparison. The input noise power of 0.5 W was also used for the other two perturbation values of 1.37 rad and 1.27 rad, which are simulated as well and can be seen in the subsequent graphs. As Figures [4.4] to [4.9] show, the system maintained stability across all perturbations, further validating the effectiveness of NMPC and PBC in managing disturbances, even in the presence of noise.

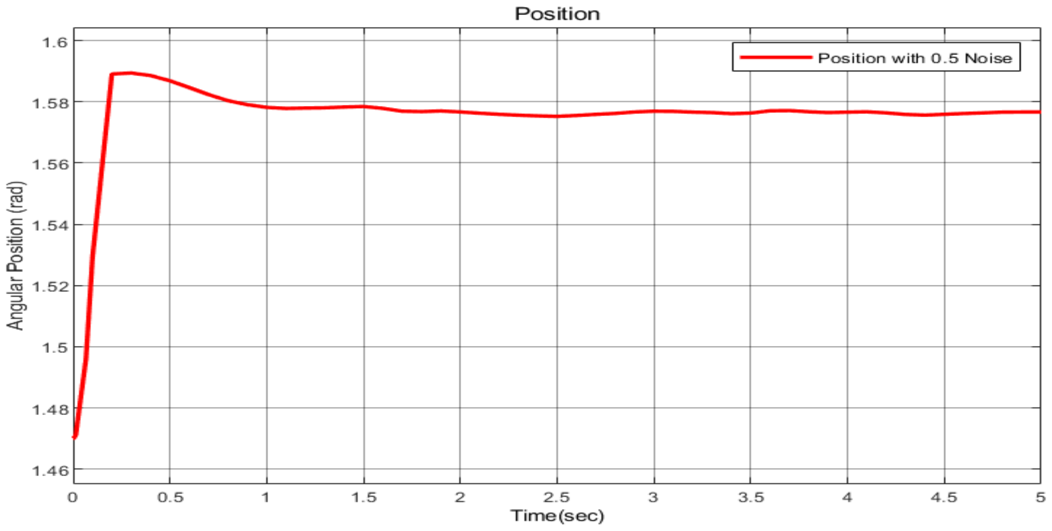

Figure 4.1: Angular Position Result

Fig 4.2 illustrates the velocity profile of the nonlinear model around the ankle joint in the presence of input white noise with noise power of 0.5 (W). The analysis shows that both the initial and final velocities are zero, reflecting a realistic physical scenario where the system starts and ends at rest. This zero-velocity boundary condition is crucial for simulating the natural physiological process in which the ankle joint returns to a stable position after a perturbation. The velocity graph shows significant changes during the transient state, which gradually diminish as the system stabilizes, with only slight fluctuations around a static state. This behavior highlights the model's adaptability and the effectiveness of the control methods in managing disturbances. By capturing these dynamics, the graph provides valuable insights into how the model regulates energy levels to maintain stability and control, aligning with the results found in [28] for comparison.

