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IDENTIFYING MUSCLE IMBALANCES IN ATHLETES VIA MOTION ANALYSIS USING SENSORY INPUTS

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Identifying Muscle Imbalances in Athletes via Motion Analysis using Sensory Inputs

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Declaration

I, M.S.Ratnadiwakara (2014/IS/069) hereby certify that this dissertation entitled Identifying Muscle Imbalances in Athletes via Motion Analysis using Sensory Inputs is entirely my own work and it has never been submitted nor is currently been submitted for any other degree.

Date	Student's Signature

I, S.S.Vithanage (2014/IS/087) hereby certify that this dissertation entitled Identifying Muscle Imbalances in Athletes via Motion Analysis using Sensory Inputs is entirely my own work and it has never been submitted nor is currently been submitted for any other degree.

Date	Student's Signature

I,Dr.K.D.Sandaruwan, certify that I supervised this dissertation entitled Identifying Muscle Imbalances in Athletes via Motion Analysis using Sensory Inputs conducted by M.S.Ratnadiwakara and S.S.Vithanage in partial fulfillment of the requirements for the degree of Bachelor of Science Honours in Information Systems.

Date	Supervisor's Signature

Abstract

The balance of muscle strength and length between muscles surrounding a joint should be maintained to have a healthy movement and function in human body. Muscle imbalances are mainly caused due to repetitive movement in one direction or sustained posture and the tendency of certain muscle groups to be tight or weak. In the context of collegiate athletes, the healthy practice of movements is essential since the incorrect biomechanics can result in injuries that would take a considerable amount of time to recover through rehabilitation. The current clinical methods of identifying muscle imbalances such as Movement analysis, gait and posture analysis, joint range of motion analysis and muscle length analysis are all observational evaluations that entirely depends on the domain knowledge and experience of the observer. Technical methods such as Electromyography and CT scan require expensive equipment and patients would only care to examine after having pains or dysfunctions.

To address the limitations of current muscle imbalance evaluation techniques such as time, cost and domain expertise, this research propose a solution that can incorporate an athlete to self-identify the certain overractive and underractive muscle groups in their body in order to follow intervention exercises. Movement analysis; one of the commonly used methods in the context of physiotherapy to identify dysfunctions in the human musculoskeletal system, is the method used in this research to identify muscle imbalances. The Overhead Squat is used as the movement pattern to be analyzed with the aid of the motion tracking device; Orbbec Astra Pro.

Two mathematical models are used to calculate the joint angles and joint distances relating to the overhead squat. The joint positional data taken from Orbbec Astra Pro is used as the input for the mathematical formula. Overhead squat movement pattern of a healthy subject is represented as graphs in order to compare graphs of a new subject to identify deviations. By identifying deviations the research propose potential overractive and underractive muscle groups that causes the muscle imbalances.

The accuracy of the proposed method was more than 75%, which is a satisfactory outcome. This method will facilitate the self-detection of imbalances in the whole body at a low-cost and with less time. Further enhancements to this proposed method can bring forth benefits to the fields of sports medicine, physiotherapy as well as physical fitness.

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Chapter 1

Introduction

The participation of college athletes in sports have increased in the last decade according to the sports sponsorship and participation research done by the National Collegiate Athletic Association in 2016-17 [1]. With this growing numbers, the musculoskeletal injuries have increased as well[2]. Although Rehabilitation after an injury is the conventional method of treating injuries, researchers have found the rehabilitation focused around a single region of musculoskeletal system is not sufficient enough to restore the performance to the previous state [3]. The main cause according to a study [4] has identified is that the injuries in one body region affect in terms of weakness, tightness or pain in another region away from the injury. In other words, muscle imbalances surrounding joints. Thus, the best way to counter injuries is to eliminate injury risk all together. In order to identify potential injury risk factors, there is a need for a criteria to routinely assess an athlete's quality of musculoskeletal system or the overall movement pattern.

1.1 Problem Definition

Every movement in our body is initiated and controlled by the muscles surrounding the joints. In order to function properly in our daily lives, these muscles needs to work as groups. As one muscle group initiates the movements, the other group needs to control them [5]. Therefore it is necessary to have a balance of muscle length and strength between these

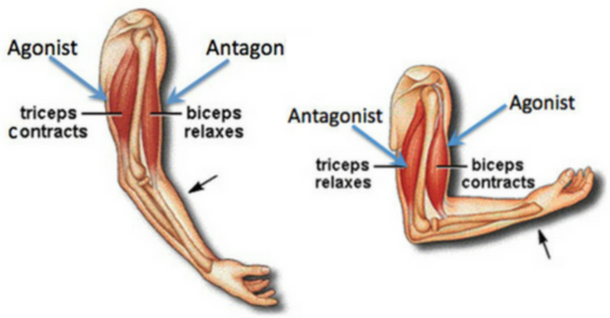

Figure 1.1: Elbow flexion (Right) and extension (left)

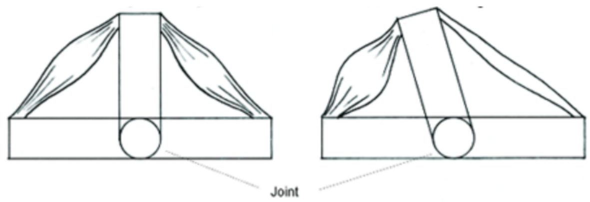

Figure 1.2: Muscle Balance (Left) and Imbalance (Right) around a Joint

opposing muscle groups around a joint. These opposing muscle groups are known as agonist and antagonist muscle groups shown in figure 1.1. For instance, when our arm is bent from the elbow, the bicep contracts and the tricep relaxes which makes the bicep muscle to act as the agonist muscle and the tricep muscle to act as the antagonist muscle. In a situation where the arm is extended, the bicep relaxes and the tricep contracts - reversing the roles of agonist and antagonist muscles. It is crucial to maintain the relative equality of these opposing muscle groups to stabilize the joints in the most optimal position to ensure efficient movement [6]. A muscle imbalance is caused when one of the opposing muscle groups becomes shorter and tighter due to reasons such as performing certain movements (movements in sports) excessively over a long period of time, holding incorrect body postures for prolonged time periods and emotional stress [7]. Human body performs complex movements which use multiple muscle groups acting as stabilizers and mobilizers [7]. The central nervous system (CNS) of humans are designed to always prioritize joint/ spine stabilization over efficient motion [6]. Once a muscle becomes underactive/ imbalanced, another group of muscles becomes overactive to compensate the under-active group of muscles as shown in figure 1.2. The overactive group of muscles eventually becomes overused and weakened which causes another muscle group to be overused. Similarly, this will create a chain of issues in the musculoskeletal system which will eventually lead to an injury [7].

Muscle imbalances can either be functional or pathological [8]. Functional imbalances usually do not show any pain and tend to happen when the body trying to adapt to complex movement patterns. Pathological imbalances may or may not be painful but it usually associated with dysfunctions and lead to functional impairment [8]. These kinds of imbalances are very common in athletes that incorporate strength, flexibility or greater inertial rotations on joints frequently. It is essential for athletes to maintain balanced muscle groups throughout the whole body to ensure their health. But the issue is that a person will not be able to identify an imbalance until it causes pain or functional discomfort. So it is noted that the imbalances should be managed before it goes into pathological state [8]. Thus identifying these imbalances have become critical regarding athletes, since clinicians or coaches can then implement preventive exercise regimes in order to restore balance if required.

1.2 Causes of Musculoskeletal Imbalance and Relative Effects

There are mainly two types of injuries associated with sports; acute injuries and overuse injuries. Acute injuries are caused by a sudden traumatic event like spraining an ankle or shoulder dislocation. Overuse injuries are a category that caused by repetitive use and stress in movement. This can be explained as a result of minor damages happening over a period of time [2]. This also can occur when there was not enough time provided to properly heal the injured area [9]. According to a study done by Yang et al in 2012 [2] comparing the rate of overuse and acute injuries in college athletes, nearly 30% of the injuries were discovered to be overuse and 70% were acute. Overuse injuries occur due to the weak musculature surrounding a joint exposed to repeating movements. These weaknesses are identified as muscle imbalances [9].

In Orthopedic practice, muscle injuries can be considered as one of the most common occurrences, especially in athletes. According to several previous studies[10],[11],[12], muscle injuries are the most common injuries occurring in sports varying from 10% to 55% of all the sustained injuries. An injury caused during a sports activity may take a considerable amount of time to recover which will prevent an athlete from taking part in competitions as well as obstruct the continuous training programs [13]. As previously mentioned, such injuries can be caused due to imbalances in the musculoskeletal system and there lies a necessity to identify potential overactive and under-active muscles for injury prevention.

1.3 Contribution

The need of a cost-effective and time efficient way of self-evaluation method that can be routinely used is evident from the previously mentioned facts. This study will contribute to the development of such a method, in order to detect muscle imbalances in early stages, so that athletes can implement preventive mechanisms to improve the overall quality and control of their musculoskeletal system.

1.3.1 Objectives and Goals

- Determining suitable movement pattern(s) to identify muscle imbalances via movement analysis.
- Determining a suitable and cost effective motion tracking device to carry out movement analysis.
- Development of a suitable criteria to map clinical measurements of identifying imbalance using the motion tracking device.
- Identifying acceptable body measurements of a healthy athlete via movement analysis with the aid of a motion tracking device.
- Identifying how the movement patterns of an athlete having muscle imbalances deviates from the acceptable movement patterns of a normal athlete via movement analysis
- Output the potential overactive and under-active muscle groups that cause the muscle imbalances.

1.3.2 Research Questions

Sub Question 1

What is/are the suitable movement pattern(s) that can be used to identify muscle imbalances in athletes and what is the suitable motion tracking device?

As mentioned under 1.5, clinical evaluation of the imbalances using movement analysis heavily depends on the expertise of the evaluator. Also, it consumes a considerable amount of time to conduct a series of movements to observe and identify muscle imbalances accurately. There are numerous methods that currently used for assessing movement quality and functionality such as Functional Movement Screen (FMS) and Movement Competency Screen (MCS) [14]. The question is to identify a suitable method or a single movement pattern that can be utilized to identify overall muscle imbalances of athletes with the aid of a motion tracking system. A reliable, conveniently accessible and an affordable motion tracking device should be selected.

Sub Question 2

What are the acceptable body measurements and movement patterns of a healthy individual without muscle imbalance and how to create a criteria to map the accepted measurements with the output of the motion tracking sensor?

After identifying a suitable movement pattern, how to identify the correct way of doing it should be defined in terms of angles and distances of the musculoskeletal system. According to a domain expert, there is a set of angles physiotherapists use to differentiate people with imbalances when analyzing the movement patterns [7]. These set of clinical rules needs to be converted and mapped, in order to track them with a motion tracking device. Since those standards can differ from person to person, there is a need to define a suitable range of acceptable measurements for athletes. The question is to identify a criteria to map the clinical rules and define standard measurements of a normal athlete without imbalances with the aid of a motion tracking device.

Sub Question 3

How to identify the deviations between the accepted measurements and the measurements taken from an athlete holding a muscle imbalance?

It needs to identify how the movement patterns of an athlete are deviated from the defined acceptable movement patterns to understand the muscle imbalances present in the body. There should be a procedure to compare and identify deviations from the established measurements and a mechanism to represent a meaningful result to the end user.

1.3.3 Research Approach

Initial interviews were conducted with a domain expert in the field of physiotherapy to gather information on the background of musculoskeletal imbalance and how it is detected and analyzed clinically at present. Information on the tests that are currently used and the grading systems and reliability were studied. The previous study of detecting muscle imbalances by analyzing gait and posture was conducted using a Microsoft Kinect version 1 sensor[15]. Since Microsoft Kinect is discontinued, a suitable replacement sensor was selected for the study which is economical and can be used by coaches, athletes and physiotherapy domain experts.

The grading systems and measurements of a suitable movement analysis method were combined with the expertise of a physiotherapist to determine the acceptable movement patterns and measurements of a healthy athlete. The motion tracker was used to collect the data and the analysis of the movements were done under the guidance of a domain expert. A sample of active sportsmen and sportswomen between the ages of 20 - 25 years were used for this task. Sample selection is explained further under topic 3.1.3

Once the standards are finalized, the data will be inserted into the system. The proposed system will be able to identify any deviations from the defined standard measurements while performing the selected suitable movement pattern(s)by analyzing the output from the sensor and comparing it with the previously fed data of the standard measurements. The output will consist of the deviations from the standard and also the potential muscle imbalances based on the deviations so that a coach, athlete or a physiotherapist can decide on what treatments or exercises should be done to fix the muscle imbalances without a presence of a domain expert.

1.3.4 Research Scope

Sample - Active sportsmen and sportswomen (20y-25y)

Context - University athletes

Approach of musculoskeletal imbalance identification - movement analysis

Applicability of the study - upper and lower body musculoskeletal system joints

1.3.5 Delimitations

The research does not encompass predicting future muscle injuries based on the possible muscle imbalances detected as there are many factors other than muscle imbalance affecting the susceptibility of an athlete getting injured.

Only a motion capture device was utilized in the research. Therefore, the research does not cover detecting of muscle imbalances using strength and length of muscles.

1.4 Muscle Imbalance Identification Techniques

The clinical way of identifying muscle imbalances is heavily dependent on the patients history of complaints, the clinicians fundamental knowledge as well as the visual observations [16]. When it comes to functional evaluation of muscle imbalance, the clinician needs to patch together all these parts of information he gathers into the entire perspective that explains the current condition of the patient.

1.4.1 Gait and Posture Analysis

Gait cycle is explained as the time period or the sequence of movements happening during one foot touches the ground to the next time the same foot contacts ground. Simply its the way of walking. Gait cycle is also known as a Stride [17]. Gait cycle can be classified into two main phases; stance phase and swing phase, which include eight sub-phases as depicted in figure 1.3.

