Balance Hip-Knee Insights and Innovative Approaches with Sliding Mode Control

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“Man can have nothing but what he strives for”

Qur’an (53:39)

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Abstract

This research investigates novel methodologies to analyze and enhance joint stability and control in human biomechanics, focusing on the Hip-Knee (HK) joint angles during single-leg stance (SLS) activity and applying Quasi Sliding Mode Control (QSMC) to a single-link biomechanical model. Identifying lower joint stability is critical, especially in older populations who are more likely to have falls and mobility limitations. This requires an understanding of joint dynamics under challenging conditions. This research aims to develop a non-invasive, cost-friendly method of identifying joint problems so that early intervention and treatment can prevent fall and instability in posture..

In the first part of the research, pose estimation techniques were employed to analyze the hip-knee joint angles in young and elderly participants during an SLS activity. The results demonstrated a huge difference between the two age groups: younger individuals demonstrated stable and consistent joint angles, reflecting strong neuromuscular control and stable posture. The mean and standard deviation values were obtained:(107.14±5, 96.42±7) for both hips and (36.76±7, 44.30±4)for both knees from one of the young participants. These values are in line with the expected joint angles(110 to 120 degrees for the hip and 45 to 60 degrees for the knee) and show stability in results In contrast, the elderly group showed significant fluctuations and deviations in joint angles, often leading to moments of instability. The results from one of the elderly participants show a high level of variability and low mean values for both hips and knees: (65.42±77, 85±76.67) and (4.15±10.8, 7±18), respectively. These findings explain the difference in participant results and pose estimation's potential as a diagnostic tool for identifying individuals at risk of joint-related issues, providing a non-invasive alternative to traditional imaging methods like MRI scans. These early detection results can prevent instability in their posture and prevent further joint issues.

The second part of the research emphasizes the utilization of QSMC to a single-link biomechanical model. This controlling technique allows us to analyze the stability of a body under multiple disturbances now QSMC was chosen for its robustness and effectiveness. Now chattering is a common issue in traditional sliding mode control techniques so to eliminate it we use QSMC which uses continuous law. The results confirmed the effectiveness of QSMC in maintaining stability under perturbations, with a significant reduction in input torque results (130Nm). However, the study also identified a trade-off, as the reduction in chattering led to an increase in settling time (2-3 Sec). Despite this, the overall performance of QSMC was better in comparison to other techniques for nonlinear systems, offering precise, stable, and efficient control.

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ACRONYMS AND ABBREVIATIONS

BOS	Base of Support
CNN	Convolutional Neural Network
COP	Center of Pressure
CT	Computed Tomography
DF	Dorsi Flexion
DSLR	Digital Single Lens Reflex Camera
HK	Hip, Knee
HKA	Hip, Knee, Ankle
LQR	Linear Quadratic Regulator
ML	Machine Learning
MRI	Magnetic Resonance Imaging
MTCs	Muscle Tendon Complexes
PF	Planter Flexion
QSMC	Quasi Sliding Mode Control
ROM	Range of Motion
SLS	Single Leg Stance
SMC	Sliding Mode Control

CHAPTER 1

INTRODUCTION

1.1 Overview

Postural stability, often referred to as balance, completely relies on the complex interplay of lower joints. It is a fundamental aspect of human movement and is essential for performing various activities of daily living, such as standing, walking, and running [1]. It encompasses the ability to maintain equilibrium and stability while stationary or in motion, thereby preventing falls and maintaining functional independence [2]. Postural stability is governed by a complex interplay of sensory, motor neurons, and musculoskeletal systems, which work in unity to maintain an upright posture against the force of gravity and external perturbations. By sorting out the major instruments of postural control and using advanced examination techniques, investigators and clinicians can work on their ability to analyze, diagnose, and treat individuals with balance shortcomings [3]. There is a way to understand human walking or any movement task to apply unforeseen perturbations [4] and examine the analysis of the steady state of human motion Magnetic Resonance Imaging (MRI) scans are indeed effective in measuring joint health, but their high cost and limited usability are cause for concern. There is a growing need for non-invasive, cost-effective methods to assess joint integrity and stability. Therefore, analysis regarding the angles and motion of Hip-Knee joints would be beneficial for understanding the stability of the joint [5] as well as any risks that participants might be at during activities such as sit-to-stand and single-leg stance. Pose estimation employs computer vision and machine learning to estimate joint motion [6], and quantitatively describe joint movement, which collects a wealth of information that can help clinicians identify persons at risk for joint instability and intervene early. However, the question of how to evaluate joint health is only half of the problem. To gain sufficient stability and increase the accuracy of movement with reduced instability targets in individuals with unstable joints, it is necessary to apply the appropriate control concepts.

Now, Sliding Mode Control (SMC) is an alternative to address non-linear systems with uncertainties like bio-mechanical models. In a system involving matched uncertainties, SMC guarantees that the system trajectory is forced to reach a desired sliding surface whilst remaining stable despite interference [7]. One primary disadvantage of SMC is the issue of “chattering” where the control action oscillates at high frequency; this is detrimental to mechanical systems [8]. To solve this problem, a control technique known as Quasi-Sliding Mode Control (QSMC) has been designed. It also reduces the control chattering

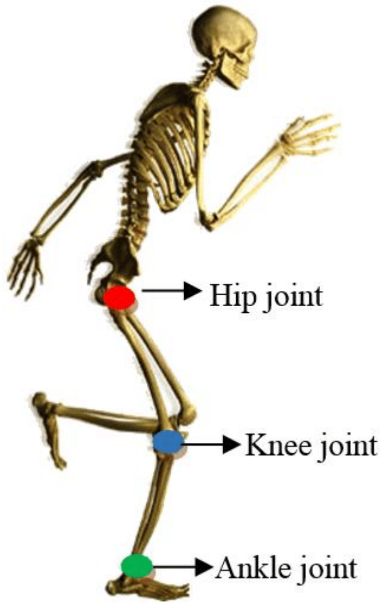

Figure 1.1: Human Lower Body Joints

by replacing the sign function, used in the ideal SMC, with a continuous function like saturation function [9]. This alteration minimizes chattering, thus achieving enhanced and more realistic control inputs adequate for real-world applications. Therefore this research is carried out in two parts first the experimental part where lower joints are evaluated, and second, the theoretical part in which we analyze the body's stability through a controller that combines pose estimation and QSMC to have a complete way of evaluating and rehabilitating human balance and stability. The proposed solution of screening many kinds of joint instabilities and corresponding interventions in a single approach may help provide early and optimal interventions for improving mobility and preventing falls in various population groups.

1.2 Problem Statement

The main aim of this study is to propose a system combination of both artificial intelligence and control theory for posture stability which provides an efficient smart system. Despite significant advances in bio-mechanics and control theory, the challenge of correctly assessing joint health and maintaining stability input in the presence of perturbations remains a challenge. Current techniques for evaluating lower joint functionality, such as MRI and CT scans, are costly and not always feasible for regular monitoring. Additionally, traditional control techniques often require high variability and require unrealistic high input gains to maintain stability, leading to inefficiencies, high cost, and mechanical loss. The research provides a cost-effective, robust method to assess lower joint health with a smart, efficient control strategy to ensure stability in dynamic conditions. A control strategy that requires less input with maximum output.

1.3 Research Gap

There are certain limitations in the effective analysis of lower joint mechanics, especially in a dynamic environment where control techniques provide less effective solutions. Recent studies either focus on experimental studies or control theory applications rarely combining both studies to provide a realistic understanding.
In this research, this gap is addressed in two parts:

- **Experimental Analysis of Lower Joints**: This part involves the assessment of the hip and knee joints during Single leg stance (SLS) activity. Thus, using pose estimation, the hip and knee angles were tracked, and information on joint stability in different age groups were obtained. This experimental approach makes it possible to work out instabilities and pinpoint possible joint problems at an early stage.

- **Application of Control Theory**: In the second part, the Quasi-Sliding Mode Control (QSMC) is implemented on a single-link bio-mechanical model. This control technique is used for increasing the stability by the means of compensation of multiple perturbations. The results also indicate that, generally, QSMC produces superior performance to traditional methods by yielding better stability.

1.4 Research Contribution

The following research will make several key contributions:

- **Pose Estimation for Lower Joints**: A system will be developed to assess the health of lower body joints (Hip-Knee) from single-leg stance activity. providing a non-invasive cost-effecting method to analyze them.

- **Advanced Control Technique**: Implementing Quasi-Sliding Mode Control for the single-link model to enhance efficiency and reduce chattering compared to Classical SMC providing realistic control inputs.

- **Integration of Approaches**: Alleviating the gap between pose estimation and control theory on the basis of the application of joint health data for the enhancement of stability control of biomechanical models. Providing a combined framework to identify the individuals being at risk and offering targeted interventions to improve their stability.

1.5 Limitations

There are some limitations to this work as well:

- **Scope of Pose Estimation**: It is to be expected that the accuracy and even reliability of the different pose estimation techniques depend on the quality of the input data and the type of used algorithms. Although these techniques provide a way to examine the joints without conducting tests that may cause additional harm or discomfort, they may not provide a detailed representation of the nature of joints [10].

- **External Perturbations**: To identify the system's stability, a certain range of perturbations are chosen in the context of the study of the bio-mechanical system. When it comes to real-world situations, the kind and intensity of disturbances are likely to differ, meaning that the control strategy results can differ a little bit [11].

1.6 Thesis Organization

The rest of the thesis is organized as follows:

In **Chapter 2**, literature review of different techniques is presented.

In **Chapter 3**, Focuses on proposed methodologies, feature extraction techniques, details of visual saliency and feature selection.

In **Chapter 4**, Experimentation is performed to evaluate the results of proposed methodologies.

In **Chapter 5**, Conclusions and implications are presented.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

Several researchers have been contributed in the domain of AI and Control theory to develop a smart efficient system for posture stability. Different methodologies have been proposed to improve the performance of Controller techniques.

2.2 Pose estimation techniques for lower joints

Where [12] the SLS test provides valuable insights into an individual's ability to control body alignment and weight distribution, which are essential components of postural stability, the complex coordination of neurophysiological (neuromuscular, cerebellum, and vestibular) and bio- mechanical (knee, hip, and ankle) systems to produce and provide equilibrium while standing on one leg makes the single-leg stance, an essential exercise to analyze the stability of a body. Furthermore, abnormalities observed during the SLS test, such as sway, asymmetrical weight distribution, or inability to maintain balance may indicate [13] underlying deficits in postural control mechanisms. The hip and knee (HK) are fundamental components of the human musculoskeletal system.

In this research the instrumented assessments utilize specialized equipment, such as force plates, motion capture systems, and wearable sensors, to obtain objective measurements of posture stability and movement biomechanics [14]. Force plates measure ground reaction forces and center of pressure (COP) sway to assess weight distribution and balance control during static and dynamic tasks. Motion capture systems track the movement of body segments and joints in three-dimensional space, enabling precise kinematic analysis of posture and gait [15].

The paper presents an overview of the accelerometers, gyroscopes, and inertial measurement units (IMUs) [16] approach in the context of characterizing gait-related movement patterns and identifies potential design issues to be taken into account in the experimental setup. It starts by outlining the principles behind accelerometer technology irrespective of walking, after which specific parameters for experimental settings necessary for assessment of gait-associated accelerations are discussed. The literature review includes the method of accelerometry to analyze basic temporospatial gait data, shock attenuation, and segmental acceleration during the walking state. Moreover, data collected from the upper body for the movements has offered information on motor control in normal walking, changes that occur in dynamic postural control for the aging adult population, and gait for those who have movement disorders.

Computer vision-based techniques utilize image processing and pattern recognition algorithms to analyze posture and movement from video or depth sensor data [17]. These techniques can automatically detect and track anatomical landmarks and joint angles, enabling quantitative assessment of posture stability and movement quality [18]. Media Pipe Pose, a popular framework developed by Google, uses deep learning models to estimate key body landmarks and infer skeletal poses from video input, making it suitable for analyzing posture stability in diverse settings [19]. The choice of using pose estimation, particularly the Media Pipe Pose framework, in our research is driven by several factors. First, pose estimation offers a non-invasive and cost-effective method for quantifying posture stability using standard video recordings, eliminating the need for specialized equipment or marker-based motion capture systems [20]. Second, Media Pipe Pose provides real-time performance and high accuracy in detecting key body landmarks, including joints and segments, facilitating efficient analysis of posture stability during dynamic tasks such as the SLS [21].