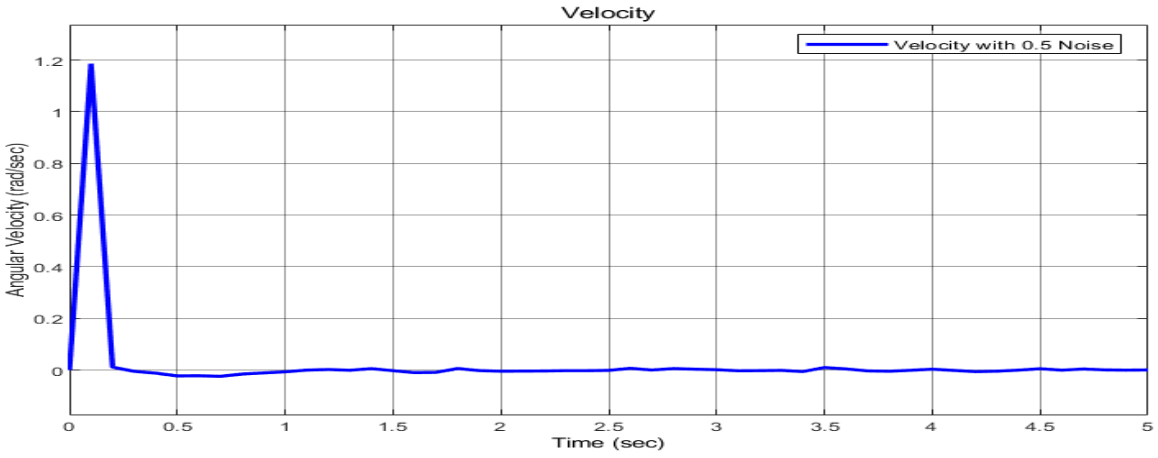

Figure 4.2: Angular Velocity The beginning and ending value for velocity is zero

While the primary focus of our study, as well as previous studies, has been on the angular position of the nonlinear model, it is still worthwhile to highlight the system's efficiency as demonstrated in earlier graphs and in Figure 4.3. These figures illustrate how quickly the input torque under the influence of input white noise with a noise power of 0.5 (W) is controlled, showcasing a significantly shorter response time compared to recent research findings such as those in [28]. The results indicate only slight differences, underscoring the effectiveness of our control approach in managing torque input efficiently.

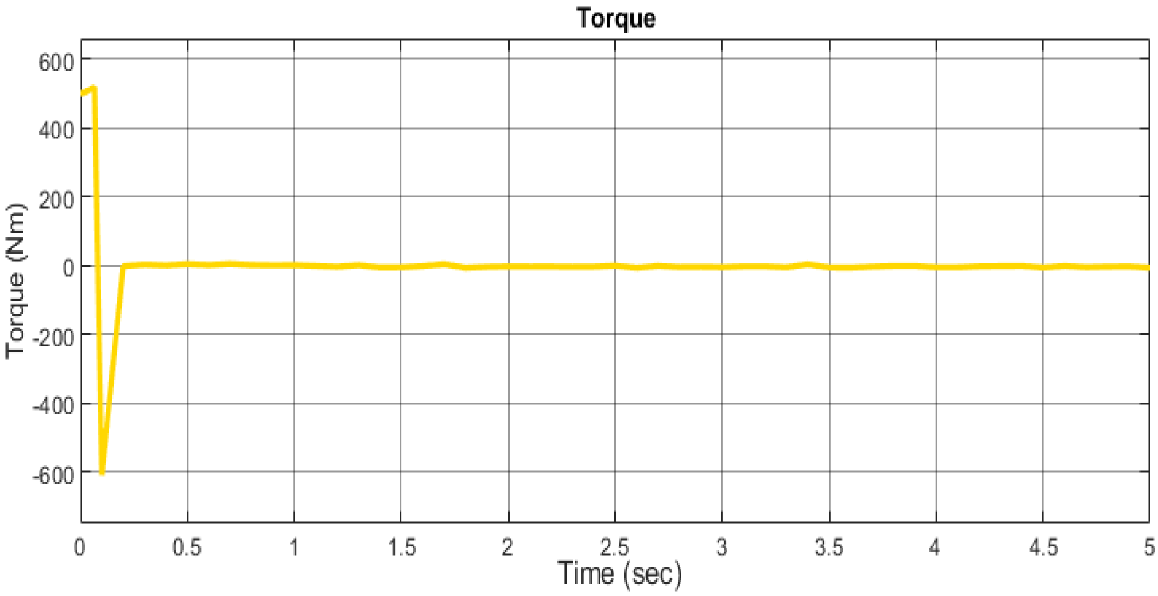

Figure 4.3: Controlled input torque in Ankle

As we already mentioned which we used different values for perturbation with ground. So in Fig 4.4 which is indicating the settling time of the controller when the initial perturbation value is getting changed from 1.47 to 1.37 and the time will be delayed like 1.8 sec but still the effectiveness of the system shows how it settles down quickly.