The first 60% of the Gait cycle is occupied by the stance phase, where it starts with the Heel Strike. In this Initial contact phase, only the heel touches the ground, the toes are yet to touch [18]. 30°hip flexion and the knee at its full extension can be observed. The knee flexion begins and increases till it goes to next phase; Flat foot [19]. Also known as the Loading Response, in which the body absorbs the impact of the foot. The hip moves into extension while the knee flexes at 15°- 20°of flexion [18][19]. In the Mid Stance, the hip moves from 10°to extension, knee moving into maximal flexion. The whole body is supported by a single leg in this phase [18]. When the heel leaves the ground, the Heel Off phase begins. 10°- 13°hip hyperextension can be observed here and the knee becomes flexed [19]. Toe off or Preswing phase is the end of Stance phase. The knee is flexed at 35°- 40°and the ankle increases its angle to 20°[18][19]. Initial Swing is the start of Swing phase, in which the hip extended to 10°and the knee flexes to 40°- 60°[18]. The next phase is Mid Swing, where the hip flexes at 30°and the knee flexes 60°which later extends to 30°. The Terminal Swing or the declaration phase starts with hip flexion of 25°- 30°, while knee fully extended [18][19]. Deviations from these walking patterns can be used to evaluate the muscle imbalance.

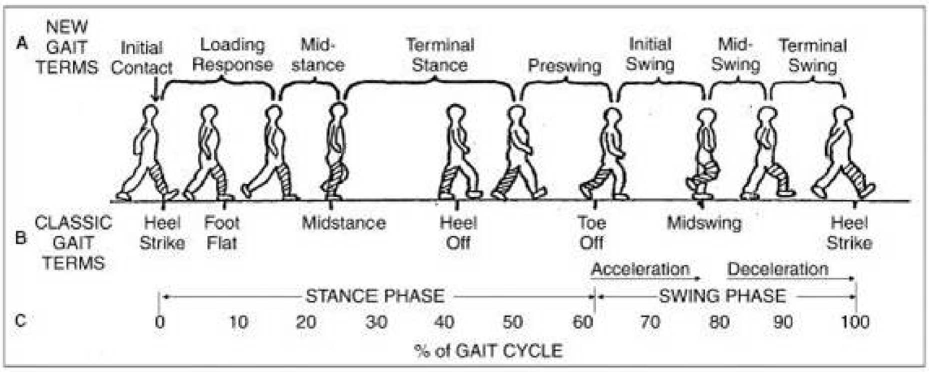

Figure 1.3: The Gait Cycle with phases

When considering the Posture analysis, standing position can be taken as a static posture. Gait cycle which discussed above can be categorized as dynamic posture. Postural analysis is done more of as a subsequent or an assisting test [8].

1.4.2 Movement Analysis

Functional Movement of the human body is not a work of an isolated muscle group since movement is produced as a combined process of several muscle groups working together [8]. Assessing these movement patterns can be done by analysing the body behaviour when a person is doing a specific movement. In order to understand the quality and control of these movement patterns, the clinician should focus on all the muscle groups involved as well as the strength the person put into these movements when doing them. Thus the knowledge and experience of the evaluator are indeed essential in these studies [16]. Specific movement pattern chosen for the evaluation can differ according to the purpose of evaluation, in order to focus on a specific set of muscle groups [8].

There are three main methods of analysing the biomechanics of sports movements, which are Movement Phases, Free Body Diagrams and Deterministic Models. First two methods mainly used by coaches whereas Deterministic models frequently used for research purposes in sports context [16].

- Movement Phases

A sports movement mainly consist of three phases, which are preparation, execution and follow-through. Preparation phase includes all the movements that prepare an athlete to perform the skill. In execution phase, the actual movement will happen. Follow-through refers to the movements occur after execution, such as slowing down the body with momentum. All these phases can further breakdown into sub-phases. Figure 1.4 shows the sub-phases of Preparation phase when throwing a ball in Baseball. These phases are analyzed to get an idea about the behaviour of a particular individual.

- Free Body Diagrams

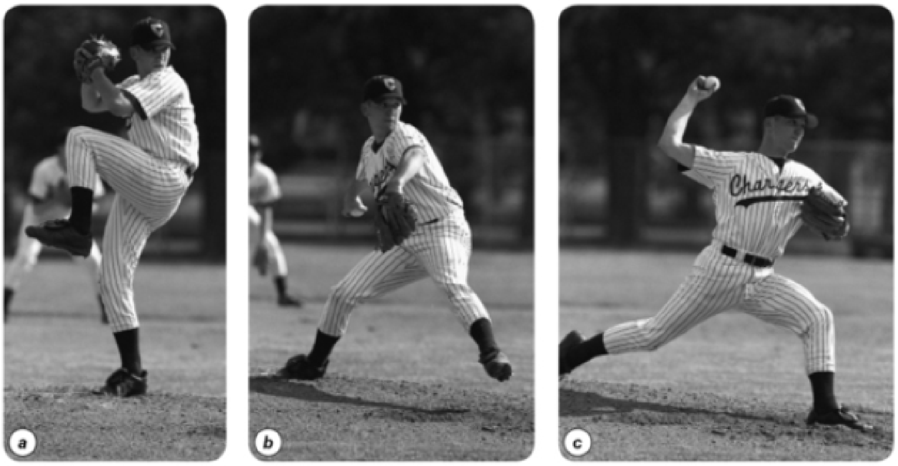

Figure 1.4: Sub-phases of Preparation phase

This is basically a diagram of expected or predicted movement drawn as a simple stick figure. This is usually used by coaches to describe a specific movement in a particular moment in time. When analysis is done, the forces involved with the movement is shown with arrows. This diagram only shows the forces acting on the system, but not the within the system.

- Deterministic Models

This model describes the biomechanical factors determining a movement and starts with a primary movement then further break it down into sub factors. Thus, a deterministic model has many levels.

1.4.3 Joint Range of Motion Analysis

The Joint range of motion analysis is done by assessing the ranges a person can extend their joints in a particular direction. Each of these joint has a maximum range in a certain direction, thus clinician needs to be careful not to extend joints beyond that. This can be assessed mainly in three ways.

- Active Range of Motion - patient extends joint by himself.
- Active-Assisted Range of Motion - patient extends joint but requires assistance to complete the joint range.

- Passive Range of Motion - patient is unable to extend joint at all and requires complete assistance of another person for the joint to extend.

The evaluator (Clinician) should first explain how to do the motion that is required, or the clinician can demonstrate to the subject how to do it. Then he can actively observe the joint movement and compare the ability of movement and the quality side by side. It can be assessed in terms of speed, stiffness, joint swelling, coordination and alignment [20]. The key joint motions that assessed are as follows.

- Shoulder - flexion/extension, rotation, abduction/adduction.
- Elbow - flexion/extension, rotation.
- Wrist - flexion/extension, medial/lateral.
- Hand/fingers - flexion/extension, abduction/adduction.
- Hip - flexion/extension, rotation, abduction/adduction.
- Knee - flexion/extension.
- Ankle/toes - flexion/extension, rotation.
- Trunk - anterior, posterior, lateral rotation.
- Head/neck - flexion/extension, rotation, side bending.
- Trunk - flexion/extension, rotation, side bending.

If the assessment results show a considerable deviation from the defined ranges of joints, it can be concluded as the patient is having a muscle imbalance.

1.4.4 Muscle Length Analysis

In Muscle length testing, it assesses the resistance to the passive lengthening of muscles. This involves stretching out the muscle in the opposite direction to its action.

The stretching of the muscle should be done slowly in order to avoid muscle contraction [8]. There are four steps in assessing the muscle length test.

- Ensure maximal lengthening of the muscle from origin to insertion
- Firmly stabilize one end (usually the origin)
- Slowly elongate the muscle
- Assess the end feel

1.4.5 Electromyography and Surface Electromyography

Electromyography is a procedure to detect nerve dysfunction, muscle dysfunction and complications with nerve-to-muscle signal transmission [21]. An Electromyography procedure is conducted by inserting a thin needle (electrode) into the muscle and observing the electrical activities in the muscles when the muscles are contracted or in a relaxed state. The electrical signals are displayed on a monitor known as oscilloscope [22]. A nerve conduction velocity test is often conducted along with an EMG test to differentiate between a nerve dysfunction and a muscle dysfunction [22].

Surface electromyography tests do not pierce the skin and electrodes are placed over the skin to detect electrical signals in muscles. Despite not causing any pain to the subject, SMEG is unable to specifically monitor deep muscles [23]. At present, both EMG and SMEG are used to detect muscle imbalances by observing the electrical signals from muscles.

1.4.6 X-ray and CT Scan

General x-ray technology can only be used to detect complications in the skeleton and not soft tissues like muscles, ligaments, tendons or nerves [24]. Computer tomography scan or otherwise known as CT scan uses specialized x-ray equipment to produce cross-sectional images horizontally and vertically. CT scan provides more clarity than the normal x-ray scan, which allows viewing more details on bones, muscles, fat and organs. In CT scan, the x-ray beam is projected in a circular motion around the body which allows many different views on muscles and organs [25]. However, it is evident that muscle imbalance cannot be detected clearly by these methods [26].

1.4.7 Ultrasound Analysis

Ultrasound scan is a very commonly used test to detect issues related to musculoskeletal system. Ultrasound imaging is considered safe compared to x-ray or CT scan since it does not use any ionizing radiation in the imaging process. The scanning process uses high frequency sound waves to create images real time and is very suitable to diagnose sprains, strains, tears and other similar soft tissue conditions [27].

1.5 Issues with Current Techniques

In the field of physiotherapy, there is a number of ways to identify muscle imbalances. Namely by using EMG or CT scan analysis of muscle activation, muscle strength analysis and ultrasound analysis to capture muscle images [7]. These methods are costly and requires visitations to the doctor/clinician. Apart from these, there are ways to clinically evaluate muscle imbalances known as functional evaluation of muscle imbalances as explained previously. This is done mainly using patients history, current complaints and by observing the movement patterns of the patient [8]. For this, the presence of a domain expert is a needed and it heavily depends on the knowledge and experience of the evaluator. Which can be resulted in erroneous evaluations, when screening in real time [14],[28]. These types of functional movement analyses take a considerable amount of time as well since it consists of several exercises.

Considering the above issues, the importance of a mechanism to identify muscle imbalances without the aid of high-cost instruments as well as the presence of a domain expert can be identified. Our research aims to facilitate an improved ICT based mechanism to cater to athletes to identify the muscle imbalances and guide them to prevent injuries with the aid of a motion tracking device.

1.6 Thesis Outline

The introduction chapter of this thesis gives an initiation to the discussion on muscle imbalance and how it affects athletes and their sports careers. Furthermore, this chapter consists of particulars regarding the contribution of the research study, current muscle imbalance techniques and their issues and a brief idea on how this study is addressing those issues.

A comprehensive background study review is covered in the second chapter. Background chapter includes previous research studies related to how muscle imbalance affects athletes, what current tools and techniques are used to detect muscle imbalance and suitability of using using motion tracking devices in the domain of physiotherapy. This chapter discusses comprehensively on current muscle imbalance identification techniques and their issues and drawbacks and how these issues can be addressed with a use of motion tracking device to detect muscle imbalance.

Methodology and design chapter addresses the specifics related to how the research study is designed to be carried out and the implementation of the design. Research methodology encompasses selection of a suitable movement pattern, selection of a suitable motion tracking device and selection of samples for the research study where as research design covers the mathematical models used to analyze captured data creation of models to classify subjects. The concluding section of the third chapter details on how the design approach described earlier is implemented in the research study.

Results and evaluation chapter comprises of the clinically acceptable graphs created from the mathematical models described in the preceding chapter and the evaluation of accuracy of the said graphs using the test sample.

Next chapter gives the reader an insight into how the results are analyzed and interpreted followed by limitations and constraints of the current research study which may have affected the accuracy of the results. Furthermore, this chapter discusses on how the conducted research study contributes in terms of creating new knowledge. Final chapter of the thesis is conclusion and future directions which elaborates the final conclusion of the research study and possibilities of improving and implementing the research solution.

Chapter 2

Background and Literature Review

2.1 Study review of the impact of muscle imbalances relating to athletes

A sports injury is defined as any traumatic or overuse impairment happened during the period of practice or competition, which leads the athlete to take time off from training or requires medical care [29]. Several previous studies[10],[11],[12] state that, muscle injuries are the most common injuries occurring in sports varying from 10% to 55% of all the sustained injuries. The factors contributing to these injuries have been studied in the literature, focusing around a specific injury. Even though musculoskeletal imbalances are mentioned as one of the causing factors of injuries [30], there is very little documentation available on the relationship between muscle imbalance and the extremity injuries [31]. As stated in [2], the overuse injuries are hard to detect since the symptoms gradually increase. Which can be lead to serious injuries later on. A previous study has found that the athletes possessing hamstring to quadriceps (H:Q) strength imbalance ratio below the normal range of 60% have a higher chance of suffering from overuse knee injuries [32]. In agreement to that, previous studies have concluded that muscle imbalance is a possible risk factor in hamstring injuries of competitive sprinters [33] and professional male soccer players [34]. They have also stated that preseason isokinetic screening would help athletes to identify the risks of hamstring muscle injuries [33], [34]. Another study [29] done with athletes in various sports including soccer, volleyball, field hockey, tennis, fencing and basketball, came to the conclusion that imbalance in muscle flexibility is contributed to muscle injuries. [34] has also agreed with it by showing a significant association between preseason hamstring muscle tightness and subsequent development of muscle injuries.

Furthermore, a previous study [35] done with wheelchair athletes has found that the shoulder muscle imbalance is one of the causes for the development of rotator cuff impingement syndrome. According to Croisier et al [31], they have observed recurrent hamstring injuries in athletes who previously suffered the injury. They have concluded that athletes who are not fully rehabilitated and still have muscle weaknesses and imbalance increase the recurrence of muscle injuries. When considering about the imbalances between two limbs, a previous study [36] has mentioned that the equal proficiency in both limbs is crucial for an athlete to enhance their in-field performance, thus such imbalances are a hindrance for athletes. The early diagnosis and prevention of these injuries is an important task since those may hinder the performance and also athletes may not be able to participate in competitions [13]. Stretching exercises, muscle strengthening and correction of muscle imbalance have proven to be effective preventive mechanisms [13]. A previous research [37] was conducted to improve the upper and lower limb muscle imbalances in elite fencing athletes which showed statistically significant improvement in balance over 12 weeks of preventive exercises. Thus, it can be concluded that by identifying muscle imbalance and taking preventive mechanisms before it turns into a serious injury, the injury risk can be avoided and the overall movement quality can be improved.