In this study, [22] they sought to understand the association between ankle muscle strength, range of motion (ROM), and body stability during quiet single-leg stance for highly trained athletes. The participants were young athletes who competed in a total of 9 different disciplines and the measurements were taken for the center of pressure velocity, amplitude, and frequency, as well as for ankle plantar flexion (PF) and dorsal flexion (DF) rate of torque development (RTD) in select time frames. The experiments demonstrated that the ankle strength index and range of motion did not show a direct relationship with the C0P velocity in different directions but instead had a positive effect on the COP amplitude in the medial-lateral (ML) direction. More importantly, ankle ML frequency went up as ankle strength went down consequently with reduced ankle ROM. The paper concludes that the range of motion of the ankle influences postural balance during a single-leg stand, especially evoking the ML direction of the COP.

The main idea of this study [23] was to establish the concordance and validity of the Open Pose algorithm, a posture detection tool that measures the hip-knee-ankle (HKA) angle in patients with knee, osteoarthritis, compared with radiography as shown in figure 2.1. Data from 60 knees belonging to 30 patients with knee osteoarthritis (OA) were collected. HKA angle was measured using both Open Pose and radiography, either before or after the total knee arthroplasty. This research is the first validation of Open Pose for calculating the HK angle in a person with knee osteoarthritis proving that the tool is reliable and valid for the case. Due to its non-invasiveness and ease of use, Open Pose may become an indispensable tool for assessing the HKA angle monitoring the progression of OA, and seeing the effectiveness of treatment after joint surgery. In addition, verified applications of Open Pose increase the possibility of its use outside clinical areas to include self-assessment and monitoring at home or in training gyms.

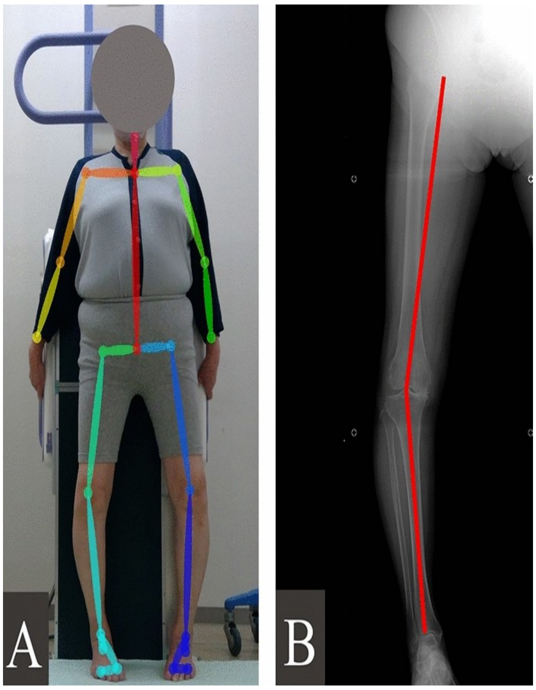

Figure 2.1: Images of Hip, Knee, Ankle angle measurement A) Open Pose B) Radiographic image

This research [24] it is devoted to identifying the foot structure and ankle characteristics associated with fall risk among the elderly. The study involved 176 retirees living in one of the retirement villages who participated in various tests related to foot structure and general fall risk factors followed by at least a 12 month period to identify any falls. The research found that those with falls revealed stiffer ankle joints and more severe hallux valgus deformity. So, this data suggests that the foot and ankle problems of the elderly are just one of the many contributing factors as causes of falls in this group of individuals.

2.3 Controlling techniques for single-link models

Posture stability is critical for human walking, running, and for daily life activity [25].In general, it can be said that a person is stable or in a stable posture unless the line of action of the weight vector is passing through the base of support of his/her base of support (BOS). However, it is realized that even when this condition is met, there are some stance postures that are relatively more stable than others and some humans which, though they do not reach the point of instability, are relatively less stable than others [26].

This paper presents [27] the dynamics of bones, muscles, muscle spindles, and Golgi tendon organs (GTO sensory receptors) modeling through the bond graph. An experimental single-link bio mechanical nonlinear model incorporating a sixth-order muscle spindle and GTO implemented in 20-Sim. The model has the capability to respond to the periphery feedback to the CNS and an applied PID control for the movements. Simulation results confirm the CNS's ability to respond to feedback regarding proprioceptive movements and provide constructive actions towards touch perceptions and control to maintain balance and stability during an action.

In this paper, the author aims to discuss the sit-to-stand movement examined in the context of the four-link model of human motion in this paper [28]. It also means that the movement is divided into phases, which are represented by local linear models. These models are then incorporated into a fuzzy system with Gaussian membership functions; knee flexion angle defines the weight of these functions. Each phase has its local model for which an H2 dynamic optimal controller is developed and integrated into the fuzzy system. This controller calculates joint torques for linear and nonlinear biomechanical models. Since the sit-to-stand transfer should be smooth and physiologically correct, an error in the knee flexion angle is minimized by using a reference trajectory. Simulation results indicate that the fuzzy model with H2 full and reduced order controllers properly controls angular profiles and kinematic values during the sit-to-stand movement.

This paper examines the physiological elements such as muscles, muscle spindles, and Golgi tendon organs as well as neural activation associated with postural control and dynamic stability [29]. From the perspective of the bond graph modeling technique, this research provides a new insight into the complexity and cooperation of these components as well as power relations in the musculoskeletal system. An H-controller for a central nervous system controller for muscle activation is developed and optimized to control musculoskeletal coupling despite neural inputs and joint interference. Computer simulations show the usefulness of this approach for stabilising postural motion in an idealised single-link biomechanical system with proprioceptive feedback.

In [30, 31] authors have used feedback linearization technique for a single-link biomechanical model to address the issue of human balance when perturbations are applied to the body and how fast and efficiently it responds. When disturbances are included in the system, these controllers cause unstabilities that can be alleviated by using high gains, which unfortunately produces high control signals that are often unrealistic. These input gains and torque create a less efficient system and also put stress on the mechanical loss of the system. Since the technique is sensible to disturbances it can lead the system to instability also this technique generates high input gains which make the system not only less robust or efficient but also the system to deviate from its behavior.

In these papers, the authors discuss a technique called Sliding Mode Control (SMC), which is a powerful control method due to its robustness in non-linearity and uncertainty. This robustness is established by a switching control law that brings the system trajectory to “slide” along a desirable surface called the sliding surface where the required system behavior is sustained. This guarantees the finite time convergence in the sliding surface thus ensuring very fast response and high precision in tracking the desired trajectories, especially in high accuracy and quick response applications [32, 33].

In these papers they discuss how SMC suffers from two significant limitations in real-time applications: This phenomenon is commonly referred to as “chattering “or high-frequency oscillation [8, 34] in control input u. So in order to eliminate it we use Quasi Sliding Mode control (QSMC), which does not involve approximation and chattering. In QSMC, the discontinuous sign function used in the classical SMC is replaced by a continuous one, for instance, the saturation function or a smooth approximation [9].

CHAPTER 3

METHODOLOGY

3.1 Overview

The chapter includes the methodology used in this research to ensure that the research objectives are achieved. They explain the experimental framework, AI techniques, control mechanisms, and analytical tools employed to assess the efficiency of the described solutions. The organization of this chapter is designed to offer a clear overview of the methods and techniques employed. The section will explain the AI technique which is used for lower joint assessment and control strategy which is applied on a single link biomechanical model its flowchart diagram is shown in figure 3.1.

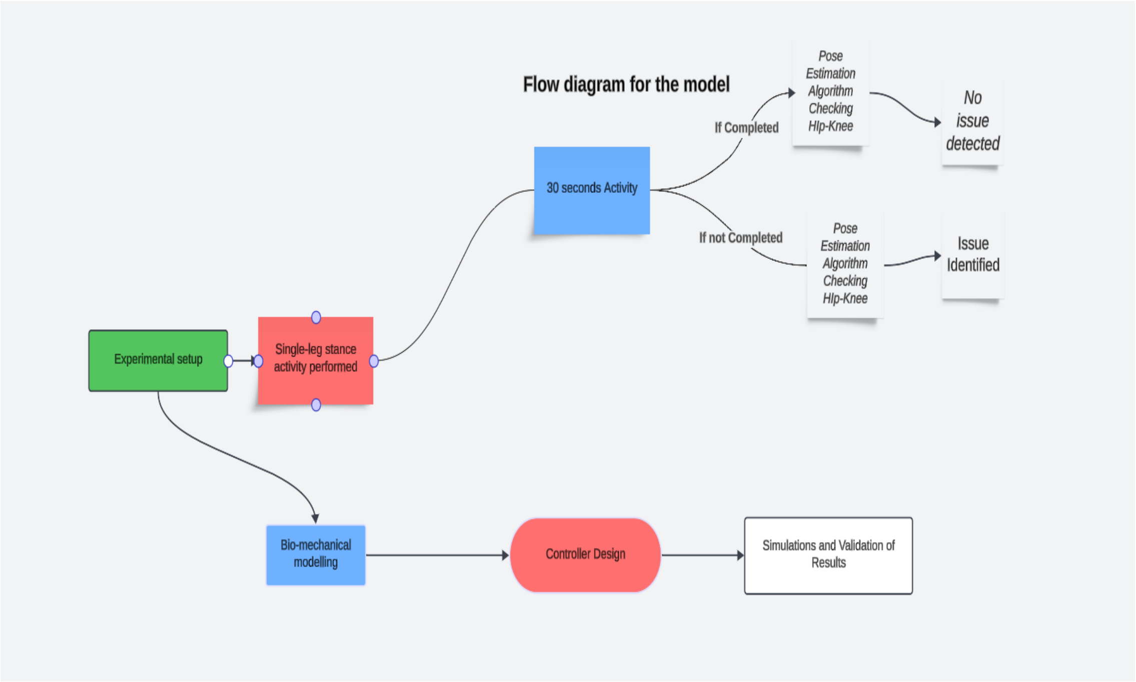

Figure 3.1: Flowchart diagram of the Proposed Model

3.2 Data Collection & Analysis

This section includes the experimental apparatus, procedure, and statistical analysis of the research and how data is being collected and analyzed for research purposes. The data was captured on a camera in a MOV file format.

3.2.1 Experimental Participants

Participants for this study were divided into two groups: young individuals and older adults. The young group consisted of 20 participants (male) with an average age of 20 years (18 to 22 years), average height of 175.5 cm (167 to 187 cm), and average weight of 65 kg (55 to 90 kg). On the other hand, the older group comprised 10 participants (8 males, 2 females) with an average age of 60 years (50 to 75 years), average height of 165.5 cm (160 to 175 cm), and average weight of 68 kg (51 to 85 kg). All thirty (30) participants were informed about the testing procedures in detail and were requested to sign a written consent form prior to the experiment. The activity for young persons was performed at the university (Bahria University) located in Islamabad, while for older persons, it was conducted at local old age homes (Zain ul Abideen Foundation, Najjat Homes) located in Rawalpindi. Before conducting this activity, consent forms or approvals were taken from the respective authorities.

3.2.2 Experimental Apparatus

The experimental apparatus utilized in this study comprised a DSLR Camera, specifically the (Nikon D5600) model, along with a tripod. This setup was employed to capture and record the motion of individuals during the experimental sessions. The DSLR camera provided high-quality video recording capabilities, additionally, the tripod ensured stability and consistency in the recording process.

3.2.3 Procedure

To ensure precise and accurate recording of lower body motion, the following procedure was punctiliously implemented. The activity involved a single leg stance, designed to assess posture stability and lower joint motion. Utilizing a DSLR camera, mounted on a tripod, participants were recorded in sagittal plane mode from a side-view perspective. In the result section, we have presented the data of young and old participants in two separate graphs to better understand the data. During the SLS activity as shown in Figure 3.2, participants were instructed to maintain balance on one leg while lifting the opposite leg, with arms crossed over the chest to prevent reliance on upper body stability. Participants were specifically instructed to refrain from using their arms for support and maintain direct eye contact. This rigorous protocol aimed to isolate and assess the motion of the lower joints, particularly the hip, and knee without interference from upper body movements. Participants were gathered for the test in a room where there was a camera attached to the tripod participants were called one by one for the activity. The activity was conducted for 30 seconds for each leg, allowing sufficient time to capture the full range of motion and stability [35]. However, if the video duration is less than the desired duration for plotting (e.g.30 seconds), setting the x-axis limit based on the actual video duration may result in empty space on the plot. To avoid this and ensure consistency across all plots, the x-axis limit was set to a fixed value (e.g., 60 seconds) in the knee angles calculation. Analysis of the bending angle of the lifted leg relative to the hip was performed to evaluate joint flexibility and stability. Notably, participants were instructed to maintain a 90-degree angle between the lifted leg and hip, providing a standardized metric for assessing joint function. The SLS activity holds paramount importance in analyzing posture and detecting diseases related to lower joints. By challenging participants to maintain balance on one leg, this activity offers valuable insights into posture stability, proprioception, and neuromuscular control. Moreover, large deviations from the prescribed 90-degree angle can indicate potential joint abnormalities or musculoskeletal imbalances, facilitating early detection and intervention for lower body conditions. Through meticulous recording and analysis, this protocol enables researchers to gain valuable insights into lower body biomechanics, contributing to advancements in sports science, rehabilitation, and clinical assessment methodologies.