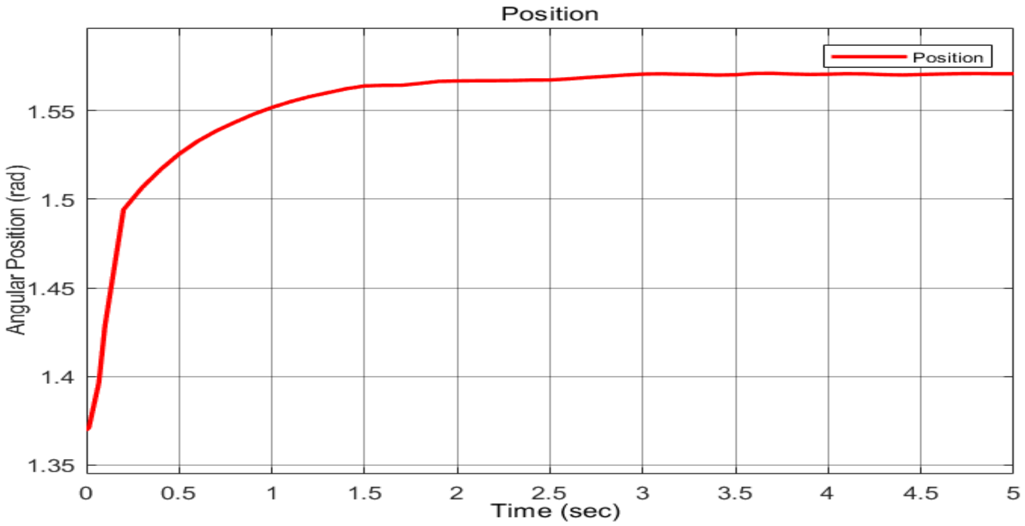

Figure 4.4: Angular Position Result

Now, we will examine the results for velocity. As expected, the velocity is drawn towards zero, with both the initial and final values set to zero. By analyzing Figure 4.5, we can observe slight changes in the velocity profile when comparing the perturbation value of 1.47 radians in Figure 4.2 to a reduced value of 1.37 radians. Despite this decrease in perturbation, the overall behavior remains consistent, with the system efficiently stabilizing and returning to a state of equilibrium. This demonstrates the robustness of the control methods in handling varying levels of disturbance.

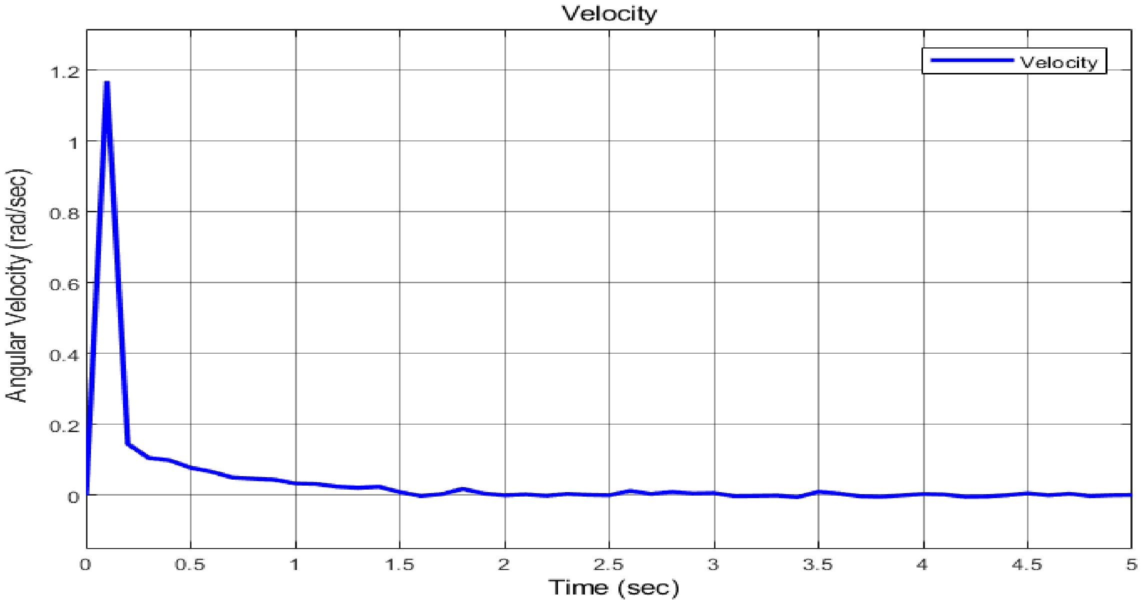

Figure 4.5: Angular Velocity The beginning and ending value for velocity is zero

It must be mentioned in Fig 4.6 which is showing the reslut of input torque for the intial changed value of 1.37. By comparing it with Fig 4.3 a slight changes can be noted in torque value with the change of the perturbation value.