2.2 Study review of using Movement Analysis to detect Muscle Imbalances

Observation of human movement patterns can be used to develop injury prevention strategies as well as to enhance the athletic performances [38]. Classical evaluation methods of detecting muscular imbalances involves applying a force on a muscle group and measuring the resistance force from the isolated muscle group. However, the mechanism is inadequate because the functional movement is never isolated and requires several muscle groups to work together as prime movers, synergists and stabilizers. Therefore, movement pattern analysis is more reliable than isolated muscle strength analysis [8]. Since the study of pain is subjective, it poses erroneous results when assessing the functional quality of muscles [8]. Thus, the assessment of movement is reliable in that aspect as well. In the clinical field of evaluation of the quality of muscles, there are several screening mechanisms. These functional movement analyses are used to draw conclusions about muscle strength, flexibility and activation based on observed movement pattern [39]. It is mentioned in a study [38], that these movement deficiencies identified during screening, represent the muscle imbalances caused by decreased flexibility, muscle weakness/ tightness and unbalanced muscle activation patterns.

2.2.1 Jandas basic movement patterns

Vladimir Janda is a renowned neurologist and a physiotherapist, who has come up with the Janda Approach which shows a unique perspective of rehabilitation. He himself has identified basic movement patterns that can be used to assess the quality and control of a person's movements [8] which covers all the key regions of the musculoskeletal system. Just like the previous movement evaluation systems, Janda's approach is also heavily based on the domain knowledge and the observation skills of the clinician. Following list shows Janda's basic movement patterns.

- Hip Extension
- Hip Abduction
- Trunk Curl-up
- Cervical Flexion
- Push-up
- Shoulder Abduction

To evaluate the Janda's tests, there are key indicators related to each of these tests. If the person contains any of the indicators associated with tests, he is identified as having a muscle imbalance within the muscles related to that specific movement pattern [8].

2.2.2 Functional Movement Screen (FMS)

FMS is a widely used screening tool to categorize the functional movement patterns, which includes a series of 7 tests. These tests are identified as fundamental movements that operate as the basis for more complex movement patterns that are being used in sports activities [40]. Thus, it is used to predict the injury risk of athletes by routinely assessing their overall quality of movements.

A previous study [28] has been done regarding the reliability of the FMS in real time field settings comparing the gradings scores from FMS and grading athletes using objective data from an inertial-based motion capture system (IMU). In real time, the evaluators have to focus on multiple areas when performing a complex movement pattern like the overhead squat. Hence, its noted that there's a higher probability of missing vital kinematic information when using such observation based tools [28]. This study also explains a few drawbacks of FMS tool such as; to assess the movement pattern with higher accuracy, it has done repetitively for 3 times for a tester to evaluate manually, which consumes a considerable amount of time. The ambiguity of the grading criteria should also be noted here since FMS is a criterion based test tool, the understandability of each of these criteria can be highly subjective to the evaluator. Adding to that fact, the positioning of the evaluator has also affected the observation angle and can be resulted in erroneous assessments. Figure 2.1 shows the seven components of FMS.

Figure 2.1: Test components in FMS

2.2.3 Clinical use of Overhead Squat to identify Muscle Imbalances

Overhead Squat test is the one test specifically used for the clinical identification of musculoskeletal imbalance [7]. National Academy of Sports Medicine (NASM) has suggested both FMS and Overhead Squat as useful indicators of movement quality [14]. When considering the assessment of movement dysfunction, overhead squat have a few advantages over above mentioned screening methods. The time consumed for just one movement pattern is considerably less than when compared to seven movements in FMS. Time plays a major role when it comes to the practical situation in athletic setting, since the movement assessments would take a considerable amount of time from the practice time of athletes. The overhead squat also covers all the key joints in the kinetic chain being a commonly used movement pattern in strength and conditioning context [14]. As an added advantage, overhead squat can be trained in one session for athletes to perform reliably [38]. By observing the behaviour of the person when performing the overhead squat, a clinician can draw a conclusion as to whether he holds a muscle imbalance or not. The movement is observed in three angles; Anterior view, Lateral view and Posterior view. Athletes who do not contain a muscle deficiency can accurately perform the overhead squat as shown in figure 2.2. Any deviations from the angles in figure 2.2 can be concluded as the patient having a muscle imbalance in

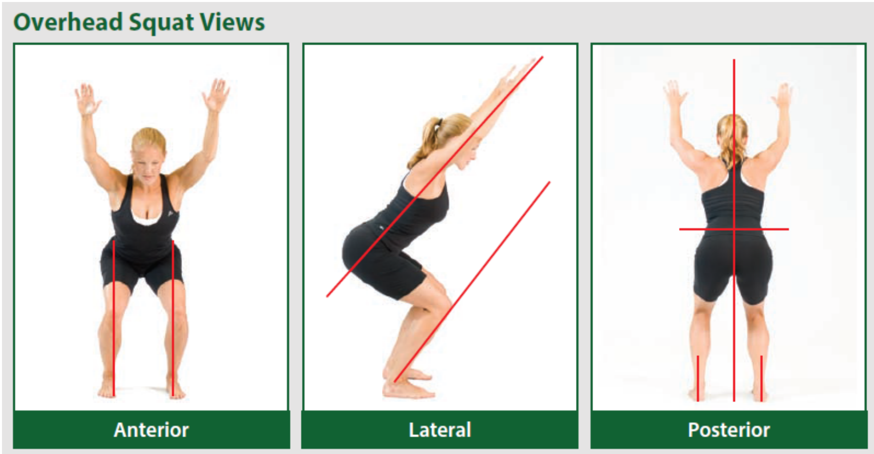

Figure 2.2: The accurate joint angles observed in overhead squat

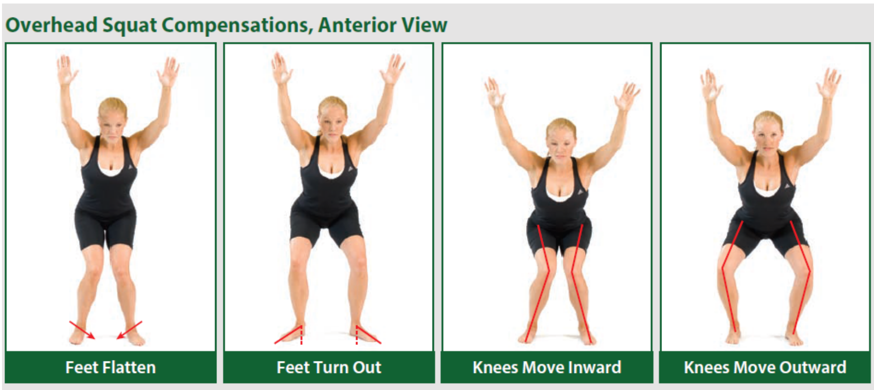

Figure 2.3: Overhead Squat compensations, Anterior view

associated joint muscle groups. The abnormal movement patterns incorporated with each of the three views are shown in figure 2.3, 2.4 and 2.5.

The observations done in Anterior view is focused around the knees and feet as shown in figure 2.3. In this view, clinicians mainly look for whether the toe is out and knee moves inwards (knee valgus) [38]. In Lateral view, the observations are related to the upper body positions as shown in figure 2.4. The movement deficiencies are focused around arms, lower back and trunk muscle groups including lumbo-pelvic hip complex [38]. Posterior view is used to evaluate the movement patterns in feet and lumbo-pelvic hip complex as shown in figure 2.5. A common compensation seen in this view is the pronation and the flattening of medial longitudinal arch [38].

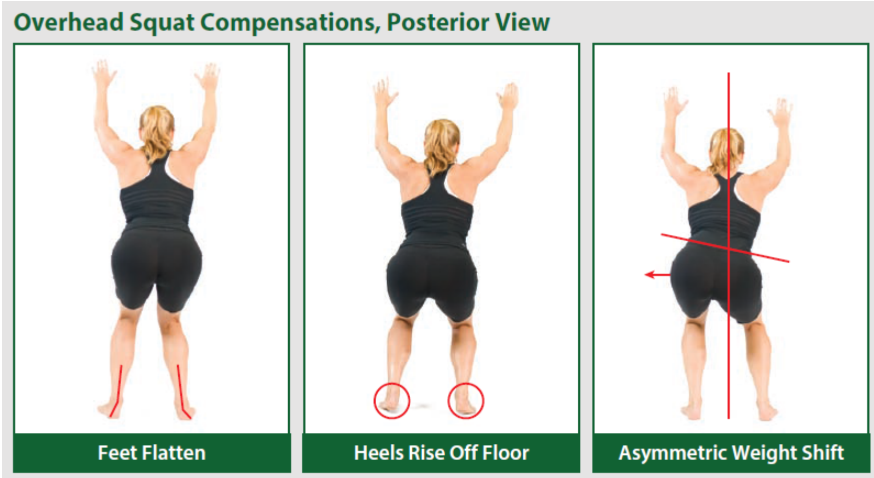

Figure 2.5: Overhead Squat compensations, Posterior View

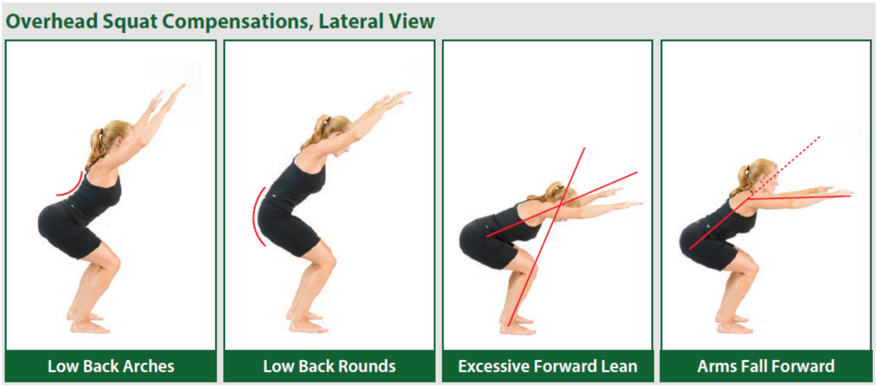

Figure 2.4: Overhead Squat compensations, Lateral View

In several previous studies [41], [42], [43], squat was taken as a suitable movement pattern to evaluate the overall quality of the functional movement. However, these studies have evaluated the squat based on the criteria defined in each of the specific screening tools such as FMS [14] which again do not address each and every aspect of a compound pattern like the overhead squat. Thus, to analyze the optimal nature of overhead squat, there is a need of a more precise mechanism that does not fall into the subjective interpretation of the evaluators. Whiteside et al [28], who compared the real-time reliability of FMS, mentioned that when using multiple exercises to assess similar functions can affect the overall compound score of the screening tool which again gives an erroneous result. For example in FMS, it uses deep squat, hurdle step and in-line lunge to assess frontal plane stability component. Thus, its more appropriate to use one exercise that can assess overall functionality like the overhead squat.

A previous study [39] has been done to analyze the muscle activity and flexibility of patients with medial knee displacement (MKD), which is a commonly observed movement dysfunction pattern. In this study, they have used the overhead squat to identify patients with MKD and compared how the muscle activation and flexibility differ with this development with the aid of EMG sensors to measure the muscle activation and a manual 12-inch goniometer to measure the peak joint angles for the range of motion (ROM) in joints. The results indicated tightness in calf muscles which restricted the range of motion in ankle caused MKD. Thus, this study validates the use of visual observations of overhead squat to identify muscle imbalances in certain muscle regions in the musculoskeletal system. This also means that the overhead squat can be used as a reliable mechanism to identify possible overactive and underactive muscle groups. Table 2.1 shows the potential overactive/ underactive muscle groups that can be assessed with the overhead squat.

2.3 Study review of utilization of motion capturing devices and sensors in the context of sports medicine

As mentioned in the previous section, theres a high probability of discovering many muscle dysfunctions by analyzing the quality of the movement patterns. Muscle balance is at the core of every movement. As pointed out in many studies related to movement screening mechanisms which are based on observation, it can be erroneous when evaluated in real time. Thus, the accuracy can be improved when the movements are analyzed with the aid of motion tracking devices.