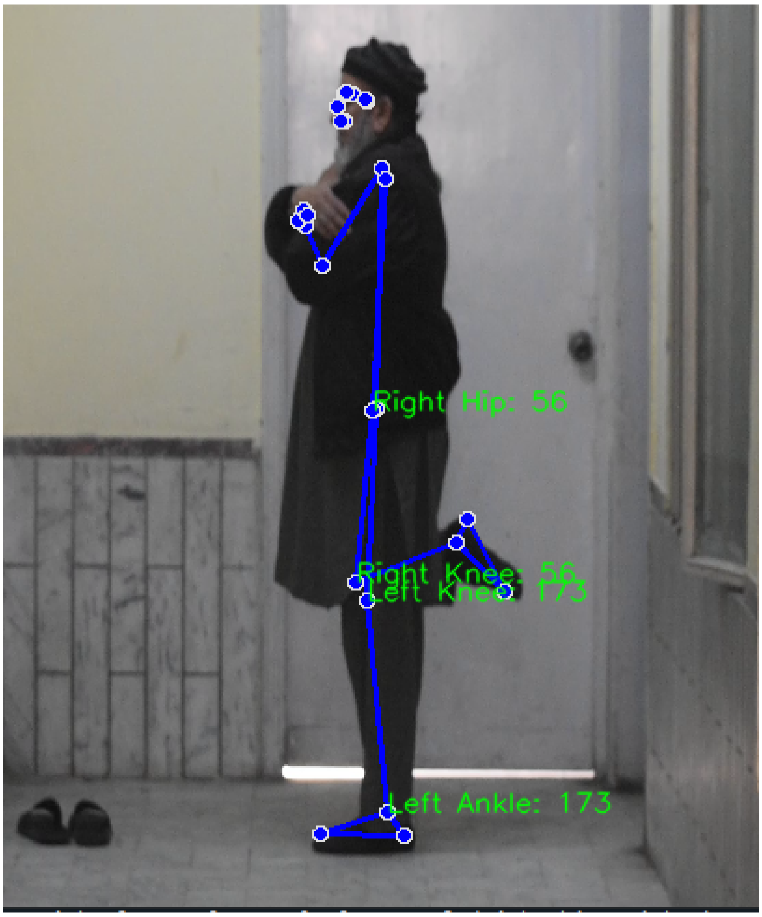

Figure 3.2: Participant performing single leg stance activity upon which Media Pipe technique is being used for key points

3.2.4 Statistical Analysis

The study employed a comprehensive statistical analysis to investigate the effects of age on posture stability and lower joint motion during SLS activity. Descriptive statistics revealed distinct demographic profiles between the young (average age: 20 years; average height: 175.5 cm; average weight: 65 kg) and old (average age: 60 years; average height: 165.5 cm; average weight: 68 kg) participant groups. We have used Media Pipe Pose model, which detects 33 landmarks (key points) for various body parts, including the upper and lower body joints. These landmarks include points such as the nose, eyes, ears, shoulders, elbows, wrists, hips, knees, and ankles but for our research, we were more focused on lower joint landmarks. Media Pipe is an open-source framework developed by Google that provides a comprehensive suite of tools and solutions for building real-time perception pipelines [36]. It is designed to enable developers to efficiently integrate machine learning-based models into various multimedia applications, including video analysis, gesture recognition, facial recognition, and body pose estimation. It employs deep learning models to detect and track key body landmarks or key points in real-time video streams. These key points represent important anatomical locations such as joints and body parts. By accurately estimating the positions of these key points over time, Media Pipe Pose can provide valuable insights into human movement, posture, and gestures. One of the main advantages of Media Pipe Pose is its high accuracy and real-time performance, making it suitable for a wide range of applications, including fitness tracking, sports analytics, and augmented reality. Overall, Media Pipe Pose is a powerful tool for analyzing human movement and behavior in real-world environments. The range of motion for hip angles during single-leg stance can vary depending on factors such as age, fitness level, and the presence of any musculoskeletal conditions. However, in general, the expected range of motion for hip flexion during a single-leg stance is typically between 0 and 150 degrees, while for hip extension, it is usually between 0 and 15 degrees [37]. These ranges may slightly vary among individuals and may also be influenced by specific activities or tasks being performed during single-leg stance. It's essential to consider individual variability and factors such as muscle flexibility, joint health, and overall biomechanics when assessing hip angles during single-leg stance. In knee angles during normal activities like walking or standing typically fall within a range of 0 to 90 degrees [38], depending on the individual's posture, gait, and activity level. Setting this range of angles ensures that variations in knee angles can be easily observed and analyzed. However, the specific range may vary depending on the context of the analysis and the expected range of motion for the individuals being studied. If a person is unable to maintain a consistent Hip-knee joint angle over a period, it may indicate instability in their posture.

3.3 Artificial Intelligence Technique

3.3.1 Pose Estimation

Pose estimation is one of the AI-based computer vision techniques capable of identifying the pose and orientation of specific joints and key points of the human body in the context of a particular picture or video. This technique often employs feed-forward as well as recurrent networks but more frequently it uses Convolutional Neural Networks (CNNs) in comprehending the correct positioning of joints and then putting together the frameworks of the body in 2D or 3D. Performing these connections creates a kinematic chain that gives a realistic approximation of the human pose, and that's why it allows for providing an accurate account of joint angles, velocities, and most of the other biomechanical values. For our research, during SLS activity, hip and knee joint pose estimation is one of the critical factors in assessing their health and stability. In this technique, we don't have to use markers or sensors like in the marker-based motion capture technique this makes the present technique advantageous over the past technique because it does not require the use of markers or sensors that limit the motion. One of the key features of Media Pipe is its robustness and versatility in handling complex tasks involving multiple modalities such as image, video, and audio data. Media Pipe Pose is a specific component of the Media Pipe framework that focuses on human pose estimation. Additionally, Media Pipe Pose provides a flexible and customized API that allows developers to fine-tune the model parameters and integrate them seamlessly into their applications.

3.3.2 Trigonometric Functions

For the calculation of angles between three lower joints multiple trigonometric functions were used in the pose estimation technique.

$$\mathrm{ab} = ||\mathbf{b} - \mathbf{a}|| \tag{3.1}$$

$$\mathrm{ac} = ||\mathbf{c} - \mathbf{a}|| \tag{3.2}$$

$$\mathrm{bc} = ||\mathbf{c} - \mathbf{b}|| \tag{3.3}$$

$$\cos(\theta) = \frac{\mathbf{BA} \cdot \mathbf{BC}}{||\mathbf{BA}||\,||\mathbf{BC}||} \tag{3.4}$$

$$\mathrm{angle\_rad} = \arccos\left(\frac{\mathrm{ab}^2 + \mathrm{ac}^2 - \mathrm{bc}^2}{2 \cdot \mathrm{ab} \cdot \mathrm{ac}}\right) \tag{3.5}$$

3.4 Bio-Mechanical Modeling

In our research, the human body has been assumed by one of the participants from experimental analysis in the sagittal plane as a single-link segment with an ankle joint and static base of support (BOS) as shown in Figure 3.3. In this model, the limb or body segment is assumed to be a single bar, which is referred to as a “link”, and is connected to a reference point, or “joint”, from which it can rotate around BOS. This is a fundamental approach to understand the movements in human bodies, which concentrates on how force and torque influence the movement of a particular limb or body segment when perturbations are given to it. Single-link models are used to analyze the stability of human posture and they can also analyze the lower joints such as knee, ankle and their contribution to maintaining stability. This approach is beneficial for both computational and experimental studies providing the complex biomechanical behaviors in a controlled manner. The segment can move around the ankle joint. The two forces that are influenced by this system are force of gravity and the net torque generated by the MTCs (Muscle-Tendon Complexes) around the ankle joint.

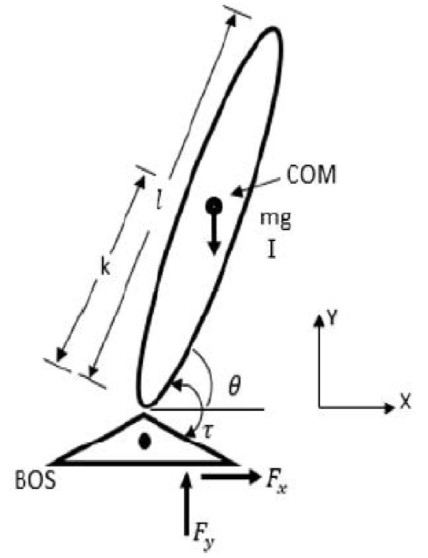

Figure 3.3: Schematic of two segments biomechanical model

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:

$$\ddot{\theta} = \frac{\tau + mgk\sin\theta}{l + mk^2} \tag{3.6}$$

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

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} x_2 \\ \frac{mgk\sin x1}{I+mk^2} \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{I+mk^2} \end{bmatrix} \tau \tag{3.7}$$

This nonlinear plant is of the form

$$\dot{x} = \mathrm{f(x)} + \mathrm{J(x)u} \tag{3.8}$$

$$\mathrm{y} = \mathrm{h(x)} \tag{3.9}$$

We assume that

$$\mathrm{f(0)} = 0 \text{ and } \mathrm{J(0)} = 0 \tag{3.10}$$

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.

3.5 Controller Design

3.5.1 Sliding Mode Control

The controller which we have used to solve this problem is Sliding Mode Control (SMC) later it will be converted into Quasi-Sliding Mode Control (QSMC). SMC is a powerful control method due to its robustness in non-linearity and uncertainty. This robustness is established by a switching control law that brings the system trajectory to “stick” along a desirable surface called the sliding surface where the required system behavior is sustained first, we have linearized the equations (3.6) so we can apply them to the sliding surface equation. In the SMC technique, we have to calculate two things, first Sliding Surface s and second control law U to obtain the controlled input u.

The SMC control law is defined as follows:

$$\dot{\mathrm{x}}_1 = \mathrm{x}_2 \tag{3.11}$$

$$\dot{\mathrm{x}}_2 = \mathrm{h}(\mathrm{x}) + \mathrm{g}(\mathrm{x})\mathrm{u} \tag{3.12}$$

Sliding Surface for nonlinear system is defined as:

$$\oe = \lambda \mathrm{x}_1 + \mathrm{x}_2 \tag{3.13}$$

λ represents behavior of the system state to move towards the desired sliding surface. In our design, λ is calculated through Linear Quadratic Regulator (LQR) Equation.

Control Law equation for nonlinear system is defined as:

$$u = -K\,\mathrm{sgn}(s) \tag{3.14}$$

where k represent the gains of the system as k_1, k_2, sgn is the sign function and s is the sliding surface equation.

3.5.2 Linear Quadratic Regulator

The nonlinear system stated in equation (3.6) has been linearized with standing upright posture i. e. $\theta = 90^\circ$ with reference to ground. The static equilibrium posture for standing upright and without any movement are $\theta eq = 0$ and $\dot{\theta}_{eq} = 0$. The linearized model is given by:

$$\begin{bmatrix} \Delta\dot{x}_1 \\ \Delta\dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ \frac{mgk}{I+mk^2} & 0 \end{bmatrix} \begin{bmatrix} \Delta x_1 \\ \Delta x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{I+mk^2} \end{bmatrix} \Delta\tau \tag{3.15}$$

The basis for the LQR is the algebraic Riccati equation that provides the optimized gain matrix for reducing the cost function. The given dynamics of the system lead to the Riccati equation, which is derived from the Hamilton-Jacobi-Bellman (HJB) equation representing the value function corresponding to the control problem. This linearized model (3.15) is an unstable system. It is also asserted that the body movement can be controlled by the feedback of states. The state feedback is adjusted to dictate the input torque τ which in return dictates the stability of body movements. As for the optimal design of the controller, we applied the Riccati equation which is given as follows:

$$A^T P + PA - PBR^{-1}B^T P + Q = 0 \tag{3.16}$$

Here each term is in the form of matrix. The input-weighting matrix which is R and the state-weighting matrix Q are tuned in such form is to minimize the performance index.The controller gain k is obtained through:

$$\begin{aligned} &\mathrm{K} = \mathrm{R}^{-1}\mathrm{B}^{\mathrm{T}}\mathrm{M}, \\ &\text{Where } \mathrm{Q} = \begin{bmatrix} 200 & 0 \\ 0 & 200 \end{bmatrix}, \\ &\mathrm{R} = 0.01. \end{aligned} \tag{3.17}$$

The gain K which we have calculated from the above equation (3.17) gives us the optimal solution for the steady state response, the initial and final position of the body, and minimizes the error in states and given control input τ. The gains obtained from the above equation are used in equation (3.14) to determine U.