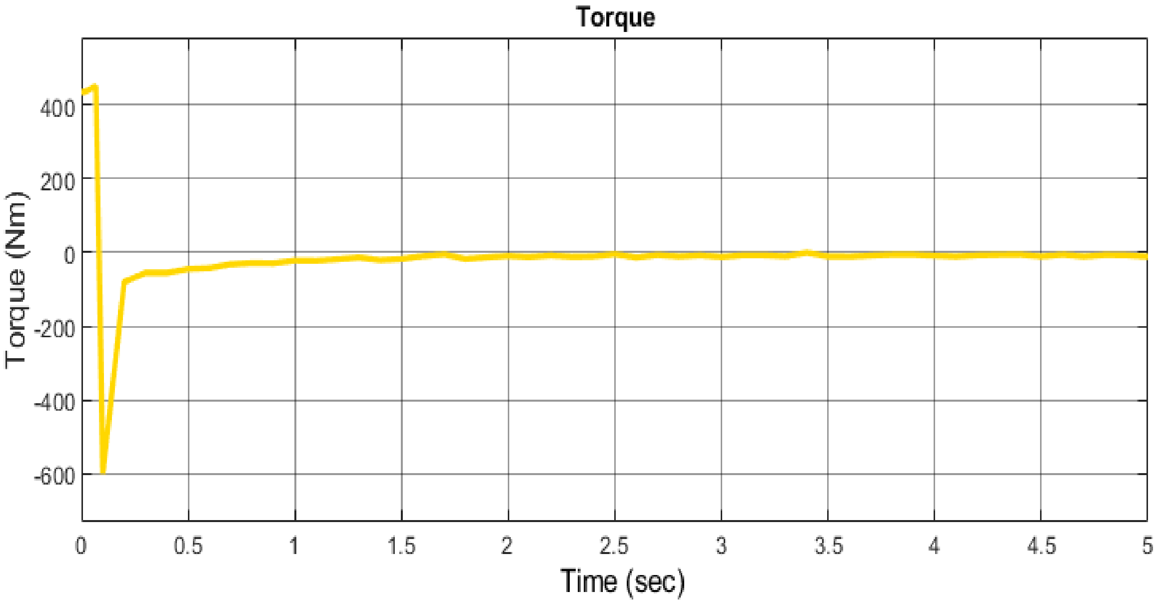

Figure 4.6: Controlled input torque in Ankle

As the final simulation value, we examined how the designed controller responds to a perturbation when the initial value is further reduced from 1.37 radians to 1.27 radians. In this case, although the settling time is slightly delayed, the system still recovers relatively quickly. This is evident in Figure 4.7, where the settling time is approximately 2.3 seconds. These results underscore the capability of the control strategy to effectively stabilize the system, even when faced with varying levels of disturbance.

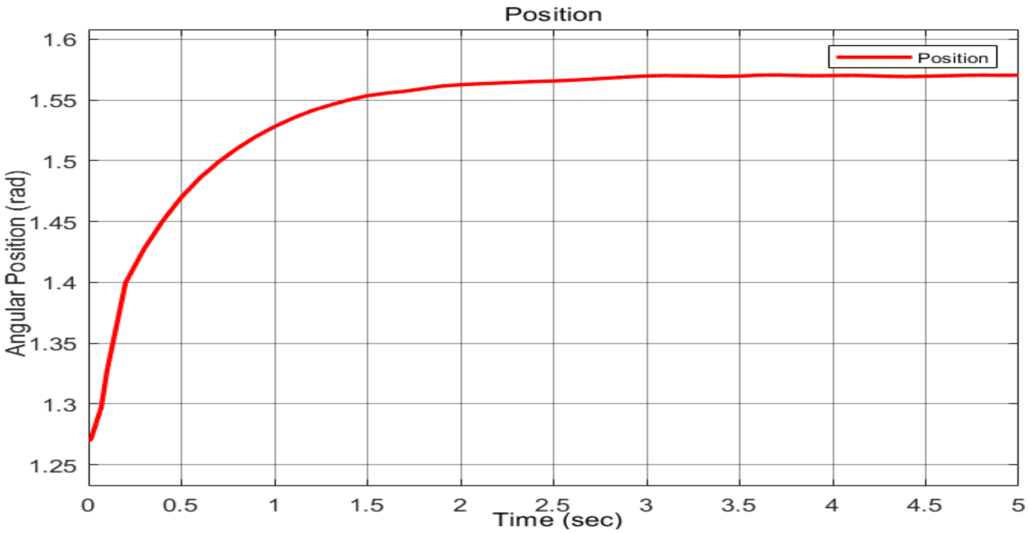

Figure 4.7: Angular Position Result

Similarly we can observe slightest change in terms of velocity profile in Fig 4.8 how the figure changes when the values is set to 1.27 as a initial perturbation value.