A previous study [42] employed a marker-based motion tracking system to analyze the peak sagittal plane joint angles and joint moments of the lower extremity during the deep squat movement in FMS. It can be noted that the deep squat is much similar to the overhead squat. The anatomical markers were placed at the distal end of the foot, 1st and 5th metatarsal head (1st and 5th of the five long bones located in the midfoot), medial and lateral malleoli (on either side of ankle), medial and lateral femoral epicondyles (on either side of the knee), left and right greater trochanters (where leg joins with the hip joint), left

Movement Pattern dysfunction	**Potential Overactive muscles**	**Potential Underactive muscles**
Feet Turn Out (Toe-out)	Soleus Lateral Gastrocnemius Biceps Femoris Tensor Fascia Latae	Medial Gastrocnemius Medial Hamstrings Gluteus Medius Gluteus Maximus Gracilis Popliteus
Knee moves inward (Valgus)	Hip Adductors Lateral Gastrocnemius Biceps Femoris (short head) Tensor Fascia Latae Vastus Lateralis	Medial Gastrocnemius Medial Hamstrings Gluteus Maximus Vasus Medialis
Knee moves outward (Varus)	Piriformis Biceps Femoris Gluteus Minimus Tensor Fascia Latae	Adductor Complex Gluteus Maximus Medial Hamstrings
Excessive forward trunk lean	Soleus Gastrocnemius Hip Flexors	Anterior Tibialis Posterior Tibialis Erector Spinae
Arms fall forward	Latissimus Dorsi Pectoralis Major Pectoralis Minor Coracobrachialis	Middle Trapezius Lower Trapezius Rhomboids Posterior Deltoid Rotator Cuff
Flattening of medial longitudinal arch	Peroneus Major Peroneus Tertius Lateral Gastrocnemius Biceps Femoris Tensor Fascia Latae	Posterior Tibialis Lower Trapezius Medial Gastrocnemius Gluteus Medius

Table 2.1: Potential Overactive and Underactive muscles related to overhead squat test

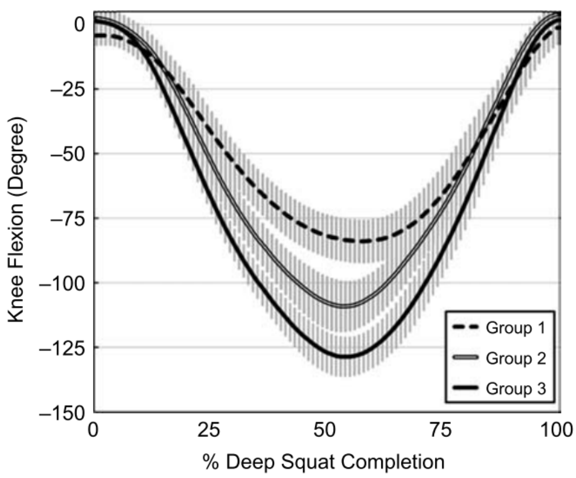

Figure 2.6: Knee flexion during deep squat

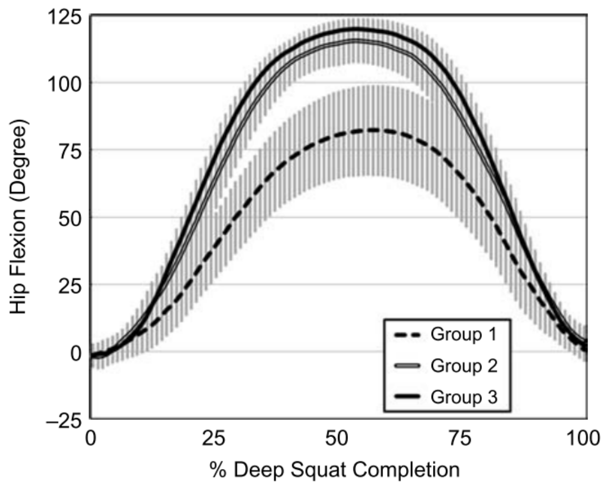

Figure 2.7: Hip flexion during deep squat

and right anterior superior iliac spine (sides of the hip), left and right iliac crest and over the L5-S1 interspace (lower back). These markers were placed using double-sided tape. Marker data were tracked at 60Hz utilizing eight VICON MX motion analysis cameras. This study has compared the differences between the groups who scored 1,2,3 according to FMS grading score. The results have shown a difference in angle ranges of each group as demonstrated in figure 2.6 and figure 2.7.

The group one was not able to perform the squat at all, while the 3rd group have successfully completed. We can see with the figure 2.6 and figure 2.7 how the ranges of knee motion and hip motion have tracked respectively with this marker-based system. A similar study [43] was done with deep squat to demonstrate the reduction in knee valgus after the intervention of rehabilitation exercises. In this scenario, they have used an electromagnetic tracking system to collect kinematic data. The EMG sensors were interfaced with a motion tracking software called MotionMonitor. They have concluded that this motion tracking method can be used to screen a large number of athletes in a short period of time and with only a few equipment. But it should be noted that in both these studies they have placed markers on athletes body using double-sided tape, which is uncomfortable and a hindrance when performing the movement.

According to Wan and Shan [30], one of the main causing factors of the muscle repetitive stress injuries (RSIs) associated with athletes is the imbalance between the agonist and antagonist muscles. They have employed a 3D motion capture system (VICON

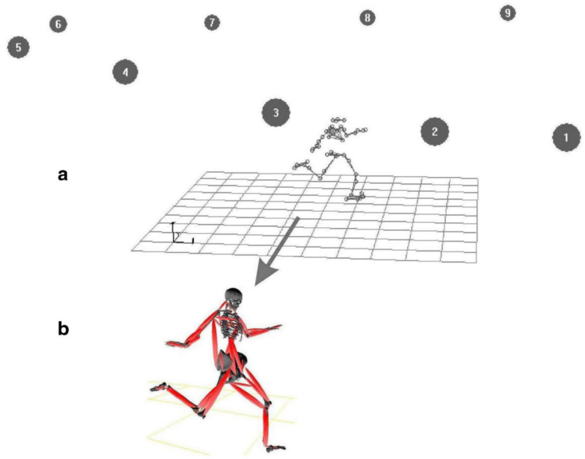

Figure 2.8: Subject construction from the data of reflective markers

MX40) to develop a biomechanical model for maximal instep soccer kicking which can then be used to identify deviating joint range of motions (ROM) and related muscle lengthening characteristics. The study has suggested that the muscle imbalance can be caused by improper training programs and insufficient time spent on healing the stress on muscles. In this study, they have used 42 reflective markers on the subjects body.

The placement of the cameras around the subject is shown in figure 2.8 with numbers. The biomechanical model of the subject is constructed from the data collected from the markers. Even though the accuracy of the data coming from the model is high, doing movements while wearing markers can be uncomfortable to the subjects. A previous study [44] has compared the accuracy of markerless motion capture system over a marker-based system when tracking knee flection during the overhead squat. The study was done with seven healthy male athletes with ages between 22-26 years. The 6 camera VICON 3D capture system and Kinect version 2 was used as the marker-based and markerless motion capture systems respectively. The results from this study suggest that markerless motion capturing can be used to evaluate squat mechanics in an objective approach, opposing subjective clinical evaluations. It also should highlight here that markerless motion capturing is cost-effective when comparing to the marker-based systems.

One of the most common fundamental movement patterns we use in daily life is raising to a standing position from a sitting position. A study [45] was done to analyze the characteristics of this pattern in 1990. Nine healthy females were taken as subjects and monitored with Selspot II optoelectronic (detects light) cameras at a rate of 153 frames per second. Multiple LEDs were placed on 11 body parts of the subjects using polypropylene molds as shown in figure 2.9. They have identified four phases with the gathered motion data as illustrated in figure 2.10 which are the start, lift off, max dorsiflexion, end hip extension. It is noted that this movement pattern largely resembles the movement of squat, and can divide into phases similar to this study.

Lai et al. [46] have developed a model to represent body posture through skeletal system equations. They have used multiple acceleration sensors and gyroscopes to detect body motion patterns, which then can be used to achieve long-term rehabilitation. They have used four main static and dynamic postures to aid the development of the model; standing, lying, sitting and walking. The results shown by this study was able to recognize most of the movement patterns accurately, though they themselves have considered the discomfort to the subjects when wearing so many sensors and the costs of the sensors as drawbacks of the study.

A previous study [47] was done to validate the reliability of the vertical jump force test(VJFT) in assessing the strength asymmetry of athletes. A single force plate was used to measure the force exerted on each leg during the execution of the jump. One leg was placed on the force plate and the other on a level wooden platform while the leg on the force plate was alternated during jumps. The reading from the force plate was compared against the results of the isokinetic leg extension test and the isometric leg press test. The results have shown a strong correlation between the readings from the vertical jump force tests and the two tests mentioned above which validates the reliability of using vertical jump force test for assessing bilateral strength asymmetry. However, the vertical jump force test does not allow the evaluation of different muscle groups in the lower limb but only considers the force exerted from the entire lower limb as a whole.

A similar study [48] was done to examine the bilateral differences in the ground reaction forces during the overhead deep squat test. As mentioned earlier in section 2.2.3, the overhead deep squat can be used to detect bilateral muscle imbalance which is a key component in promoting the musculoskeletal health in athletes. A twin-force plate system was used to measure the peak ground reaction force during the deep overhead squat. The

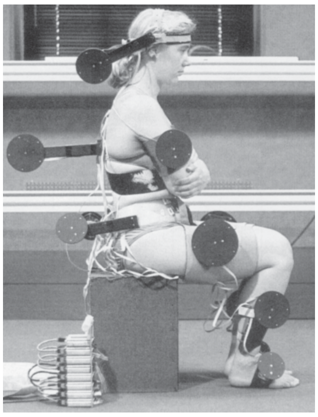

Figure 2.9: Subject instrumented with arrays of LEDs

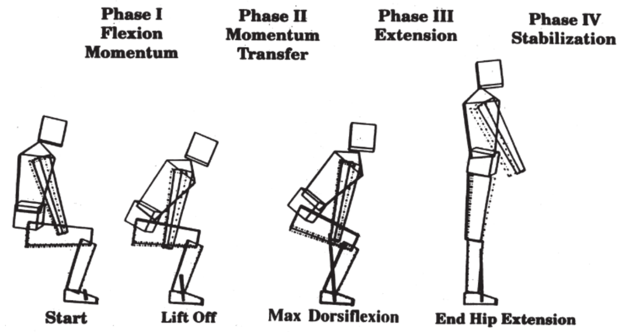

Figure 2.10: Four phases of raising

study was done on a sample of young soccer athletes and the results indicate that there appears to be a trigger point during early adolescence that mark bilateral imbalance and the magnitude of imbalance increases as the players get older. The results of this study suggest that early detection of bilateral imbalances and taking corrective measures is crucial in preventing musculoskeletal injuries. According to Mauntel et al [49], there can be biomechanical differences between the male and female during the overhead squat. Their study was using an electromagnetic motion tracking system interfaced with a force platform to measure the lower extremity kinematics and kinetics during the descent phase of the squat. The results have indicated several differences between the males and females such as males having a greater peak knee valgus angle, peak hip flexion angle, peak vertical ground reaction forces, peak hip extension moments, less ankle dorsiflexion with the knee extended and less hip internal and external rotation than females. It can be concluded that gender-specific injury prevention programs should be developed based on the results of this study.

The deep overhead squat used in the two studies mentioned above is a component of the functional movement screen which is explained in section 2.2.2. A study was done to compare the objective methods and manual (real-time) methods in grading the functional movement screen [28]. The study was done by comparing the FMS grades given by a certified FMS tester and those given by an objective inertial-based motion capture system. The inertial measurement unit sensors were placed in the subjects body and the readings obtained while executing the components of the FMS was used to score the subjects. According to Whiteside et al, manual evaluation of the FMS is susceptible to error and there lies a need to develop a standard procedure in grading FMS performance.

Only one research [15] has been previously conducted to detect muscle imbalance using a motion sensor and it was limited to the lower body. Furthermore, there was no positive identification of potential overactive and underactive muscles. The objective of the study was to detect muscle imbalances by identifying abnormalities in the gait cycle. A marker-less motion capturing device was used to capture different phases in the gait cycle. Three graphs were generated to denote the variation of the ankle, knee and hip angles against time. The resulting graphs were compared against the standard gait cycle graph to detect a person with muscle imbalances.

There are several research studies that have been done to detect muscle imbalance and asymmetry using a variety of sensors mentioned in this section. However, most of the above-mentioned studies have used force plate systems, electromagnetic tracking systems and inertial movement sensors to detect human movement which cannot be considered as practical solutions to detect muscle imbalances due to the high cost of the equipment [13] and the difficulty to implement in field settings. Although the above mentioned study [15] has provided a cost-effective solution, it does not detect muscle imbalances in the upper body and it can not help identify possible overactive and underactive muscle groups. This study is focused on providing a solution which is cost effective and can be used to identify muscle imbalances in both upper body and lower body by oneself.

2.4 Generic overhead squat measurements in medical domain

Although overhead squat is a widely used tool when determining muscle imbalance, there were no studies done to quantify the standard measurements of the overhead squat in the medical domain at the time of writing this document. However, standard measurements for gait cycle which is another tool to identify muscle imbalances has been measured and available in the medical domain [50]. In gait cycle measurements, minimum and maximum threshold values are defined for the knee angle, hip angle and the ankle angle for a single gait cycle. Figure 2.11 shows how the minimum and maximum threshold values for ankle angle vary during a single gait cycle.

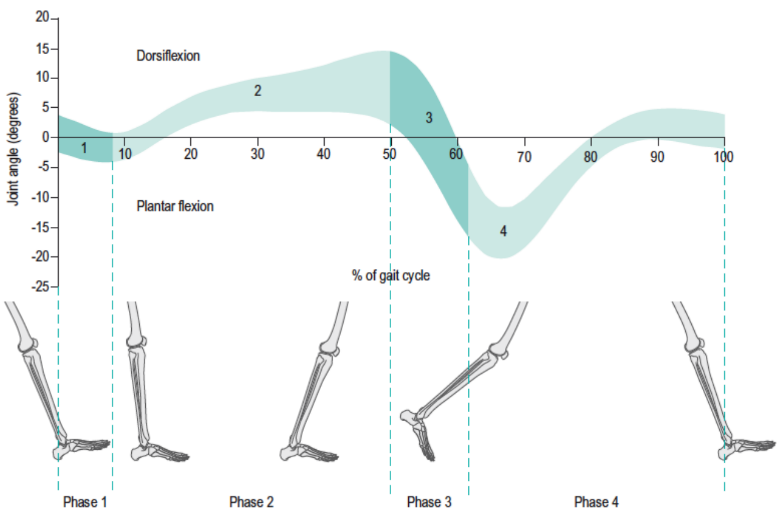

Figure 2.11: Plantar dorsiflexion of ankle joint angle during the gait cycle

As mentioned earlier, Tennakoon et al [15] have done a study to detect muscle imbalance using gait cycle. In this study, they have used a similar approach where minimum and maximum threshold values were defined to determine whether a subject has a muscle imbalance or not.

Schenkman et al [45] have used a similar approach when conducting their research on whole-body movements during the movement pattern of sit-to-stand. They have recorded hip-flexion and trunk angle during the period of rising to standing position from sitting.