3.5.3 Quasi Sliding Mode Control

Quasi Sliding Mode control smooths the control signal function by using continuous law instead of discontinuous law so to eliminate the chattering effect or high oscillation from results we have used QSMC. Now to avoid chattering we have to provide a smooth control signal, one way was to replace the sign function from equation (3.14) with the following equation. The value of ε should be selected to trade off the requirement to maintain an ideal performance.

$$sign = \frac{\sigma}{|\text{œ}| + \varepsilon} = func \tag{3.18}$$

where:

- U is the control input,
- |u| denotes absolute value,
- ε is a small positive constant.

After substituting equation (3.18) into equation (3.14) we got:

$$U = -k_1 \cdot \mathrm{func}(s) - k_2 \cdot x_2 \tag{3.19}$$

where:

- U is the control input,
- k_1 and k_2 are the gain coefficients,
- func represents function block,

- s represents sliding surface
- x_2 is the state variable.

After obtaining gains from equation (3.17), the states of the controller, x_1 and x_2, are the estimated states scaled by the optimal control gains, and they form the input signal U that controls the system. The simulation diagram of the controller is shown in Figure 3.4.

$$U = -147.2669 \cdot \text{func}(s) - 141.444 \cdot x_2 \tag{3.20}$$

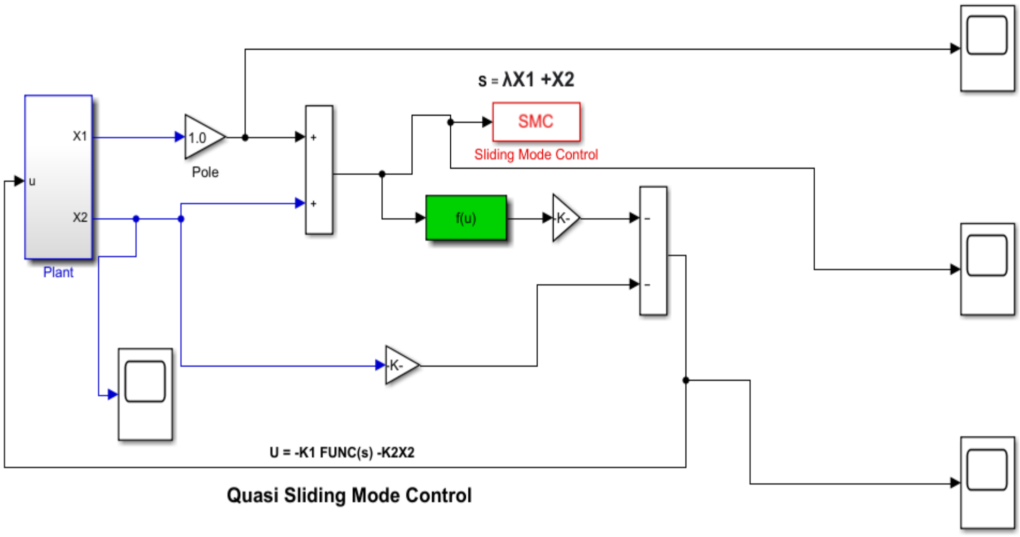

Figure 3.4: Quasi Sliding Model Control

3.6 Summary

This study employs two complementary techniques to analyze and enhance posture stability: Pose Estimation for joint health evaluation and Quasi-Sliding Mode Control (QSMC) for single-link models.

Pose estimation was utilized to evaluate the health, and orientation of lower limb joints, particularly the hip and knee, during single-leg stance activity. This technique provided valuable insights into the biomechanical mechanisms involved in balance maintenance by tracking joint angles and detecting potential instabilities earlier. The data gathered through pose estimation offered a non-invasive method for assessing joint health and the risk of falls, serving as an alternative to traditional diagnostic tools like MRI scans or CT Scans.

To further enhance stability, Quasi-Sliding Mode Control (QSMC) was applied to a single-link biomechanical model. The model was subjected to various external perturbations to simulate real-world conditions. While traditional Sliding Mode Control (SMC) is effective in managing system uncertainties, it often introduces a chattering effect or undesirable high-frequency oscillations in the control signal. QSMC addresses this limitation by smoothing the control signal, and reducing chattering while retaining the robustness of SMC. The application of QSMC in this study led to better control input efficiency, minimized overshoot in angular velocity, and significantly improved the model's stability under perturbations. Together, these techniques provided a comprehensive approach to understanding and enhancing posture stability, contributing valuable insights to the field of biomechanics.

CHAPTER 4

EXPERIMENTATION AND RESULTS

4.1 Overview

The result section contains the simulation results of our work which have been divided into two sections first Experimental analysis of lower joints and second Controller-based analysis of the biomechanical model.

4.2 Experimental Setup

The experimental apparatus utilized in this study comprised a DSLR Camera, specifically the (Nikon D5600) model, along with a tripod. This setup was employed to capture and record the motion of individuals during the experimental sessions.

4.3 Health Evaluation of Lower Limb Joints

4.3.1 Hip Results

The results of the left hip in flexion movement of twenty young participants are presented in two separate graphs figures 4.1 and 4.2. In Figure 4.1 the first ten participants' data is presented which shows, the starting range of their hip angles ranging from 75 to 120 degrees. However, these angles are close to each other indicating less deviation and showing consistency. This consistency means they are likely to possess stable and upright posture; which indicates good posture and overall stability. In addition, their left hip angles also do not show any major variations which proves the absence of any obvious problems with their hip. Similarly, Figure 4.2 shows the data of the other ten young participants. Among participants (1, 2, 3, 5, 9, and 10), the angles observed similar ranging and consistency like Figure 4.1, meaning that the posture is stable and shows minimal deviations. However, individuals (4, 6, 7, and 8) whose hip angles alternate and deviate from the baseline show a lot of inconsistency and deviation in their angles. This inconsistency indicates difficulty in maintaining their upright posture and hints at potential issues with their left hip and would be advised to see a medical expert for further diagnosis and treatment.

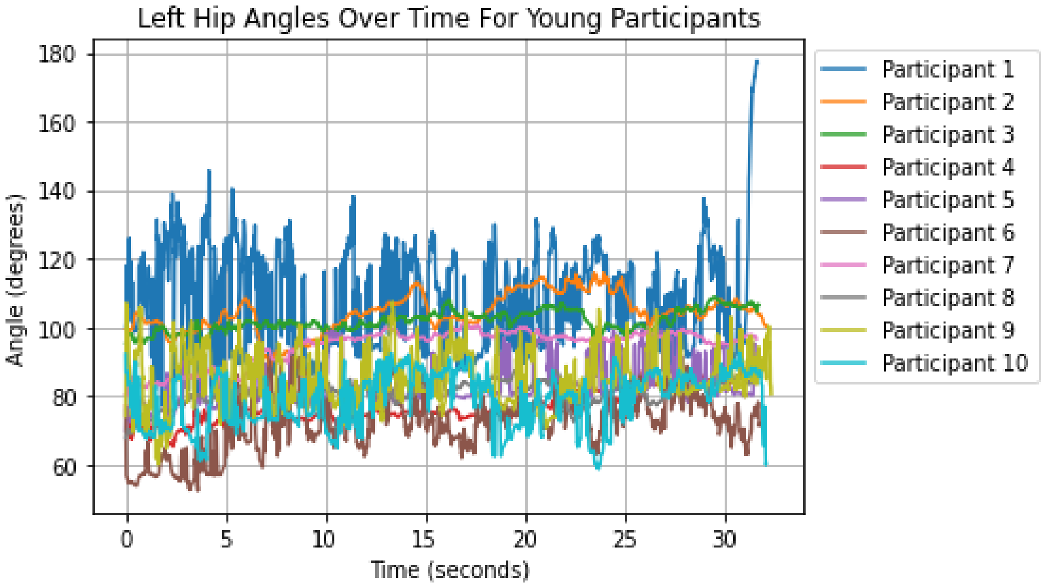

Figure 4.1: Left Hip Results for Young Participants

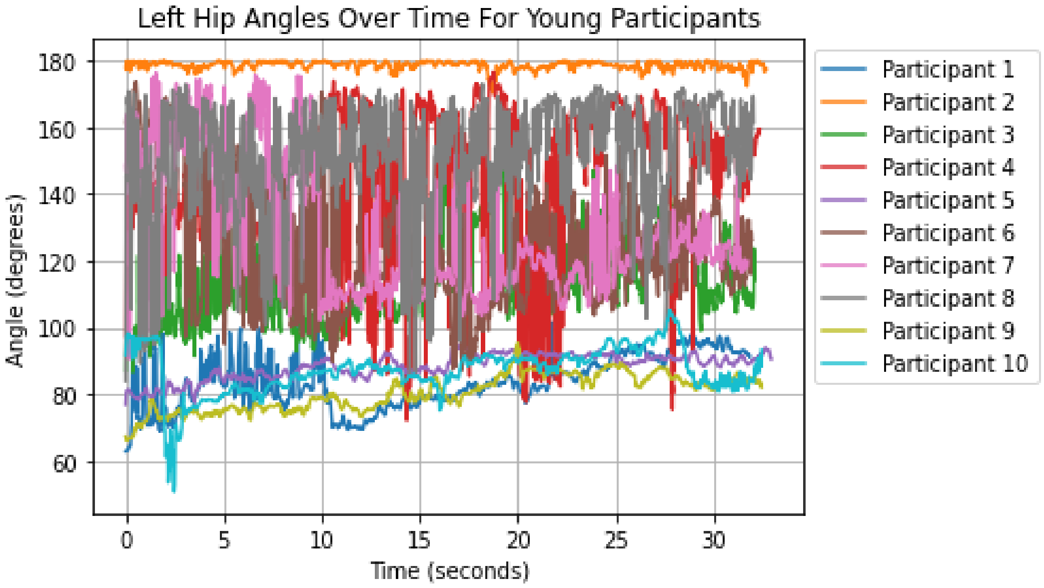

Figure 4.2: Left Hip Results for Young Participants

The results for ten older participants' left hip angles are shown in Figures 4.3 and 4.4. Figure 4.3 shows that every one of the individuals had failed to keep their stance stable at the 30-second stop which is the activity time. The results show that it was difficult to maintain a stable posture and there are obvious differences and vacillations. This shows left hip dysfunction and necessitates clinical consideration. The only participant in the second graph of Figure 4.4, who is unable to maintain an upright posture after 20 seconds is participant number 5. Nonetheless, others showed better results with less movement yet for certain deviations. As a result, older people may suffer from left hip joint dysfunction and require additional medical care.