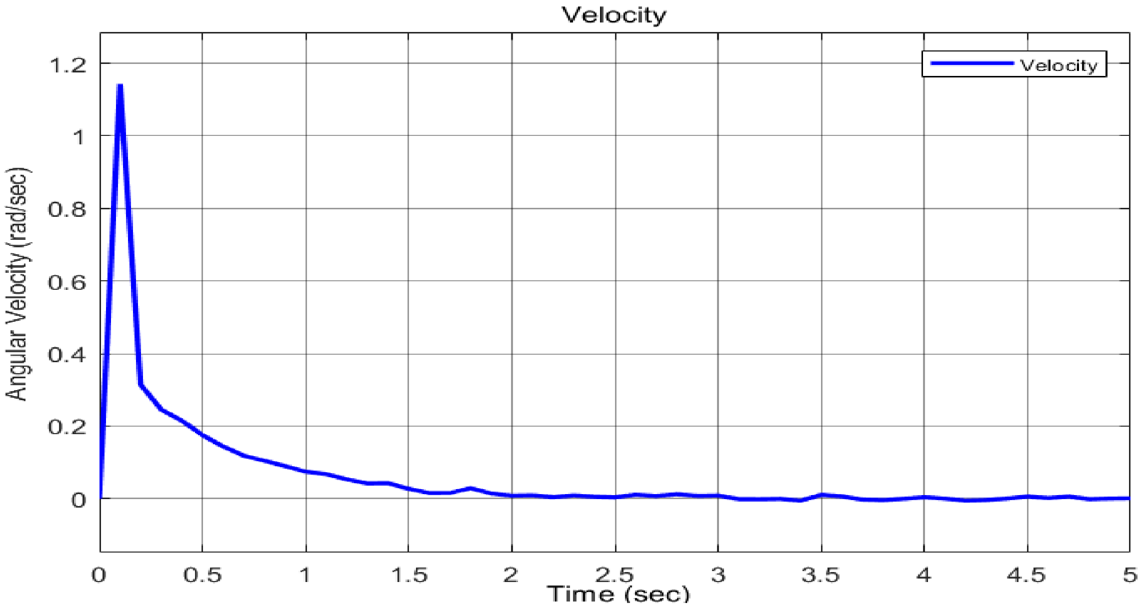

Figure 4.8: Angular Velocity The beginning and ending value for velocity is zero

Finally, the input torque value also exhibits a slight change when the perturbation value is reduced from 1.47 radians, as observed in Figure 4.9. Despite this change, the input torque is managed effectively, demonstrating that the control strategy maintains quick and efficient control over the system. This adaptability to different levels of perturbation highlights the robustness of the implemented controller in maintaining postural stability.