2.5 Study review of motion tracking devices

There are two main types of sensor technologies that are being used in motion capturing; The optical sensor technology and on-body sensor technology. Applications of optical sensor motion capture can be done in two methods; marker-based and marker-less [46]. Prior to the use of marker-less motion capturing systems, marker-based optical motion capturing systems were used in the field of sports medicine. Optical motion capturing systems which use reflective or active markers are considered to be highly accurate when tracking human motion. During a study done using a calibration and measurement robot [51], the optical motion tracking system performed with an overall accuracy of 65 +/- 5 microm and overall precision (noise level) of 15 microm.

One of the most popular markerless motion capturing sensors within the time period of 2010 to 2015 was Microsoft Kinect. A study was done in 2012 to evaluate the accuracy of the Microsoft Kinect sensor against an optical motion capturing system [52]. According to the study, an approximate error of 10°occurs when therapists visually control the range of motion. When compared, the Kinect performed with errors less than 10°in the knee and hip angles and highest error of shoulder angle being slightly above 10°. The results of this study prove that Kinect motion tracking system is suitable for rehabilitation treatments. In another study [53], the researchers have combined the inertial sensors and Kinect sensor in order to measure joint motion in the context of rehabilitation. They have made use of two types of inertial sensors; 3-axis accelerometer and 2-axis gyrometer, to estimate joint angles. Kinect was used to develop the 3D position of joints. The movement patterns used in this study were, sit to stand, squat and shoulder abduction. The study has concluded that by integrating both type of sensors, it will decrease the error in overall estimated motion.

Kinect was discontinued in 2015 and there have been several alternatives since then. Asus Xtion [54], Intel RealSense [55], Orbbec Astra and Orbbec Persee [56] are some of the popular sensors that can provide skeletal tracking data similar to Microsoft Kinect and act as a suitable replacement. The number of joints tracked and the quality of the skeleton data may vary based on the SDK used. Figures 2.12, 2.13 and 2.14 show the joint maps of Orbbec SDK, Kinect SDK and Nuitrack SDK [57] respectively.

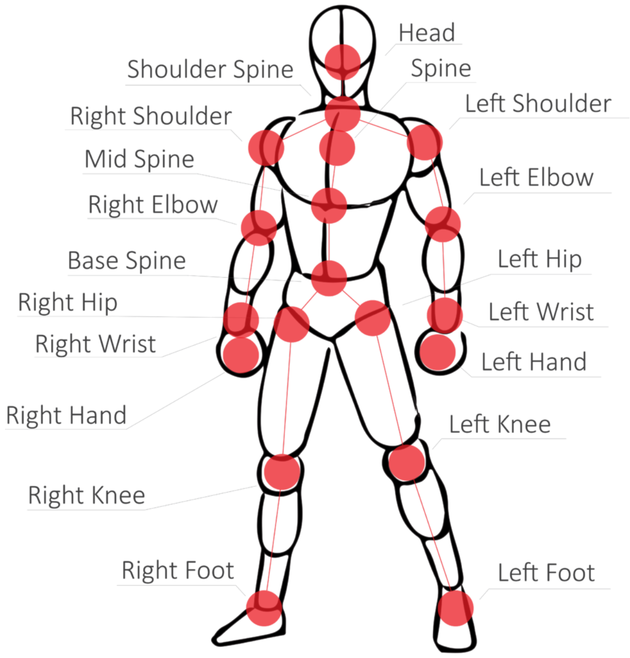

Figure 2.12: Joint map of Orbbec SDK

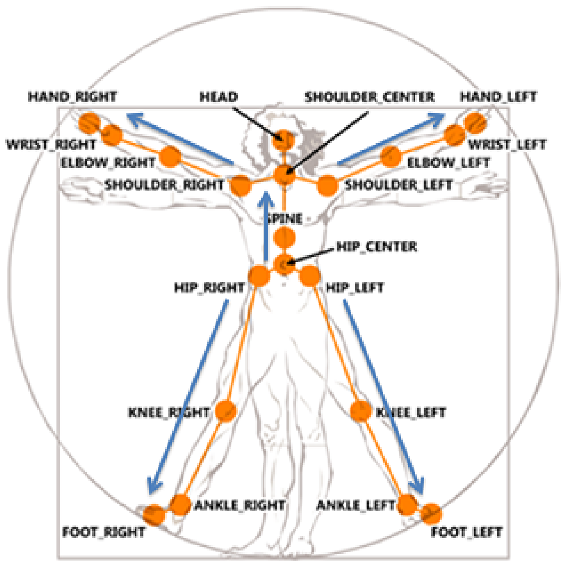

Figure 2.13: Joint map of Kinect SDK

Figure 2.14: Joint map of Nuitrack SDK

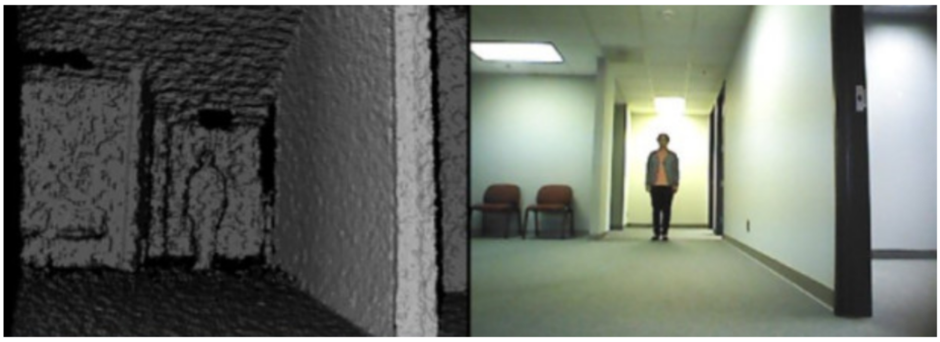

Figure 2.15: The depth image and the RGB image of Astra 3D sensor

Orbbec Astra 3D sensor is one of the recently found depth sensors that use a similar technique to Microsoft Kinect. There are a few advantages; better accuracy, portability, miniaturization and compatibility according to Zeng et al [58]. It also supports main operating systems such as Windows, Linux, OSX and Android. It is also mentioned that this sensor is the most similar to Kinect. Astra 3D sensor is comprised of four parts; the RGB camera, infrared launcher, infrared camera and microphone. This sensor uses an optical coding technique to obtain the depth distance and then turn it into depth image. A depth image and corresponding the RGB image from Orbbec Astra is shown in figure 2.15. A study [58] was done using this sensor to detect the sitting posture with depth images. In this study, Astra 3D sensor was able to effectively detect 14 different sitting postures and has shown a good real-time performance.

2.6 Summary

The literature review encompasses four major aspects related to the current research. Firstly, a review of muscle imbalance in the context of sports is carried out, followed by a review of the current clinical muscle imbalance identification techniques such as the Jandas basic movement patterns, functional movement screen and the deep overhead squat. The next section consists of previous research studies done with the use of motion tracking devices in the field of sports medicine and the final section consists of the review done on markerless motion tracking devices currently available in the market.

Muscle injuries are a very common aspect in the field of sports and with the growing number of athletes each year, there exists a need for solutions that can prevent sports injuries. The literature review done on the effects of muscle imbalance in the context of sports medicine includes research studies done previously that highlights serious effects of injuries caused due to muscle imbalance in athletes. Currently, there are many clinical muscle imbalance identification methods as mentioned earlier. This literature review consists of important factors that need to be considered when using each of these identification techniques. Some of such factors would be heavy dependence on a domain expert when carrying out the tests, errors that may occur when evaluating a subject manually and consumption of a considerable amount of time which may discourage athletes in taking the identification tests regularly.

The study review of the use of motion capturing devices and other sensors in sports medicine consists of research studies done with the use of sensors such as electromagnetic motion capturing systems, optical motion capturing systems, force plate platforms and markerless motion capturing systems. The advantages and limitations of each technique and the device used are included in this study review. Final section encompasses a review done on markerless motion tracking sensors which can be used for the current research that is currently available in the market. The review includes studies that are done to validate the reliability of the devices when tracking motions during rehabilitation treatments. Currently, there are many limitations in the clinical methods used to detect muscle imbalance and there are no previous research studies done to provide a cost-effective solution to detect muscle imbalance in both upper body and lower body. This research focuses on minimizing the said disparity by providing a solution that can be used to self-evaluate and identify muscle imbalances in the entire body.

Chapter 3

Methodology and Design

3.1 Research Methodology

3.1.1 Selection of suitable movement pattern

As discussed in the previous chapter, there are several movement patterns used in the clinical field to evaluate the functionality and the quality of the musculoskeletal system. In order to select a suitable movement pattern for the research study several factors were considered relating to the context of collegiate athletes.

When considering the main concern of collegiate athletes relating to the assessment of their movement behavior, the limited time can be highlighted. Most of the collegiate athletes try to balance their sports with their respective academic studies, leaving them to contribute a limited amount of time for their sports. Thus, it's quite impractical to use a screening method such as Functional Movement Screen which contains seven exercises. Also to get more accurate results each test component needs to perform several times in a row. Which takes a considerable amount of time to evaluate a team of athletes. Thus there is a need for a movement pattern that consumes less time to evaluate which covers all key joints in the musculoskeletal system.

Next factor being the ability to assess overall musculoskeletal functionality, the movement pattern selected should be able to measure all the key joint measurements in the kinetic chain. Screening tools such as FMS or Movement Competency Screen carry several advantages since they provide a numerical grading system. Having final scores at the end of an assessment make it easier to analyze movement functionality over a period of time, also it gives ability to do comparisons when doing re-assessments. However, taking the sum of scores of seven different assessment components can be erroneous according to a previous study [28] done by Whiteside et al. as we mentioned in the previous section. However, the overhead squat is one fundamental movement pattern that covers overall kinetic chain in human body. Which is also a common denominator in widely used screening tools such as FMS (Functional Movement Screen) and MCS (Movement Competency Screen) [14].

Considering these factors, it can be concluded that the Overhead Squat is a suitable movement pattern for the research study. Mainly because it is the exercise clinicians use to evaluate patients having muscle imbalances via movement analysis. It consumes less time to assess the overhead squat when compared to screening tools like FMS which contains several test components. Also, it's based on fundamental movement pattern that's commonly used in strength and conditioning context. Thus, easy to train the athletes on how to perform the overhead squat in a brief time. Overhead Squat is proven to be ideal for this study as the movement pattern to be assessed.

3.1.2 Selection of suitable motion tracking device

As mentioned earlier in section 2.5, there are different portable motion tracking sensors that are currently available in the market that can be used as a suitable replacement for Microsoft Kinect. This section focuses on the different specifications of the following listed sensors.

- Asus Xtion/ Xtion Pro/ Xtion 2
- Intel RealSense
- VicoVR

- Orbbec Astra/ Persee
- Stereolabs ZED
- Openpose

Asus Xtion/ Xtion Pro/ Xtion 2

The first 3D camera to be released by Asus is Xtion, which was followed by Xtion Pro and then Xtion 2. Out of the three versions, Xtion 2 has the best specifications with a better field of view and a RGB camera in addition to the depth sensors. Both Xtion Pro and Xtion 2 can be operated in multiple operating systems such as Windows, Linux and Android while Xtion can only be operated in Windows 7 OS. Asus Xtion series cameras do not come with a bespoke SDK but they can be used with OpenNI SDK. All three of these cameras are suitable for indoor use only.

Intel RealSense

Intel RealSense camera series include two depth cameras namely, D415 and D435 with the latter having slightly better specifications in terms of the range that the camera can capture. Both of these cameras are equipped with a depth sensor and a RGB sensor. The cameras can be used in both indoor and outdoor environments and supports multiple operating systems; Windows, Linux, MacOS. Unlike the Asus depth sensors, Intel has a SDK of their own to be used with the senors which includes a comprehensive list of features and samples.

VicoVR

VicoVR depth cameras are mainly focused on enhancing mobile gaming experience. The sensors are designed to work with the VR headset to make the mobile gaming experience more enjoyable. There are two types of depth cameras under VicoVR series; VicoVR Game Edition and VicoVR Makers Edition. The game edition is focused on mobile games while the latter is focused on developers. Therefore, the makers edition come with a bespoke SDK as well. However, both of these cameras work with only mobile operating systems, which are Android and IOS.

Orbbec Astra/ Persee

Orbbec has two main types of cameras; Astra and Persee. Astra series includes many cameras such as Astra, Astra S, Astra Pro, Astra Mini and Astra Mini S. All the cameras discussed above including the Astra series are designed to be used as a peripheral device with a computer. However, Orbbec Persee is developed as mini computer which has a RAM of 2GB, a processor, Wifi and also Blue-tooth connectivity. This camera can be used as a standalone unit without plugging into another computer and an optional display unit can be connected with Persee if needed. When considering about the Astra series the two cameras Astra Mini and Astra Mini S are designed for short range depth image processing. The other three cameras; Astra, Astra S and Astra Pro are more suitable for full body skeletal tracking and act as a better replacement for Microsoft Kinect. The specifications of these three cameras are almost identical except that Astra Pro has a better RGB resolution than it's predecessors and a higher depth range. Orbbec provides a SDK to be used with their cameras but since the cameras are highly compatible it can be used with any other third party SDK as well.

Stereolabs ZED

All of the previously listed sensors measure depth distance using an infrared emitter and an infrared sensor. Stereolabs ZED uses different technology which allows this camera to perform far better than all of the above mentioned devices. This device mimics human stereo vision to identify depth and create 3D images which enables the camera to record 2K video and get depth images up to 20m at 100fps. The device can be used in both indoor and outdoor environments and can be operated with Windows or Linux.