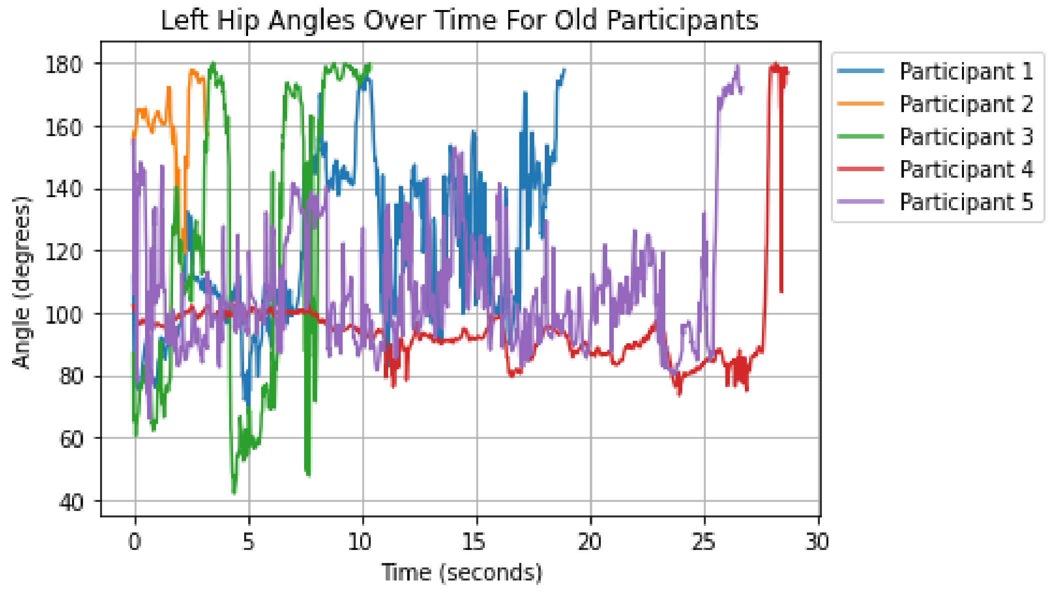

Figure 4.3: Left Hip Results for Old Participants

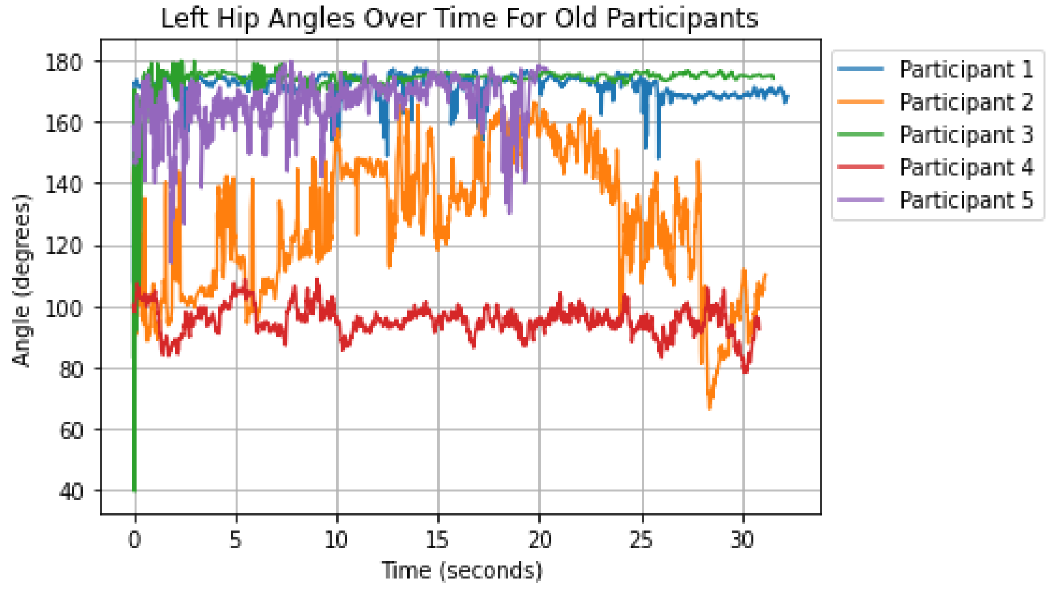

Figure 4.4: Left Hip Results for Old Participants

Figures 4.5 and 4.6 analyze the right hip joint angle in flexion movement of the same twenty young participants whose left hip joint was analyzed before. In Figure 4.5, we can notice that angles are stable, no posture loss happens and there is less movement in their results which shows stability. Figure 4.6 shows that only participants (1, 9, and 10) maintain stability linearly within the normal line the rest of the participants show very high instability and deviations in their outcomes although they manage to keep their posture balance throughout the activity which means their right hip joint should be addressed immediately as soon as possible.

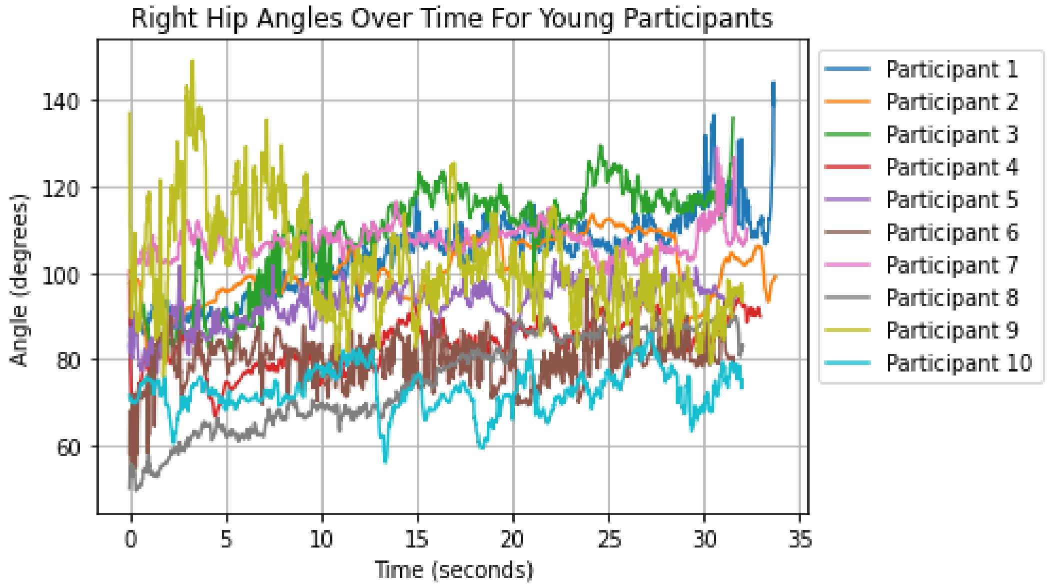

Figure 4.5: Right Hip Results for Young Participants

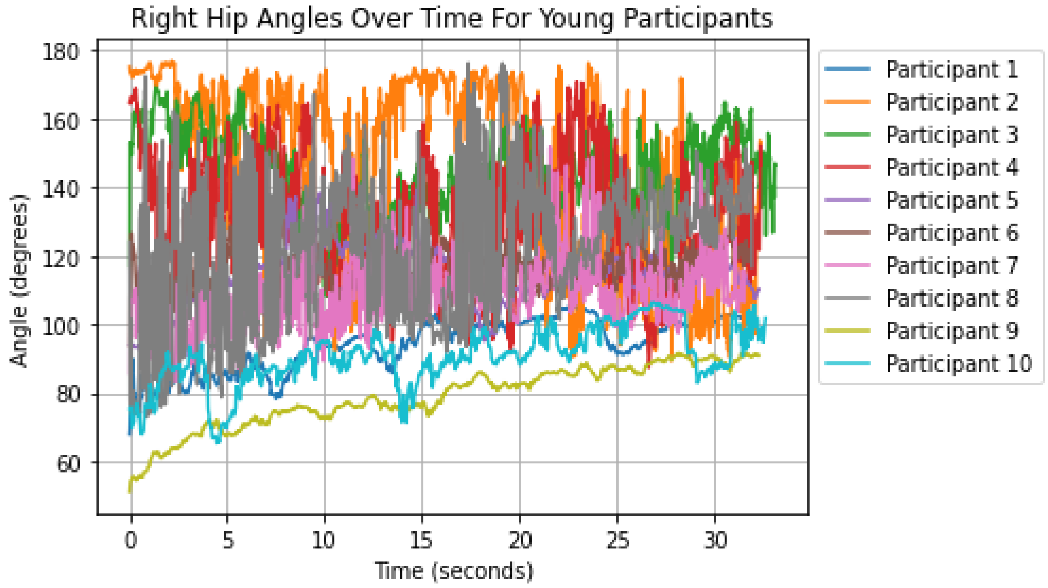

Figure 4.6: Right Hip Results for Young Participants

Figures 4.7 and 4.8 show the right hip angles of ten older participants. In Figure 4.7, we can analyze data of five individuals in which participants (1 and 5) are the only ones to keep their posture still throughout the activity otherwise participants (2,3 and 4) loss their balance before completing their task which shows that these individuals having a severe right hip issue which needs medical attention as soon as possible. The remaining five participants were able to maintain an upright posture, as shown in Figure 4.8, but their results showed significant variation, indicating that they were having difficulty maintaining an upright posture. Their joint points are frail and they also need clinical evaluation.

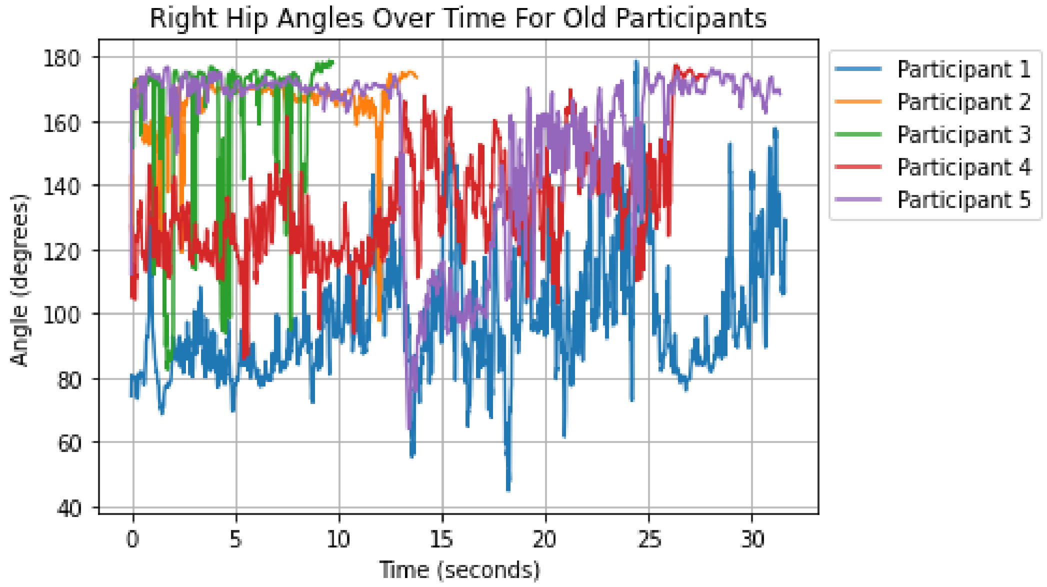

Figure 4.7: Right Hip Results for Old Participants

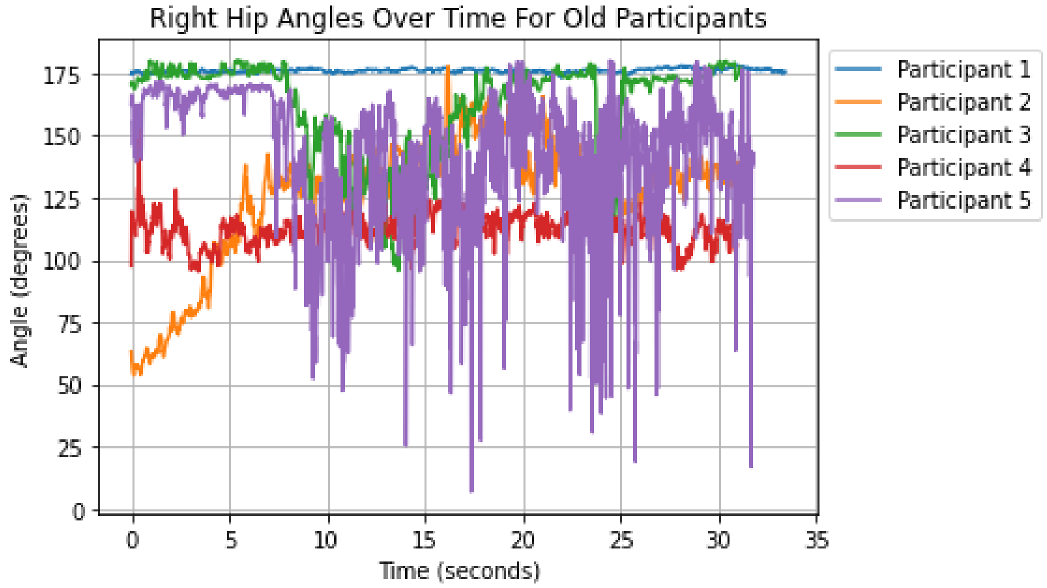

Figure 4.8: Right Hip Results for Old Participants

4.3.2 Knee Results

This section discusses the knee results of the participants as the angles of the left knee of twenty young participants, are shown in Figures 4.9 and 4.10. However, due to the video being shorter than the desired duration for plotting (e.g.30 seconds), setting the x-axis limit based on the actual video duration may have resulted in empty space on the plot. To ensure consistency across all plots, the x-axis limit in knee angler results was fixed at a value of 60 seconds. The data of the first ten young people are presented in Figure 4.9, which shows consistency in their angles with less movement and instability in their results. There was no loss in their posture. Similarly, Figure 4.10 also depicts a similar kind of steadiness with minor spikes, and no loss in stance was observed, indicating that these individuals do not possess any issues with their left knee joint.