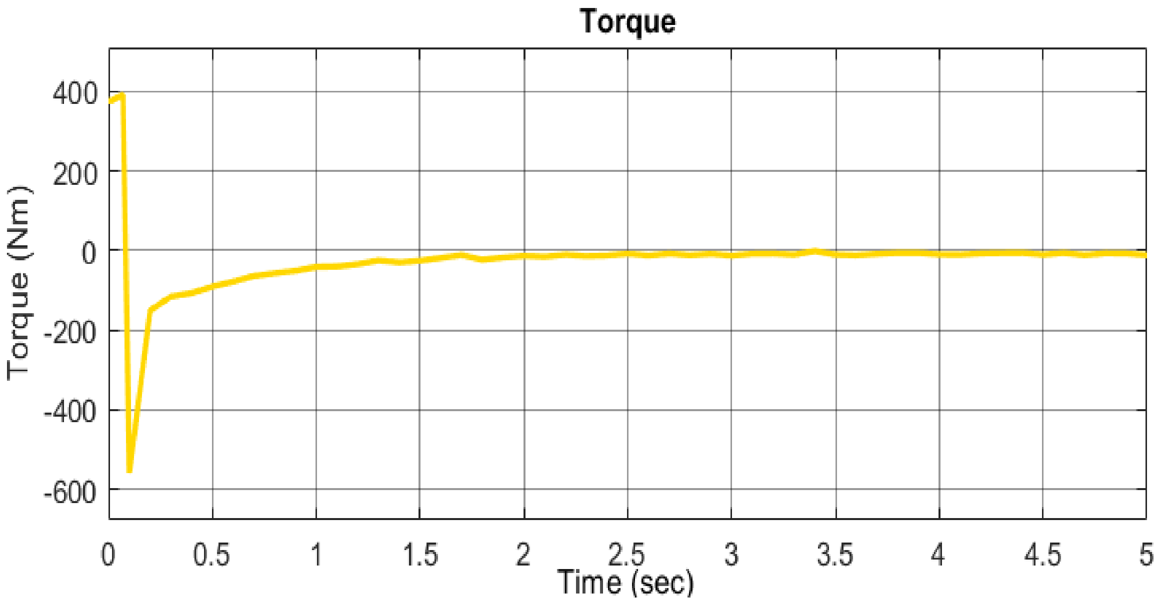

Figure 4.9: Controlled input torque in Ankle

The following table shows all the values:

Table 4.1: Simulation results with different values

Current study with reference trajectory of 1.57 rad	**Settling Time (Sec)**	**Earlier Study (rad) in [28]**	**Settling Time (Sec)**
Angular Position (1.47, 1.37, 1.27) Initial Perturbations	1.047, 2, 2.375	0.1	3
Angular Velocity (1.47, 1.37, 1.27)	0.4, 1.4, 1.75	0.1	0.27
Controlled Input Torque (1.47, 1.37, 1.27)	0.25, 1.5, 2	0.1	2

Based on the results obtained and illustrated through various system graphs, two key conclusions can be drawn:

- **Direct Relationship Between Initial Perturbation Values and Settling Time:** The results indicate a clear relationship between the initial perturbation values and the settling time of the system. Specifically, higher initial perturbation values lead to a lower settling time. This finding suggests that the intensity of the perturbation is inversely proportional to the system's ability to regain stability. It demonstrates the effectiveness of the NMPC and PBC strategies developed in this study, as they not only reduce the settling time but also show robustness across different levels of perturbation.

- **Efficiency and Future Application of NMPC and PBC Strategies:** The control strategies implemented have proven to be robust and efficient, capable of handling varying degrees of perturbations effectively. This robustness suggests that these strategies have significant potential for future applications in biomechanical control systems. The study establishes a solid foundation for future research aimed at optimizing balance control in real-world environments, paving the way for more advanced and complex control strategies that can further enhance postural stability.

These conclusions highlight the potential of the NMPC and PBC approaches to be utilized in future developments of biomechanical control systems, contributing to the advancement of balance control solutions in practical, real-life scenarios.

4.3 Chapter 4 Summary: Discussions and Results

In this chapter, we present the outcomes of the experiments performed on the single-link biomechanical model of the ankle joint, utilizing Nonlinear Model Predictive Control (NMPC) and Passivity-Based Control (PBC). The primary focus is on the effectiveness of these control strategies in stabilizing posture under different perturbation scenarios, including the presence of external noise. The inclusion of a 0.5 white noise input in the Simulink system introduces realistic disturbances, allowing for an in-depth analysis of the robustness and performance of the controllers in more practical settings.

The simulation results highlight the ability of NMPC and PBC to maintain stability despite various perturbations and external noise. Key metrics, such as settling time, control effort, and the system's response to different magnitudes of perturbations, were compared across different control strategies. Graphical representations were used to visualize the system's performance, showing that the NMPC algorithm excels in minimizing settling time, while the PBC method ensures long-term system stability, even under noise.

The noise factor further emphasizes the practical relevance of the control strategies, simulating real-world biomechanical scenarios where random external factors impact stability. These results showcase not only the efficacy of the control strategies but also the system's adaptability and resilience. Future studies can build upon this foundation by incorporating more complex models, such as multi-link systems or neural delays, to enhance postural stability research further.

4.3.1 Insight for the next chapter, Conclusions and Future Work:

In the next chapter, you can discuss the broader implications of your research and how the findings from this study can contribute to real-world applications. Focus on summarizing the major achievements, such as the controllers' ability to stabilize the system under noise and varying perturbations, and outline areas for further research. Highlight future directions, including exploring multi-link models, integrating advanced neural feedback mechanisms, or developing more adaptive control algorithms that can respond dynamically to different biomechanical challenges.