Device	Price and source	OS
Asus Xtion 2	$269.99 (Amazon.com)	Windows, Linux, Android
Intel Realsense D435	$259.00 (Intel.com)	Windows, Linux, MacOS
Intel Realsense D415	$229.00 (Intel.com)	Windows, Linux, MacOS
VicoVR Gaming Ed.	$249.00 (vicovr.com)	Android, IOS
VicoVR Makers Ed.	$299.00 (vicovr.com)	Android, IOS
Orbbec Astra/S/Pro	$149.99 (3dcartstores.com)	Windows, Linux, MacOS, Android
Orbbec Persee	$239.99 (3dcartstores.com)	Linux, MacOS, Android
Stereolabs ZED	$449.99 (stereolabs.com)	Windows, Linux

Table 3.1: Potential Overactive and Underactive muscles related to overhead squat test

Openpose

Openpose is a software library which uses a normal web-cam and therefore this cannot capture depth data. However, this library can accurately detect the human skeleton using complex algorithms which requires a powerful computer to perform the calculations and a considerably high amount of effort when setting up the software.

The table 3.1 compare the above listed devices with based on their prices at the time of writing this document.

When considering the specifications of the above sensors, it is evident that Stereolabs ZED outperforms all of the other devices which also explains the high price overall. Since the research study is focused on providing a cost effective solution to detect muscle imbalance, the cameras of Orbbec Astra series can be considered as suitable for the situation. Out of Astra, Astra S and Astra Pro, the latter can be considered as most suitable because of the higher depth range.

3.1.3 Sample Selection

The population that this research study is concerned with is collegiate athletes. The subjects for this study were taken mainly in two sample groups; the group of healthy athletes and general athlete group. Also, can be described as the control group and the test group respectively. Both the control group and the test group consisted of collegiate athletes between ages 20 - 25 years. Subjects who professionally practice sports were not included in the sample, since they may have developed specific movement patterns according to their specific sport in order to enhance their performance which can be outliers in this study [7]. The samples included both male and female athletes within the healthy BMI range for adults (18.5 to 24.9) in each category of sport. Several factors were considered when selecting subjects for samples with the assistance of a domain expert; Dr. Chathuranga Ranasinghe (Allied Health Sciences Unit, Faculty of Medicine, University of Colombo) in order to avoid outliers that may affect the results of the study as much as possible. The sample did not include any subject with musculoskeletal injuries, or those that are currently undergoing any rehabilitation treatments. Subjects weight and height (BMI) were taken into consideration when drawing the initial sample for the preliminary test (control group) to identify the acceptable joint measurements of overhead Squat. Prior to the participation on the test, each subject gave their written consent on the matter. See appendix for the context form.

Convenient Sampling

Since the research study is for collegiate athletes, convenient sampling method was implemented to draw a sample. A convenient sample was drawn from the athletes of University of Colombo considering the ease of access to subjects and the laboratory environment where data was recorded. Since there are approximately more than 1000 students currently engaged in more than 20 different sports activities, it can be taken as a diverse group of collegiate athletes which is suitable for the research study. The samples were drawn from sport teams such as Swimming, Hockey, Football, Rugby, Badminton and Basketball. As illustrated in figure 3.1, samples of collegiate athletes were filtered out.

Sample of healthy athletes

The sample of healthy subjects were selected with the help of the domain expert as mentioned in the figure 3.1. Those that were able to perform the Overhead Squat as accurately as defined in the figure 2.2, were identified as healthy subjects. This group consisted of subjects that did not have any previous or current injuries. Any kind of discomfort or pain were not shown while performing the movement pattern.

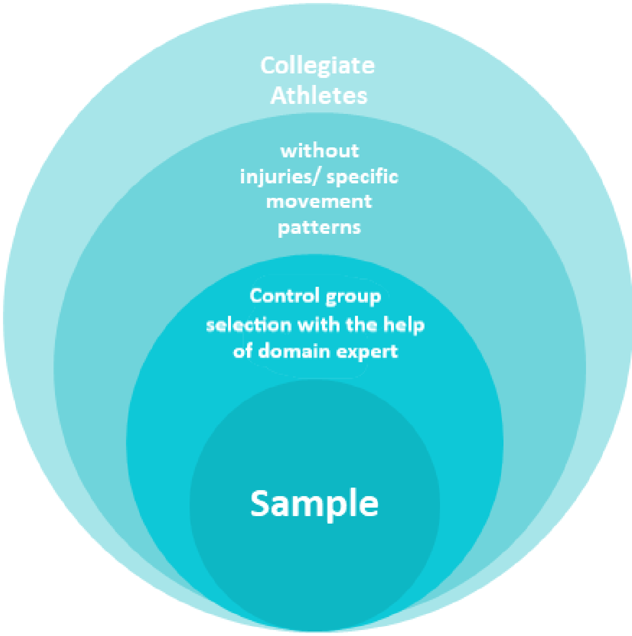

Figure 3.1: The illustration of the sample

These subjects were evaluated and selected by the domain expert as correctly performing the overhead squat. Thus, concluding as not having any muscle imbalance. These subjects were assigned to the control group, that used to derive the acceptable joint measurements and threshold values, which will be discussed in the next section.

3.1.4 Data Collection Method

Orbbec Astra Pro, a device that is equipped with a depth sensor, was used to collect joint measurement data in this study. With the inputs collected from this depth sensor, it is possible to identify the correct joint positions of a subject without any on-body markers. Data collection process was carried out in a laboratory environment to increase the accuracy of the results by avoiding unnecessary noise. Since the device does not affect the movement of the subjects, they performed the overhead squat as they naturally do in front of a physiotherapist or a clinician.

Laboratory Setup

The indoor research facility was used as the setting to carry out the experimental tests. The windows in the room had to be covered up so that the sunlight would not interfere with the infrared rays emitted from the sensor. The device was placed at a range where it can capture the whole body movement of the subject, which was determined as 3 meters from away the device.

The subjects were instructed to perform the Overhead Squat in front of the sensor. The data gathered was used to map the joint positions of the overhead squat, to give a clear understanding of the joint angles and joint distances involved. The mapping of the data was done using mathematical models, which will be discussed in the research design section.

Training Protocol before collecting data

Prior to data recording, the following instructions were given to the subjects as to how to perform the overhead squat accurately. This protocol was devised to give the subjects an understanding of the correct technique to perform the overhead squat. Otherwise, the readings maybe erroneous due to the wrong technique rather than the muscle imbalance.

1) sit on a chair

2) spread the feet space up to shoulder width

3) stand up while maintaining straight body posture

4) repeat 5-10 times

5) push from the heel when standing up

6) ask whether the subject feels the Gluteal (back) muscles engage

7) sit while slightly touching the chair

8) ask to push the weight with heels

9) observe knee movement

10) ask not to move knee beyond toes

11) repeat 5 times

After successfully training the sample, they were asked to perform the overhead squat without the chair and with the correct technique.

Data Cleansing and Noise Reduction

For better and accurate measuring of joint positions, the subjects are instructed not to wear very dark or black color clothing during the data recording process as it may affect the accuracy of the device. Furthermore, the subjects were asked to remove any foot wear before performing the movement as footwear might affect correct execution of the squat. The windows in the laboratory environment were covered to avoid sunlight. The reason for this setting is that the sun also emits IR rays, which may interfere with the infrared waves emitted from the device sensor.

The data was collected during afternoon hours, from 1 pm to 4 pm. The athletes were not exhausted or expressed any form of difficulty during the data collection period. The instructions were given to everyone in the sample by the same person (experienced with the training protocol) in order to avoid any misinterpretations in the training session. The observations were done under the guidance of a domain expert.

Furthermore, the subjects were asked to raise their arms along the Coronal plane (so that their arms are perpendicular to their body) and that position for approximately three seconds and then raise their arms over head to perform the series of squats. After the squats were completed, they were asked again to bring their arms back to the previous perpendicular position for approximately three seconds before dropping them. The purpose of this procedure was to detect the starting and ending point of the sequence of squat movement.

3.2 Research Design

3.2.1 Mathematical Models

The following joint positions were captured by the motion tracking device to proceed with the mathematical model creation of overhead squat. These joint positions were required to measure angles and distances and identify the compensations stated in section 3.2.2. The Astra SDK was used to implement it.

- Wrist (left and right)
- Shoulder (left and right)
- Spine (mid and base)
- Hip (left, right and center)
- Knee (left and right)
- Ankle (left and right)

The sensor uses an Infrared emitter and a depth sensor to capture X, Y, Z coordinates of the joint locations in the world coordinate platform. The coordinates were used to obtain joint measurements using the mathematical models that are suggested below.

Mathematical model to measure the distance between two points in the 3D space

Points P and Q are two points in the 3D space as shown in figure 3.2. The coordinates of point P is given by (x_1, y_1, z_1) and point Q by (x_2, y_2, z_2). Using the pythagorean theorem, the distance between two points in a 2D plane is calculated by the equation:

$$d(P,Q) = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2} \longrightarrow (1)$$

Similarly the distance between two point in the 3D space can be calculated by the following equation:

$$d(P,Q) = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2} \longrightarrow (2)$$

Mathematical Model to measure joint angle values

Consider PO (a) and QO (b) as two vectors that intersects in the 3D space as illustrated in figure 3.3. The angle between the two vectors POQis denoted by θ. $|a|$ signifies

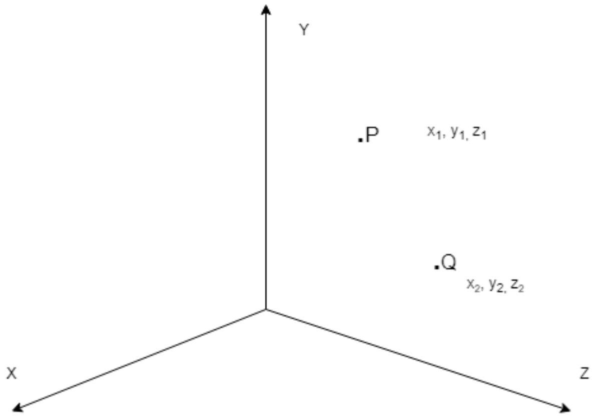

Figure 3.2: Mathematical model for measuring joint distances

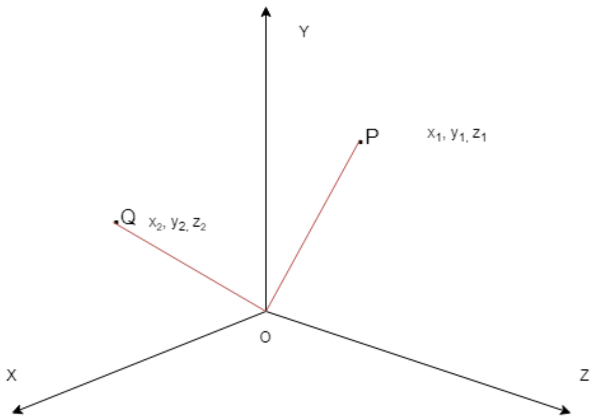

Figure 3.3: Mathematical model for measuring joint angles

the magnitude the of the vector PO (a) which is equal to:

$$|a| = \sqrt{x_1^2 + y_1^2 + z_1^2} \longrightarrow (1)$$

The dot product of the two vectors can be calculated using the following formula.

$$a.b = x_1 * x_2 + y_1 * y_2 + z_1 * z_2 \longrightarrow (2)$$

Angle between two lines in a 3D space is equal to the angle subtended by the two vectors which are parallel to those lines. The angle between the two vectors can be calculated from the (3) and $(3)'$ formula. The final angle θ is denoted in the formula $(4)'$.

$$a.b = |a| * |b| * \cos(\theta) \longrightarrow (3)$$

$$\cos(\theta) = \frac{a.b}{|a| * |b|} \longrightarrow (3)'$$

Substituting from (1), (2) and $(3)'$,

$$\cos(\theta) = \frac{x_1 * x_2 + y_1 * y_2 + z_1 * z_2}{\sqrt{x_1^2 + y_1^2 + z_1^2} * \sqrt{x_2^2 + y_2^2 + z_2^2}} \longrightarrow (4)$$

Therefore;

$$\theta = \cos^{-1} \frac{x_1 * x_2 + y_1 * y_2 + z_1 * z_2}{\sqrt{x_1^2 + y_1^2 + z_1^2} * \sqrt{x_2^2 + y_2^2 + z_2^2}} \longrightarrow (4)'$$

3.2.2 Clinically acceptable model for Average Healthy Athlete

Clinically acceptable model creation

There are certain areas that a clinician observes for compensations when the subject performs the overhead squat, starting from the standing position, going through the squat position and back to standing position as represented in figure 3.4. The above mentioned mathematical models were used to measure and represent the movement pattern of a subject when they performed the overhead squat in order to identify compensations. First, the accurate measurements of a healthy athlete who doesnt hold musculoskeletal dysfunctions were identified based on the compensations a clinician observes in the three viewpoints in overhead squat discussed previously.

Figure 3.4: Standing position and Squat position[38]

- Anterior view

  Observations in this view mainly focused on knees and feet. Compensations to look out for are the toes moving out, knees move in and knees move out. When the overhead squat is executed correctly and viewed form the Anterior view, the hip joint, the knee joint, the ankle joint and feet on either side of the body should be aligned. The distance between the two knee joints was measured over the span of a single overhead squat. If there's a considerable change of the distance (above the defined threshold values), the subject was identified that as having a compensation. Figure 3.5 shows the knee moves in and knee moves out compensations when performing the overhead squat.

- Lateral view

  Lateral view observations involves the lumbo-pelvic hip complex (LPHC) and upper body positions. Compensations often observed are excessive forward lean and arms falling forward. According to National Academy of Sports Medicine (NASM) [59], the trunk should be parallel to the lower leg during the descent phase of the squat. If not, it can be concluded as excessive forward lean. The arms falling forward is

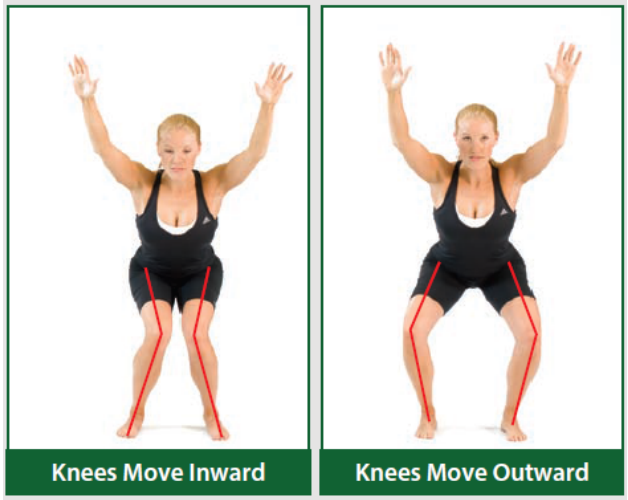

Figure 3.5: Anterior view compensations[59]

observed when elbows are fully extended above head, elbow joint, shoulder and hip center should be aligned as a straight line. In order to measure this, the shoulder joint angle was measured with respect to the hip joint and the elbow joint. If the angle value is out of the range of the normal threshold, the subject can be concluded as having a compensation. Figure 3.6 shows the excessive forward lean and arms fall forward compensations respectively.