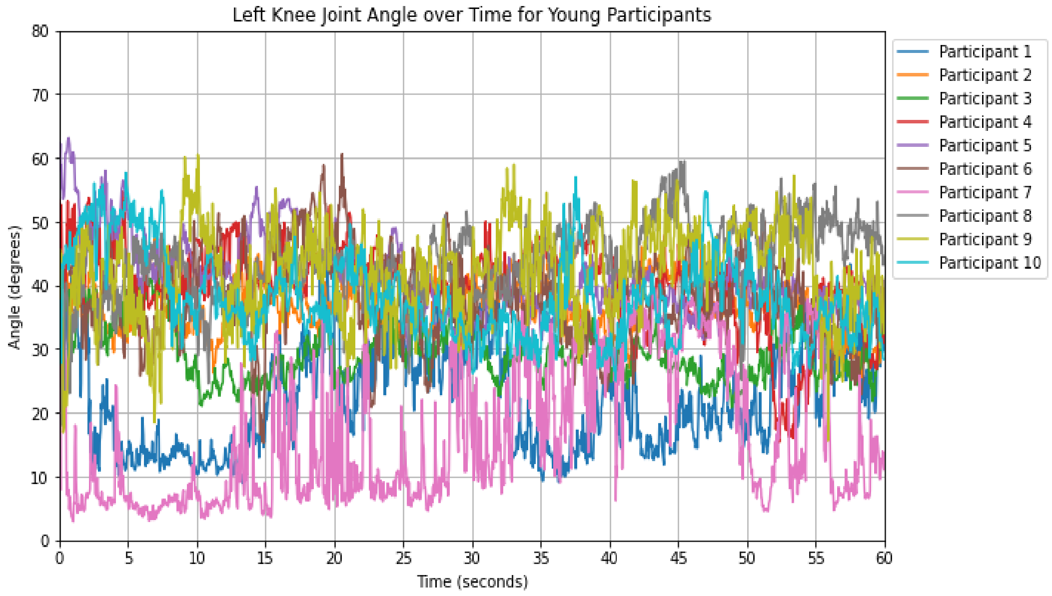

Figure 4.9: Left Knee Results for Young Participants

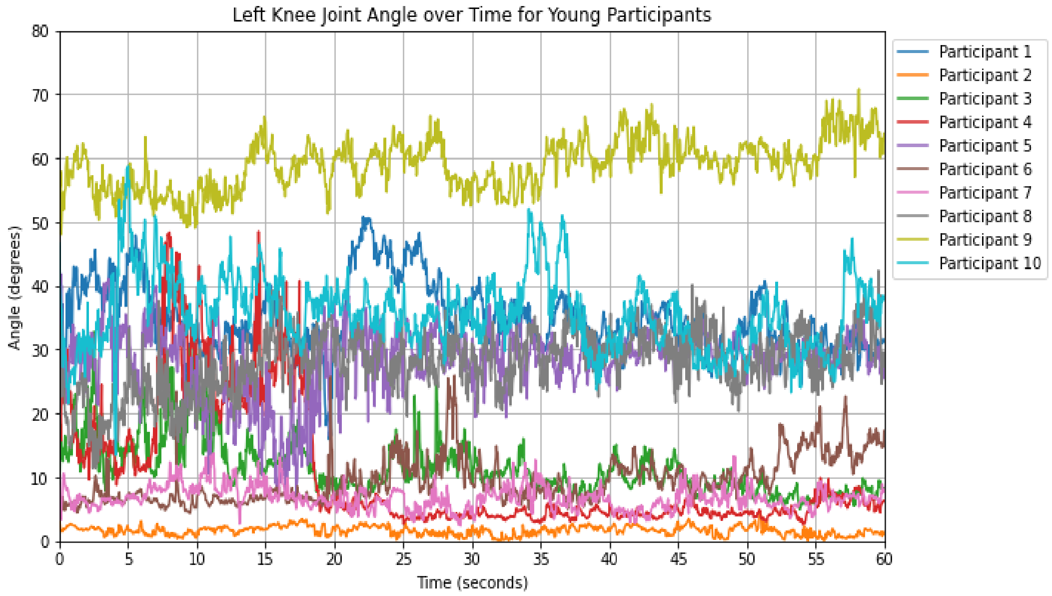

Figure 4.10: Left Knee Results for Young Participants

Figures 4.11 and 4.12 show the data of ten older participants for left knee angles. In Figure 4.11 we can see the data of the first five individuals which shows that none of them was able to maintain their posture and shows huge fluctuations in their knee results before losing their posture. Their results show huge deviations in their knee angles and indicate that their left knee requires medical attention before fracturing it completely. Figure 4.12 shows that the primary member, number five, failed to complete his activity and had a significant increase in outcomes before losing his posture. The other four members completed their tasks. Members two and four had significant fluctuations in their outcomes, but they were able to complete the activity it shows participants (2 and 4) have knee issues but not major but Participant 5 is having a severe issue with his left knee.

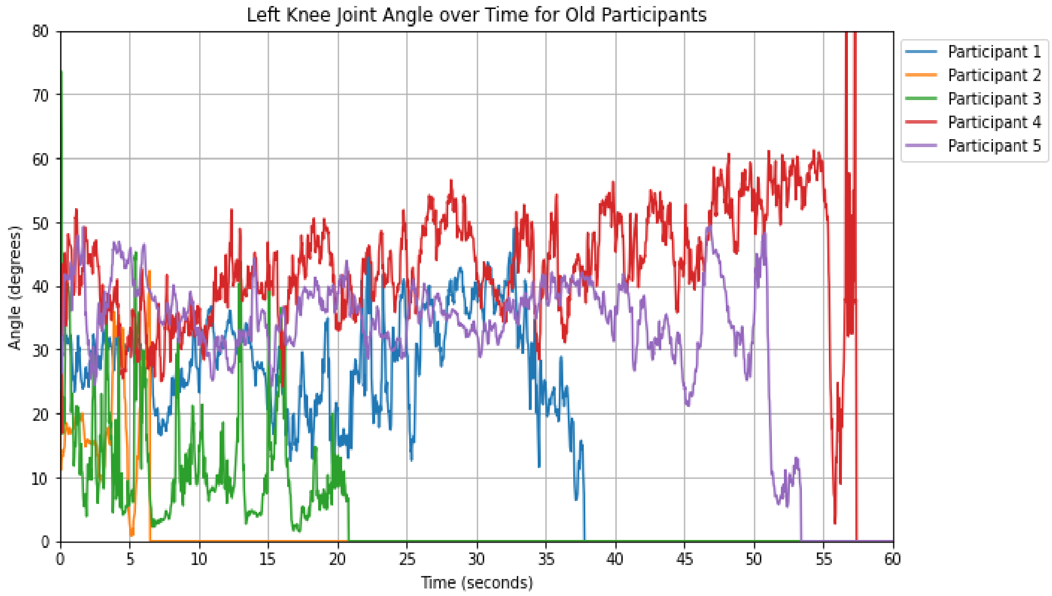

Figure 4.11: Left Knee Results for Old Participants

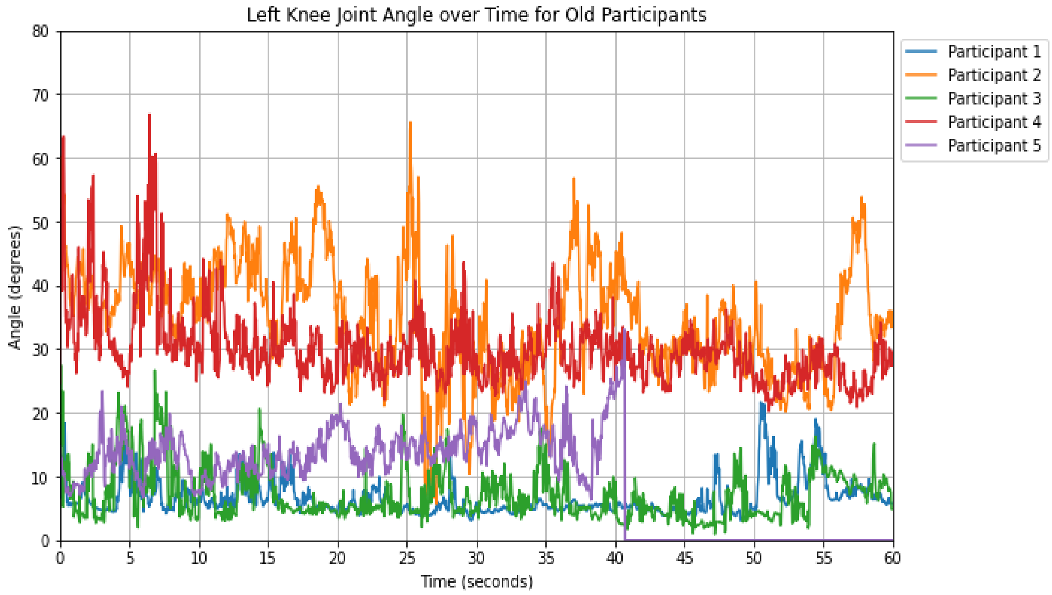

Figure 4.12: Left Knee Results for Old Participants

Figures 4.13 and 4.14 present the measurements of right knee angles for twenty young participants. Figure 4.13 displays the data for the first ten individuals, showing a high level of consistency in their angles with minimal fluctuations. These results demonstrate stability in their posture with no loss of stability. In Figure 4.14, we can see the same level of consistency with even fewer fluctuations and no loss of posture stability. These findings indicate that all participants have no issues with their right knee angles and thus they possess a stable posture.

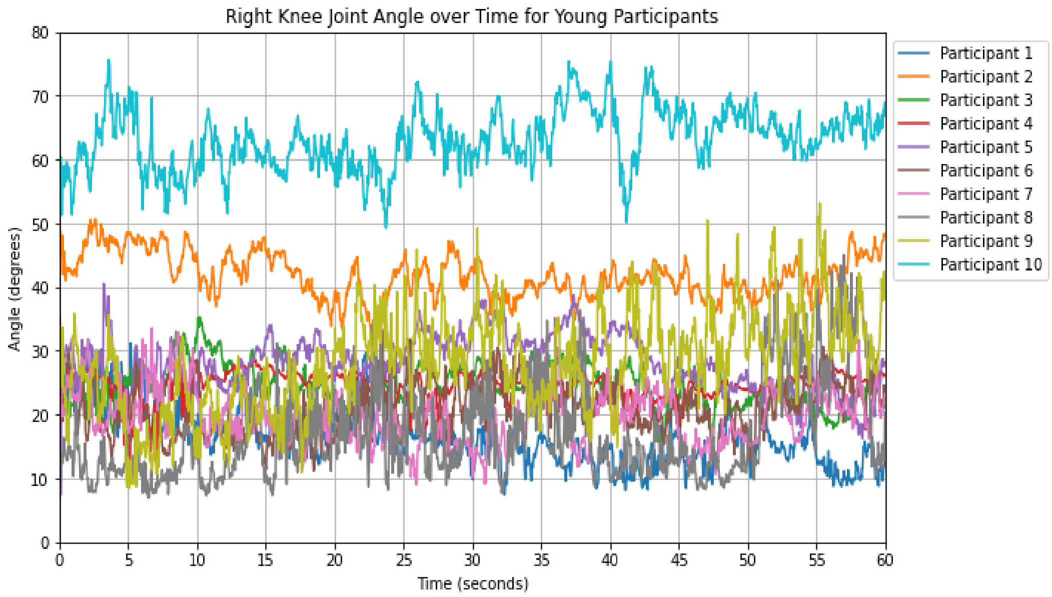

Figure 4.13: Right Knee Results for Young Participants

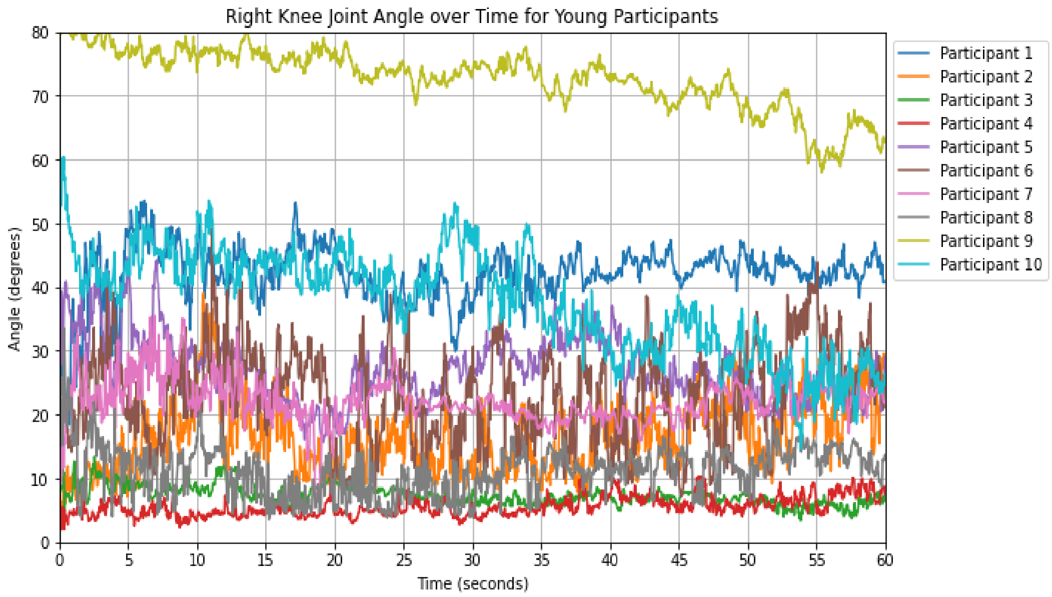

Figure 4.14: Right Knee Results for Young Participants

Figures 4.15 and 4.16 illustrate the right knee angle results of ten older participants. In Figure 4.15, the data of the first five participants showed significant spikes in their results, indicating that participants (2, 3, and 4) have problems with both of their knees. They lost their posture stability, which is a clear sign that they require medical attention for both knees. The other two participants' results were also abnormal, showing spikes, which is a strong indication that they also need medical attention. In Figure 4.16, participants (2, 4, and 5) showed significant spikes in their results, indicating that their knees require medical attention. It's clear that medical attention is necessary for these individuals, and they must receive the care they need to restore their knee health.