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

5.1 Overview

This Chapter focuses on overall performance analysis and future recommendations.

5.2 Conclusion

This research successfully developed and analyzed a robust framework for enhancing postural stability through the application of Nonlinear Model Predictive Control (NMPC) and Passivity-Based Control (PBC) to a single-link biomechanical model of the ankle joint. The study demonstrated the effectiveness of these advanced control techniques in addressing the challenges posed by nonlinearities, external perturbations, feedback delays, and proprioceptive delays, all of which are critical factors in maintaining balance.

By implementing NMPC, the system was able to predict future states and optimize control inputs over a finite horizon, thereby minimizing the tracking error between the desired and actual ankle joint angles. This predictive capability was essential in handling the dynamic nature of the biomechanical model, ensuring precise control under varying conditions. PBC was employed to reinforce the system's stability by designing a control law that regulates the energy within the system. This method ensured that the ankle joint maintained its desired trajectory, even in the presence of significant disturbances. The combination of NMPC and PBC not only enhanced the accuracy and robustness of the control strategy but also deepened the understanding of the biomechanical factors influencing postural stability.

The integration of these techniques provides a powerful tool for evaluating and enhancing joint stability, offering potential applications in clinical assessments and rehabilitation programs. The research outcomes suggest that the methods developed can be effectively used to monitor and improve the stability of the lower joints, particularly in populations at risk of balance-related issues, such as the elderly or individuals with musculoskeletal disorders.

5.3 Future Work

Building on the success of this study, several avenues for future research are proposed to expand the scope and applicability of the developed control strategies:

- **Extension to Multi-Link Models:** Future research could extend the application of NMPC and PBC to more complex multi-link biomechanical models. By analyzing the interaction between multiple joints and links, it would be possible to develop more sophisticated control strategies that better mimic the complexities of human movement.
- **Incorporation of Feedback and Proprioceptive Delays:** Future studies could incorporate both feedback and proprioceptive delays into the model to more accurately simulate the physiological processes underlying postural control. This approach would offer a realistic representation of how these delays impact joint stability and could lead to the development of control strategies that are better aligned with the body's natural responses.
- **Integration with Advanced Diagnostic Techniques:** The methodologies developed in this research could be combined with advanced imaging and deep learning algorithms to enhance diagnostic capabilities for joint health assessment. For instance, extending pose estimation techniques to other joints, such as the elbow or shoulder, could be used alongside NMPC and PBC to detect abnormalities or diseases early.
- **Clinical Application and Personalized Rehabilitation:** Translating these techniques into clinical settings could enable the creation of personalized rehabilitation protocols for patients with joint health issues. Tailoring interventions based on precise biomechanical data and predictive control models could significantly improve patient outcomes by addressing specific needs and conditions.
- **Exploration of Trade-offs in Control Parameters:** Further research could explore the trade-offs between different control parameters, particularly in the application of NMPC and PBC. Understanding the balance between factors such as control effort, energy efficiency, and response time could lead to the refinement of these techniques, making them even more effective and reliable for real-world applications.

By pursuing these research directions, the methodologies developed in this study could be further refined and adapted to a wider range of applications, ultimately contributing to the advancement of biomechanical control systems and improving the quality of life for individuals with joint stability issues.

5.4 Chapter 5 Summary: Conclusion and Future Work

This research successfully developed a robust control framework using Nonlinear Model Predictive Control (NMPC) and Passivity-Based Control (PBC) to improve postural stability in a single-link biomechanical model of the ankle joint. The study demonstrated that these advanced control methods effectively address nonlinearities, external perturbations, and proprioceptive delays, enhancing system stability and precision in joint angle tracking. NMPC provided predictive capabilities for optimizing control inputs, while PBC ensured energy regulation and system robustness, even under disturbances.

The combined control strategies offer valuable insights for clinical assessments and potential rehabilitation applications for individuals at risk of balance issues.

For future work, several avenues are suggested, including extending the methodology to multi-link models, incorporating feedback and proprioceptive delays for more realistic simulations, integrating diagnostic techniques like imaging and deep learning, applying the methods in clinical rehabilitation, and exploring trade-offs in control parameters. These directions aim to refine the control strategies and broaden their application, contributing to advancements in biomechanical control systems and improving outcomes for patients with joint stability issues.

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