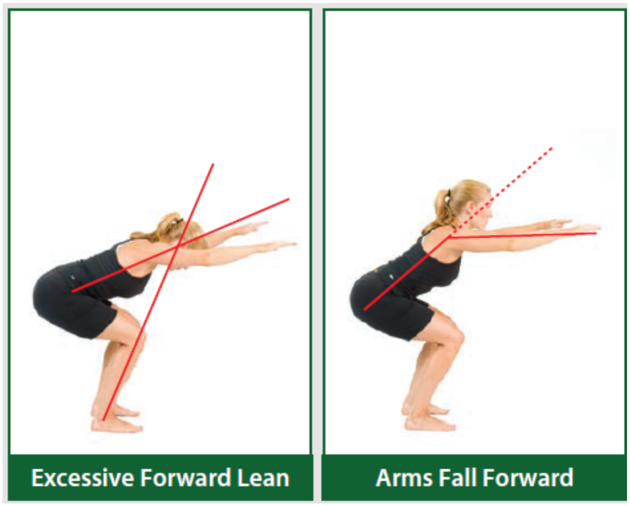

Figure 3.6: Lateral view compensations[59]

- Posterior view

Posterior view observations include the areas of feet and lumbo-pelvic hip complex. The behavior of the feet can be observed when doing the overhead squat in this view. The feet should be touching the ground in the entirety of the squat. To observe the flattening of the medial longitudinal arch, we used the deviations of the ankle joint measurements from the normal measurement range. Figure 3.7 shows the compensations that can be detected in the posterior view.

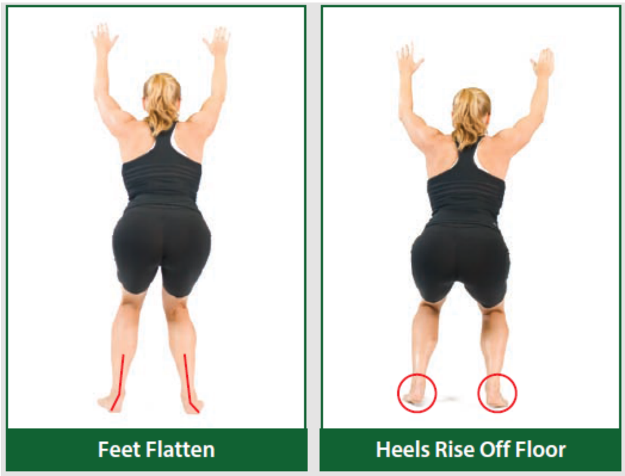

Figure 3.7: Posterior view compensations[59]

3.2.3 High level research architecture

In order to determine the muscle imbalances, both upper body and lower body were considered in this research study. The high level research design illustrated in figure 3.8 consist of mainly two parts; data collection and data analysis. In the data collection phase, the data from the overhead squat was used as the specific movement pattern which was performed by the selected subjects in front of the sensor under laboratory conditions. Joint positions were captured with the device as X,Y,Z coordinates data. These data were used to calculate the respective joint angles and distances with the aid of the mathematical models described in section 3.2.1. Five graphs were created to represent the movement pattern of each subject.

The relative graphs generated from the data collection act as the input for the analysis phase. These graphs were compared with the respective acceptable graphs that were previously developed. If the values deviate from the defined minimum and maximum threshold values of the acceptable graphs, it was identified as having an imbalance in the area covered by that graph. From the deviations, potential overactive and under-active muscle groups were identified. As the final output, the statuses of the subjects were given.

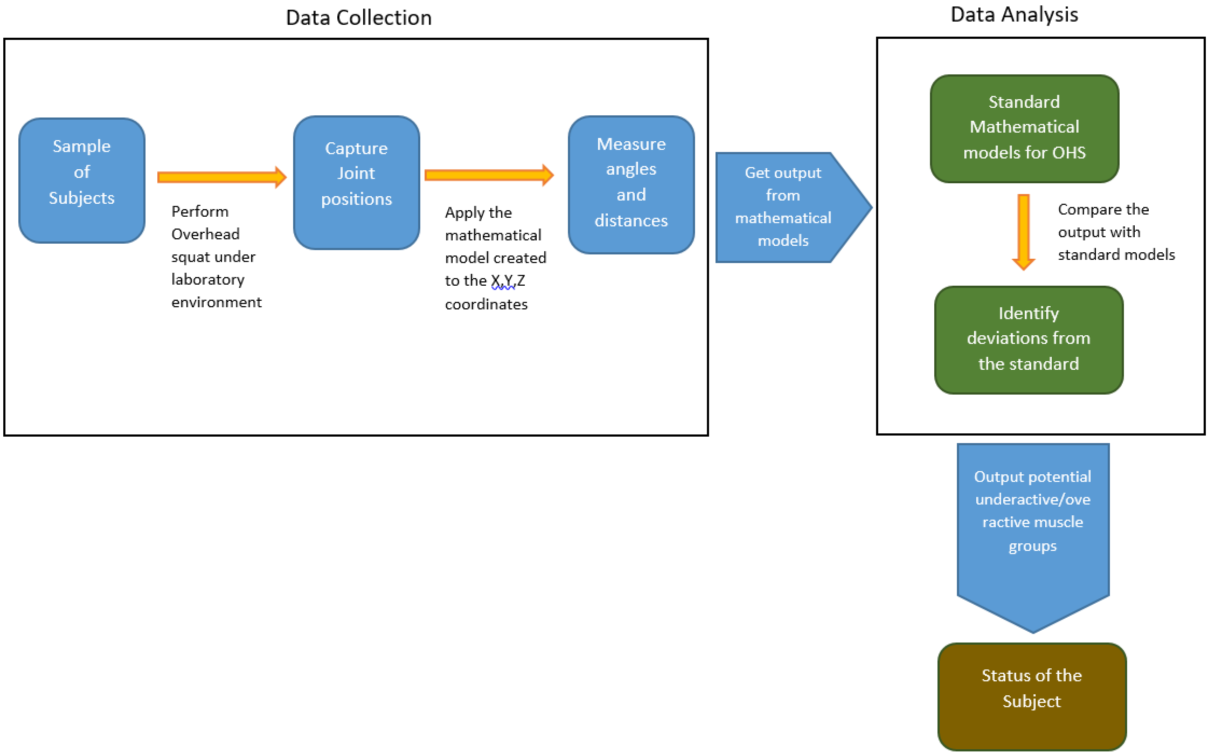

Figure 3.8: High Level research design

3.3 Implementation

3.3.1 Implementing mathematical models with Astra SDK

The software code which was used to gather data was developed with the use of Astra SDK. This is the official software development kit for Orbbec 3D sensors which was downloaded from their official website. The SDK consists of several code samples by default that can be modified to achieve different requirements of the users. As mentioned in the methodology chapter, the SDK was used to obtain joint positions in terms of X.Y and Z coordinates in the world coordinate system. When considering about the three body planes, the movements along the Coronal plane is tracked with the variation of the X coordinate. The movements along the Sagittal plane is tracked using the Y coordinate while the movements along the Transverse plane is tracked using the Z coordinate. The following code which was used to gather joint data, process data and write results into a CSV file was written in C++ language.

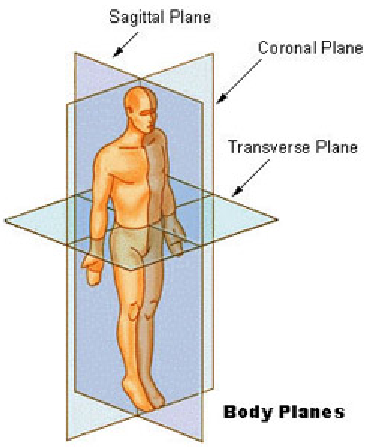

Figure 3.9: Body Planes

Obtaining joint positions

Initially three dimensional vectors are specified for each of the joints that are tracked using the device. Three dimensional vectors were initialized in this instance because the joint coordinates consists of three dimensions.

```
astra::Vector3f leftKnee {};
astra::Vector3f rightKnee{};
astra::Vector3f leftFoot{};
astra::Vector3f rightFoot{};
astra::Vector3f rightShoulder{};
astra::Vector3f rightHip{};
astra::Vector3f rightElbow{};
astra::Vector3f leftElbow{};
astra::Vector3f leftHip{};
astra::Vector3f leftShoulder{};
```

After the initialization, the joints values were assigned to these vectors using the following code. The joint stream was sent through a 'for loop' and the joint positions were assigned to specific arrays using 'if' conditionals.

```
for each (auto & joint in joints)
        {
                astra::JointType type = joint.type();
```

```
if (type == astra::JointType::LeftKnee) {
        leftKnee = joint.world_position();
}
else if(type == astra::JointType::RightKnee)
{
        rightKnee = joint.world_position();
}
else if (type == astra::JointType::LeftFoot)
{
        leftFoot = joint.world_position();
}
else if (type == astra::JointType::RightFoot)
{
        rightFoot = joint.world_position();
}
else if (type == astra::JointType::RightShoulder)
{
        rightShoulder = joint.world_position();
}
else if (type == astra::JointType::RightHip)
{
        rightHip = joint.world_position();
}
else if (type == astra::JointType::RightElbow)
{
        rightElbow = joint.world_position();
}
else if (type == astra::JointType::LeftElbow) {
        leftElbow = joint.world_position();
}
```

```
        else if (type == astra::JointType::LeftHip) {
            leftHip = joint.world_position();
        }
        else if (type == astra::JointType::LeftShoulder) {
            leftShoulder = joint.world_position();
        }
    }
```

Calculating distance between joints

The following function was used to calculate the distance between joints.

```
float calculateDistance(astra::Vector3f pos1, astra::Vector3f pos2) {
    // distance calculation logic
    float Xcord1 = pos1.x;
    float Ycord1 = pos1.y;
    float Zcord1 = pos1.z;

    float Xcord2 = pos2.x;
    float Ycord2 = pos2.y;
    float Zcord2 = pos2.z;

    float Xdiff = Xcord1 - Xcord2;
    float Ydiff = Ycord1 - Ycord2;
    float Zdiff = Zcord1 - Zcord2;

    float result1 = pow(Xdiff, 2);
    float result2 = pow(Ydiff, 2);
    float result3 = pow(Zdiff, 2);

    float result = sqrt(result1 + result2 + result3);
```

```
        return result;
}
```

The function 'calculateDistance' accepts two parameters as input which are three dimensional arrays previously initialized and assigned value to. The first two code blocks assign the X,Y and Z coordinate values to variables. The third code block calculates the difference between the coordinates in each plane and assigns them to new variables. The next code block calculates the squares of these differences and the last code block adds the squares, calculates the square root of the total and returns the value.

Calculating joint angles

Similar to the above function, another function which accepts three arrays as input for the function was used to calculate angles between the required body lines.

```
float caluculateAngle(astra::Vector3f pos1, astra::Vector3f pos2, astra::V
        //calculate angle between two lines
        float Xcord1 = pos1.x;
        float Ycord1 = pos1.y;
        float Zcord1 = pos1.z;

        float Xcord2 = pos2.x;
        float Ycord2 = pos2.y;
        float Zcord2 = pos2.z;

        float Xcord3 = pos3.x;
        float Ycord3 = pos3.y;
        float Zcord3 = pos3.z;

        float a1 = Xcord2 - Xcord1;
        float b1 = Ycord2 - Ycord1;
        float c1 = Zcord2 - Zcord1;
```

```
        float a2 = Xcord3 - Xcord2;
        float b2 = Ycord3 - Ycord2;
        float c2 = Zcord3 - Zcord2;

        float result1 = (a1*a2) + (b1*b2) + (c1*c2);
        float result2 = sqrt(pow(a1, 2) + pow(b1, 2) + pow(c1, 2));
        float result3 = sqrt(pow(a2, 2) + pow(b2, 2) + pow(c2, 2));

        float result = result1 / (result2*result3);
        float answer1 = acos(result)*(180/ 3.14159);
        float answer = 180 - answer1;
        return answer;
}
```

In the above function, the three array inputs represents the three joint locations used when calculating the angle. Pos2 represents the angle vertex while pos1 and pos3 are the joint locations which the lines will be drawn from to the angle vertex. The first three code blocks assigns the values from the three dimensional arrays to the variables. Then the differences in coordinates are calculated in the next two blocks. The final angle value is derived in the last two code blocks which performs the required mathematical operations which also includes converting the radian value to degrees.

Detecting movement off the floor

Identifying movement off the floor is required when detecting the presence or absence of heel lift. Since the heel lift movement occurs along the Sagittal plane, a simple function was used to track the Y coordinates of the ankle joint.

```
float caluculateDistancefloor(astra::Vector3f pos1) {
        float Ycord1 = pos1.y;
        return Ycord1;
```

}

Running the code and collecting data

The table 3.2 summarizes how the previously mentioned software functions are used when gathering the data related to the physical attributes when performing the overhead deep squat.

When the code is executed, a new windows is opened and the real time skeleton data is displayed along with the depth data of the surrounding environment as shown in 3.10.