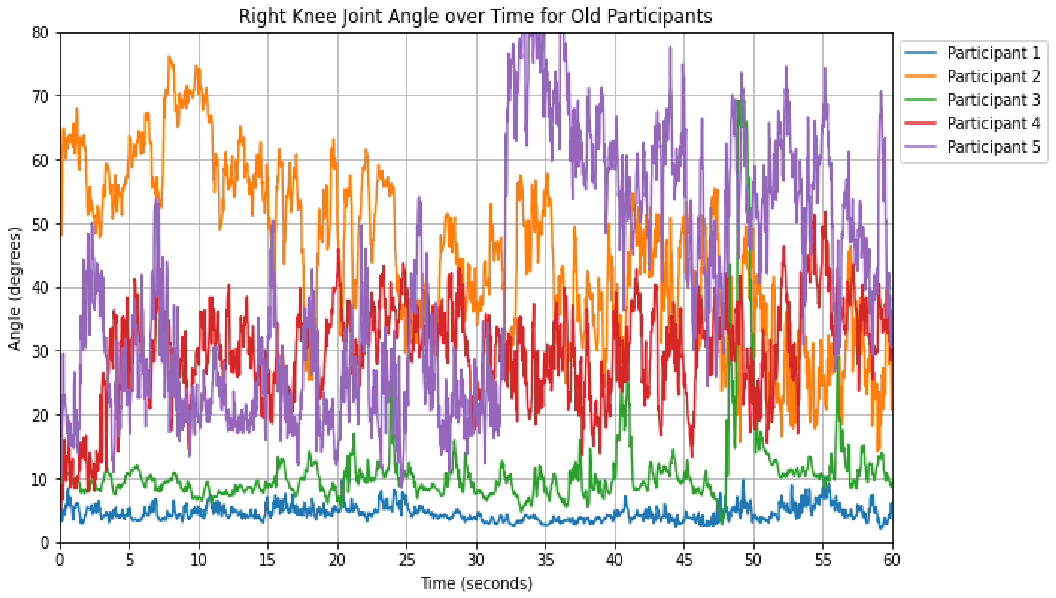

Figure 4.15: Right Knee Results for Old Participants

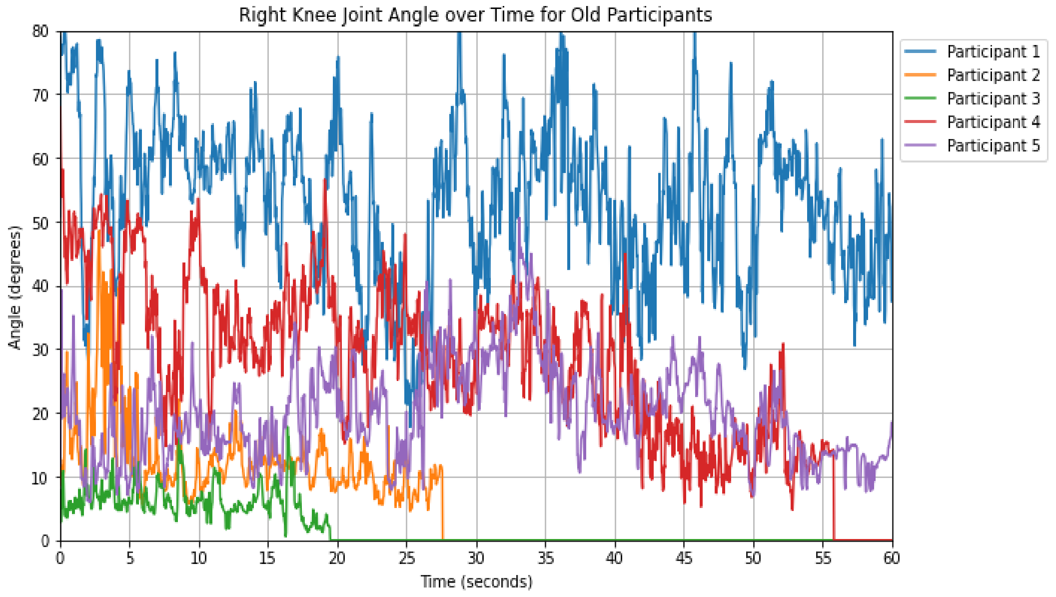

Figure 4.16: Right Knee Results for Old Participants

4.3.3 Statistical Analysis of Young and Old Participants

For a clear understanding, the statistical analysis of both participants is shown in Tables 4.1 and 4.2 the mean and standard deviation values extracted from graphs of the HK joints. The first table shows data gathered from twenty young subjects, with their mean and standard deviation value of both hip and knee joints. The results indicate satisfactory joint performance among the young subjects, with posture stability observed. Although some concerns were seen in the Hip results from young participants, the remainder of the results were satisfactory. Further research showed that most of the subjects had good posture with excellent results. These facts testify to the strong state of participants' joint health and show that their upright posture is balanced. The following mean and standard deviation values were obtained:(107.14±5, 96.42±7) for both hips and (36.76±7, 44.30±4)for both knees from one of the young participants. These values are in line with the expected joint angles (110 to 120 degrees for the hip and 45 to 60 degrees for the knee) and show stability in results On the other hand, the second table shows data obtained from 10 older participants, revealing an alarming situation for the participants. Indeed, as many as 60 percent of them displayed symptoms of balance loss, combined with other concerning posture and joint measurements. The results from one of the elderly participants show a high level of variability and low mean values for both hips and knees: (65.42±77, 85±76.67) and (4.15±10.8, 7±18), respectively. This is indicative of deviations from the expected norm, this locates particular worries pertaining to the general health and stability of the older participants' joints, which may suggest immediate medical intervention. These findings necessitate immediate action to allay any possible risks that could manifest due to joint wear and tear and poor posture. Such findings suggest the importance of considering individual differences and variability when analyzing biomechanical data, and how early detection in the lower joints not only helps maintain proper posture but also prevents undue stress and strain from burdening other joints. Based on the results obtained from the analysis of hip and knee joint angles in both older and younger individuals, several key findings can be drawn. It was demonstrated that there were various kinds of hip and knee joint angles between older and younger individuals when they carried out functional tasks. The elderly group, in general, seemed to display higher averages of joint angles and more variability compared to their young counterparts. These experiments show that age-associated changes in joint biomechanics, muscle strength, and neuromuscular control can impact posture stability, movement coordination, and balance during daily activities. Thus, the levels of individual joint angle fluctuation assessed via standard deviations allow differentiating between the abilities of the subjects to maintain stable postures and movements. The findings also show an opportunity for early detection of joint problems without the need for invasive methods such as MRI scans or CT scans.

The following table shows young participant's Mean and Standard deviation values Table 4.1

Table 4.1: Young Individuals Mean and SD Data

Individuals Data	**LH Mean±SD**	**RH Mean±SD**	**LK Mean±SD**	**RK Mean±SD**
Young person 1	123.5±8	103.5±13	27±8.6	18±6.6
Young person 2	107.1±5	96.4±7	36.7±7	44.30±4
Young person 3	102.2±3	107.1±15	31.1±7	32.30±5
Young person 4	75.7±5	84.2±9	31.9±7	27.30±5
Young person 5	77.85±6.4	95±4.6	36.5±9.4	31.7±3.8
Young person 6	77.5±52	80±13	32.6±7	31.1±4.4
Young person 7	95.7±7	107.8±5	23.6±11	22.7±7
Young person 8	92.8±9	73.5±14	35±6.5	31.15±7
Young person 9	94.5±7.5	95±10	40.5±12	34±11.44
Young person 10	95.4±7	74±4	35.7±8.5	62.1±6.8
Young person 11	87.4±13	94.28±5.6	34.2±6	43±5.3
Young person 12	178.5±3	145.7±35	3±1.1	22.3±8.2
Young person 13	114.2±21	140.7±18	13.3±4	8.3±3
Young person 14	147.1±31	141.4±21	15±14.5	9.6±3.2
Young person 15	78.5±3.4	125±25	32.3±6.3	32.3±5.4
Young person 16	125.7±25	114.2±12	14.4±4.5	32.5±7.2
Young person 17	132.8±21	120±18	11.61±2	25.38±6.6
Young person 18	147.1±31	134.2±22	32.5±6.6	32.6±6.6
Young person 19	79.2±5	77.7±14	60±5.3	72.2±6
Young person 20	85.4±4	85±12	42.3±6.3	42.6±11

The following table shows old participants' Mean and Standard deviation values Table 4.2

Table 4.2: Old Individuals Mean and SD Data

Individuals Data	**LH Mean±SD**	**RH Mean±SD**	**LK Mean±SD**	**RK Mean±SD**
Old person 1	103.71±72	122.1±36.4	17.8±14	46±16.35
Old person 2	65.4±77	85±7.6	4.15±10.8	7±18
Old person 3	54.2±86	87.14±79	7.15±11.7	3.5±15
Old person 4	105±31.2	145.2±19.2	44.16±18	30±18
Old person 5	134.7±23.1	156.4±26.5	31.30±12.14	30.15±12
Old person 6	161.4±10	175.5±5	9.8±4.5	6.7±2
Old person 7	135.7±19	121.4±7	34±14.63	46.16±15
Old person 8	164±30.3	157.14±17	18.8±5	14.15±16
Old person 9	98.5±8.3	120±7	34.4±10.3	31.7±11
Old person 10	145.7±60.4	144.2±32.4	12.2±9.6	45.6±25

4.4 QSMC Based Nonlinear Model Results

In this section, we will present the simulation results of our bio-mechanical model which we have discussed earlier in chapter 3. The nonlinear model described in Figure 3.3 and the controller outlined in 3.18 operate together as a closed-loop system. The Nonlinear Bio-mechanical model in (Fig. 3.3) is an unstable system so, we have applied a nonlinear controller technique (QSMC) for optimum results. We have applied perturbation of three different values (0.1, 0.2, 0.3) rad to our model for results as in previous work also, they have applied a single perturbation of 0.1 rad for results but, we have generated our results for three different values for better understanding of the results and to check our system robustness against disturbances.

Figures 4.17 and 4.18 depict the controlled plant's simulated result for angular position and velocity. From the position response in Fig. 4.17, this profile goes to a zero as it reaches a steady state. These results of the simplified simulation are for 0.1, 0.2, and 0.3 rad. The body returns to the stable upright state in 5 and 6 sec respectively as compared to [30-31] where it reaches within 3 sec.

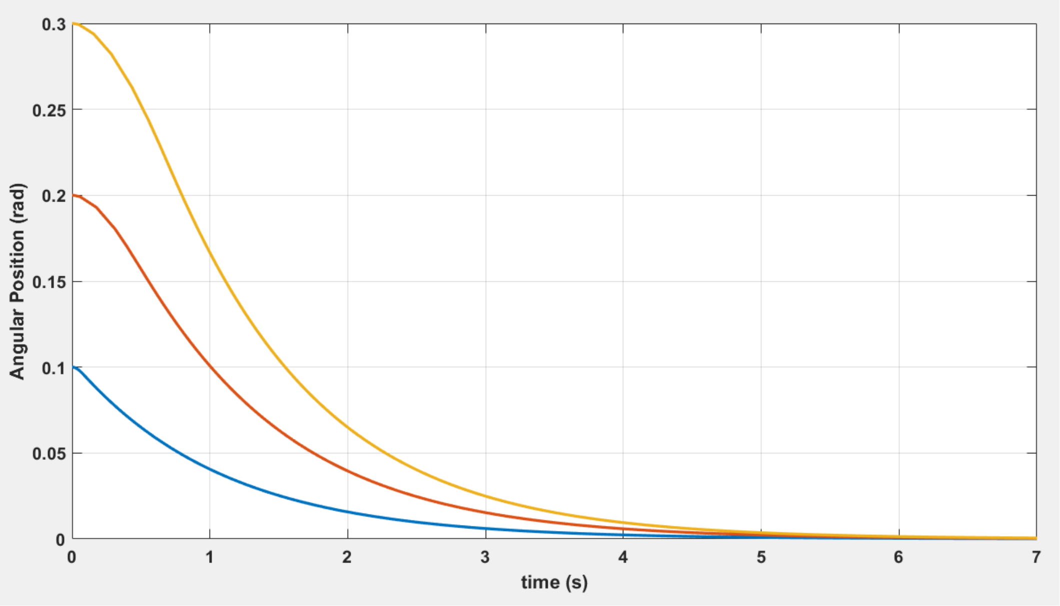

Figure 4.17: Angular Position Result

Fig.4.18 shows us the angular velocity of the controlled plant in which we get a maximum overshoot of 0.18 rad/sec for 0.3 rad. This response goes to zero in a steady state. Nonzero initial velocity means including reaction forces in the model. Our controlling technique shows less overshoot value as compared to the previous studies [27-30-31].

The effectiveness of our control system is demonstrated in Figure 4.19 when the sliding surface tends to zero within 3 sec after given multiple angular perturbations of (0.1,0.2,0.3)radians. This rapid convergence ensures a highly effective control strategy, which ensures that system return towards its equilibrium position. The consistent settling time across different perturbations ensures its robustness and effectiveness, that it can handle various disturbances while maintaining stability. This shows the robustness of

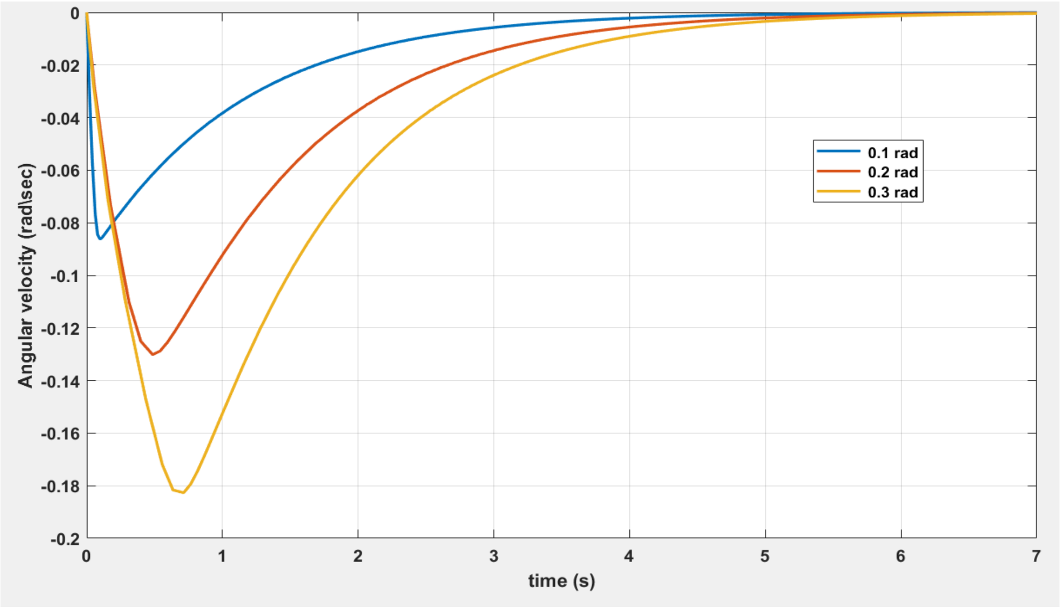

Figure 4.18: Angular Velocity Result

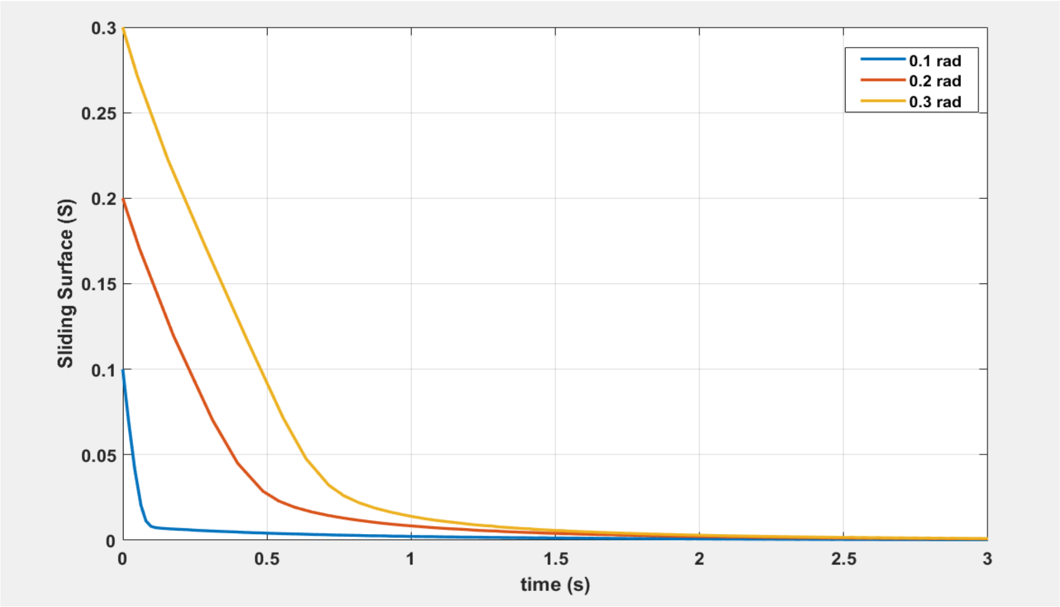

Figure 4.19: Sliding Surface Result

QSMC technique, which is essential for real world applications where the margin of error is less.

The controlled plant's input torque profile is displayed in Figure 4.20. The perturbation applied to the upright body is 0.1, 0.2, and 0.3 rad. The Muscle-Tendon-Complexes (MTC) produces torque of 135 Nm for 0.1 rad, 140 Nm for 0.2 rad, and 200 Nm for 0.3 rad to resume the body upright posture in 6 sec. These torque profiles settle to zero in 5 sec. Our Controller (QSMC) produces input torque of 135, 140, and 200 Nm for different input values while other controllers [27-30-31] require a torque of 180 Nm and so on thus it provides evidence of the efficiency and effectiveness of our approach. This substantial decrease in torque corresponds to the effective use of system resources for the control objectives, further asserting that the system is more efficient in using control resources. The lower torque requirement not only entails lower energy consumption but also reduces mechanical stress, which may increase the life expectation of the mechanical parts and decrease their frequency of failure. Furthermore, the ability to achieve and execute control actions with less torque means that the QSMC system is more accurate, proving its effectiveness.

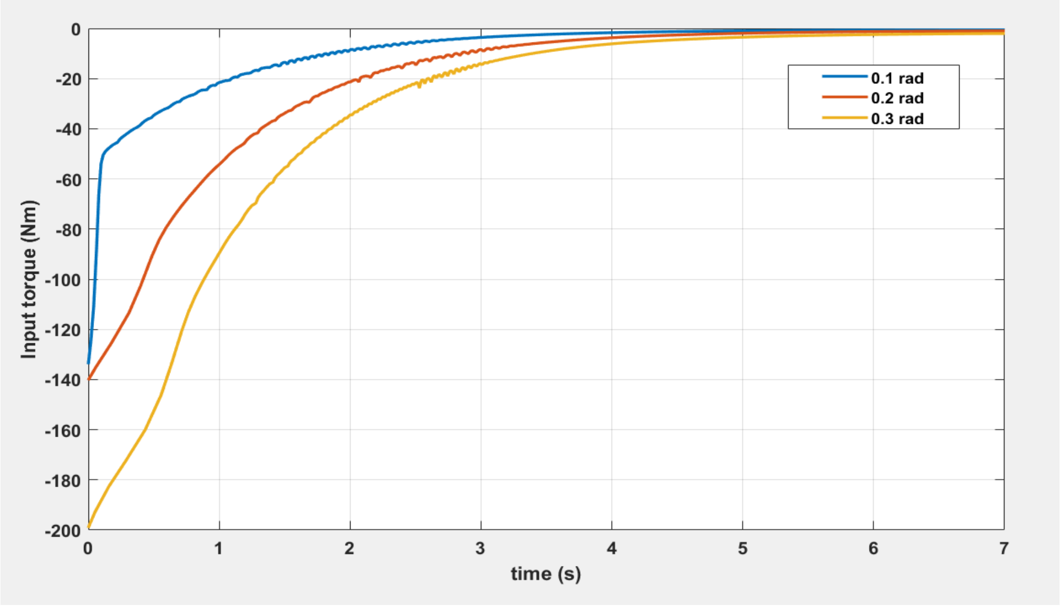

Figure 4.20: Input Torque Result

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

5.1 Overview

This Chapter focuses on overall performance analysis and future recommendations.

5.2 Evaluation of Proposed Methodology

In this research, we have analyzed and understand the dynamics and stability of lower joints by innovative approaches such as the analysis of Hip-Knee (HK) joint angles during single-leg stance (SLS) and the implementation of Quasi Sliding Mode Control (QSMC) to the biomechanical model. The study analyzed the changes in joint stability and control between young and elderly groups, showing the possibility of identifying joint problems in their early stages without MRI scans or CT Scans. QSMC integration into the single-link biomechanical model shows that it can effectively refute perturbation instability. The QSMC technique offers better control with small input torque rather than applying the traditional sliding mode control in which chattering plays a critical role. In general, the study of the angles of Hip-Knee joint in flexion movement during single-leg stance activity can indicate aging-related changes in joint dynamics and posture stability. Young people show remarkable stability, while elderly participants struggle to maintain posture integrity. This may result from age-related changes such as muscle weakness, reduced proprioception, and damaged neuromuscular system.

Incorporating joint angle analysis in our assessment protocol can detect hip or knee problems early on and enable positive interventions for patients. Detecting hip or knee issues without MRI scans represents a significant innovation in this research. This new approach may provide a basis for personalized rehab programs for musculoskeletal disorders. The study which demonstrated the effectiveness of Quasi Sliding Mode Control (QSMC) for a single-link bio-mechanical system. The QSMC enabled stability, settling perturbations within 5 seconds, and required significantly lower input torque which shows its robustness and effectiveness towards nonlinear systems but there is always a trade-off between parameters in the control system, and in applying QSMC the chattering was removed but settling time was increased to 5 to 6 seconds. These results highlight QSMC's superior efficiency and robustness, reducing energy consumption and mechanical stress. The findings suggest that QSMC offers a precise, stable, and efficient control solution, addressing the limitations of traditional techniques and making it a valuable approach for applications requiring high performance and reliability. These insights suggest that the enhancement of advanced control and pose estimation techniques can greatly help patients with joint health and stability. The integrated approach may enhance the utility and significance of the clinical assessments as well as biomechanical control systems, and expand their range of applications.

Table 5.1 shows a comparison between QSMC and other controllers which are mentioned in Chapter 2.

Table 5.1: Comparison between QSMC and other Controllers

Controller	**Settling Time (s)**	**Max Overshoot Time (rad/sec)**	**InputTorque (Nm)**
QSMC	5-6	0.18	130
Feedback Linearization	2-3	0.27	180
PID Controller	3-4	0.29	190

5.3 Future Recommendations

There are several research directions for this work where the novel QSMC technique will be applied to more complex multi-link models and where neural delays will be added to the model. Furthermore, the methodology used for pose estimation could be generalized for other joints and combined with complex image processing and deep learning algorithms to improve diagnostic capabilities and rehabilitation protocols tailored to the specific patient. In future work, we can add certain disease detection techniques for these lower joint angles like the application of image processing, and deep learning plus, we can also use this technique for elbow or shoulder joint abnormalities and detection of disease or dislocation in them as well. For QSMC this technique could be applied to three-link or four-link models and can also introduce a neural delay in the system which comes through neurological transmission.

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