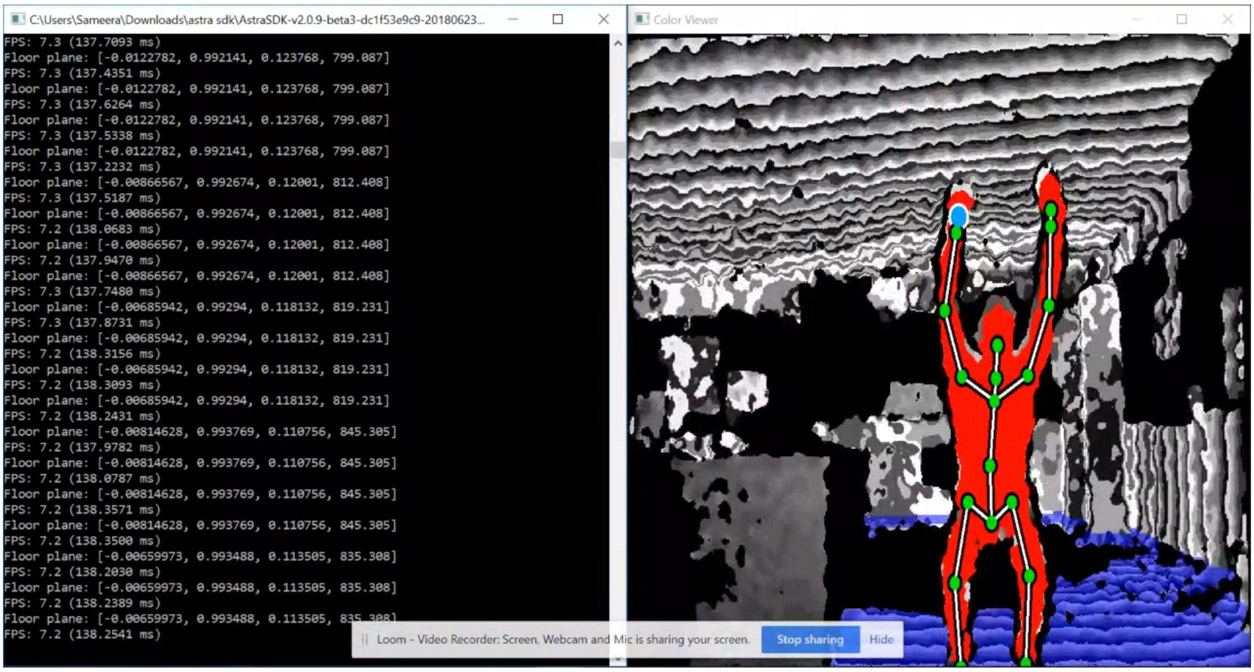

Figure 3.10: Squat position

Function	Attribute
angle between body lines	Hip angle Knee angle Arm angle
distance between joints	Distance between knees Distance between ankles
distance off the floor	Heel lift

Table 3.2: Summary of software function and related body parts

CSV file

After the code is executed, the data will be recorded to into a CSV file. The 3.3 table depicts the columns and the data values stored in each of those columns. Figure 3.11 shows how data values depicted the above mentioned table is stored in a CSV file.

Column	Data Value
1	Time
2	Distance between knees
3	Hip angle
4	Knee angle
5	Right arm angle
6	Left arm angle
7	Distance between ankles
8	Right ankle Y coordinate
9	Left ankle Y coordinate

Table 3.3: Columns and data values

3.3.2 Data Preparation

Filtering the squat movement data

Data in CSV format as shown in figure 3.11 contained all the data values from the start of the data recording till the end which includes preparation for the squat and movements after the squats. As mentioned in 3.1.4, the subjects were asked to hold their arms in a perpendicular position to their body before and after the specified squat movements. The fourth and fifth columns (right arm angle and left arm angle) in table 3.3 were used to detect this arm movement and the data prior and after the said arm movement was removed from the data set.

	A	B	C	D	E	F	G	H	I
1	Time	Knee distance (cm)	Hip Angle	Knee Angle	Right arm angle	left arm angle	ankle distance	right ankle/floor	left ankle/floor
2	1	31.4677	158.552	157.545	173.841	173.002	304.031	-1167.84	-1171.6
3	2	31.488	157.626	157.002	173.922	173.461	303.959	-1168.78	-1169.62
4	3	31.5576	156.016	156.152	174.185	173.445	303.918	-1168.76	-1164.4
5	4	31.6094	153.037	152.002	174.864	172.388	304.315	-1160.93	-1153.3
6	5	31.8032	147.331	144.852	175.097	167.851	304.555	-1146.09	-1138.14
7	6	32.5001	140.938	135.898	171.112	162.294	304.194	-1137.58	-1132.03
8	7	33.6233	133.648	126.378	164.385	161.936	303.018	-1138.36	-1138.96
9	8	34.8325	127.587	117.121	157.613	162.4	301.148	-1152.66	-1156.25
10	9	35.5223	121.694	109.866	154.835	163.087	301.544	-1177.41	-1170.31
11	10	35.7941	118.072	101.845	154.725	161.9	300.882	-1199.58	-1180.81
12	11	36.0932	114.683	94.3774	155.83	164.753	303.212	-1219.15	-1188.22
13	12	36.3119	112.669	87.1637	155.672	160.882	304.732	-1219.69	-1195.11
14	13	36.4248	109.525	81.3331	155.034	155.981	309.199	-1211.7	-1205.05
15	14	36.7626	107.308	78.0603	156.317	152.467	313.835	-1203.76	-1204.2
16	15	36.8357	109.663	81.1513	150.957	148.758	318.621	-1205.16	-1198.09
17	16	36.5796	112.001	88.2676	156.13	151.906	321.884	-1218.97	-1199.53
18	17	35.4389	117.228	98.0788	147.879	155.915	323.895	-1214.85	-1205.23
19	18	34.2635	119.15	109.008	149.059	159.512	326.387	-1203.21	-1196.37
20	19	33.5104	120.999	116.373	152.174	159.027	326.646	-1186.81	-1181.77
21	20	32.8399	124.033	123.794	155.399	160.531	323.208	-1163.47	-1157
22	21	32.1509	129.243	131.347	157.154	158.982	313.059	-1145.13	-1137.86
23	22	31.5934	133.099	137.233	161.364	161.218	304.1	-1136.68	-1127.74
24	23	31.2799	137.106	142.835	165.26	164.513	301.412	-1128.44	-1124.77
25	24	31.2774	140.738	148.391	167.794	170.123	302.377	-1124.81	-1124.49
26	25	31.4317	143.864	152.697	167.356	169.917	303.871	-1127.73	-1130.75
27	26	31.4536	147.649	157.798	167.058	170.725	305.978	-1130.28	-1131.64
28	27	31.4646	150.4	161.858	167.32	169.563	306.99	-1128.77	-1130.24
29	28	31.4336	152.024	162.84	168.168	168.015	306.497	-1128.04	-1128.76
30	29	31.352	152.933	162.509	169.162	166.268	304.648	-1125.84	-1128.03
31	30	31.2628	153.661	162.139	169.074	165.447	302.374	-1123.79	-1127.31
32	31	31.2399	153.905	161.518	168.545	164.243	301.559	-1122.17	-1125.68
33	32	31.322	153.013	160.225	169.057	165.414	301.339	-1123.06	-1125.45
34	33	31.5332	151.726	157.461	167.51	166.314	301.463	-1125.46	-1126.56
35	34	31.8258	148.355	152.273	166.338	166.935	301.648	-1124.82	-1122.13
36	35	32.6536	143.61	144.969	164.136	167.75	302.185	-1129.34	-1120.6
37	36	33.4118	138.04	137.533	157.949	162.691	303.101	-1128.41	-1118.74

Figure 3.11: CSV file sample

Splitting of data files

Analysis and the calculation of threshold values were done based on a single squat for all the subjects (one squat represents one subject). However, the data file contains data of five squats in sequence. A single data file was split into five files based on the knee angle and hip angle columns. Both knee and hip angles have a value which is approximately equal to 180 degrees prior to the starting of the squat and gradually decreases when the squat is performed. The angle values gradually increase again when the subject stand up from the squat position. This pattern was identified and the original data files were marked to indicate the starting and ending point of each squat. The file was read and split into five new files (each containing the data of a single squat) using a python script (see appendix).

Scaling of data

When the original data file was split, it was split based on the knee and hip angle values and not based on the time column. Therefore for a single subject, the time duration taken for each of the five squats varied slightly as the subject cannot perform all five squats at a precisely uniform speed. Therefore, the data had to be rescaled based on the time column which would be used as X axis when analyzing data later in the study. The time column was rescaled into hundred units for each squat and the remaining columns were recalculated using the following equation. The formula for the rescaling is denoted by (1). The rescaling of all the files were done using a python script(see appendix).

$$Y_3 = (X_3 - X_2)/(X_1 - X_2) + Y_2 \longrightarrow (1)$$

Y_3 - New data value to be found

X_3 - Time value of Y_3

X_1 and X_2 - Adjacent time values in the original file

Y_1 and Y_2 - Adjacent data values in the original file.

Averaging data files

After splitting and scaling of data files there are five CSV files for each subject, each file containing data of a single squat. This means that for each value in the time column, there are five values in in each of the other columns. In this step all files were averaged together and a single file was created for each subject. After taking the average values, the distance columns in the data set (column 2, column 7, column 8 and column 9) were edited so that the column starts with value 0 and varies from that point onward along the time axis. This was also done using a python script (see appendix).

Removing of outliers

As mentioned in section 3.1.3, there were two groups of sample recorded in the study; control group and the test group. The data from the control group was used to define the generic minimum and maximum threshold values. However prior to further analysis with the objective creating the said thresholds, it is important to remove any outliers in the control group sample.

To remove outliers, box plots were used. For each of the five measures (distance between knees, distance between ankles, heel lift from the floor, arm angle and angle difference between hip and knee) five box plots were created based on five points along the time axis. As such 25 box plots were created for male subjects and 25 were created for female subjects. Three data files were removed corresponding to two male subjects and one female subject based on box plots generated.

Chapter 4

Results and Evaluation

4.1 Clinically acceptable graphs creation

The categorization of healthy samples were done based on each of compensations that were observed in the overhead squat in the context of physiotherapy. As discussed in the previous chapter, there are mainly six compensations focused in this study, which can be categorized into 5 pattern analyses as knee distance variation, ankle distance variation, shoulder angle variation, hip and knee angle difference variation, variation of the heel lift from the floor. For each of these categories, a separate healthy sample was selected to carry out the analysis. As discussed in the previous chapter, each subject completed a total of 5 squats and the average was taken of these 5 when deriving the maximum and minimum threshold value patterns. The clinically acceptable movement patterns were created by fitting the maximum and minimum value curves with 6th order polynomial equation. These graphs can be used as the model to compare values of new athletes to identify imbalanced movement patterns with respect to each compensation observed.

4.1.1 Anterior view compensations; Knee valgus and knee varus

The above compensations are quantified using how the distance between right and left knee varies in the span of a single squat cycle. We have identified 20 subjects with no compensations observed by the domain expert. The distribution of the sample of healthy athletes for the anterior view are listed in Table 4.1. The generic graphs creation was done as described above. Ideally the distance between the knees should not change during the overhead squat. Thus the difference should amount to 0. However, in the sample selected as healthy by the domain expert the minimum distance difference takes a positive value. Thus, only the subject graphs which containing negative values are considered as having knee valgus compensation, not the graphs below the minimum threshold. This is a special behavior observed in the anterior view due to the fact that the sample not having subjects who can perform an ideal squat.

Males	Females	Total
10	10	20

Table 4.1: Healthy Subjects for Knee valgus and knee varus

Min and Max threshold for Males

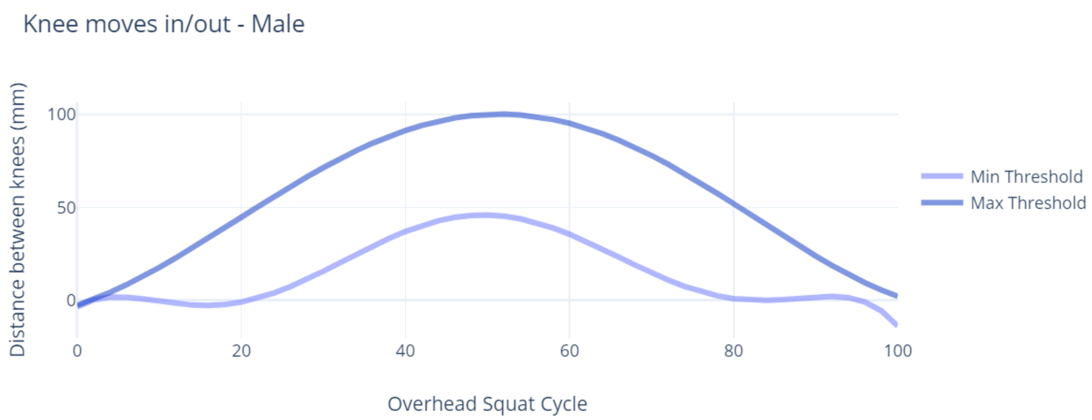

Figure 4.1: Minimum and maximum threshold values in Knee distance variation of an healthy male athlete

Two equations were generated to fit the maximum and minimum patterns with 6th order polynomial curve. The 6th degree polynomial regression was selected as it generates the R-squared value that is closest to 1, which suggests a good fit for the observed pattern. Figure 4.1 shows the minimum and maximum threshold variation for knee distance along a single squat cycle for males.

Equation for knee distance maximum curve - male : $y = -2.60E + 00 + 1.48E + 00x + 6.46E - 02x^2 - 8.47E - 04x^3 - 1.19E - 05x^4 + 1.78E - 07x^5 - 5.32E - 10x^6$

The R-squared value generated for the above equation is 0.9923945161. Since it's very closer to 1, this can be concluded as the best fitting curve for the observed values.

Equation for knee distance minimum curve - male : $y = -3.53E + 00 + 2.69E + 00x - 4.24E - 01x^2 + 2.30E - 02x^3 - 4.96E - 04x^4 + 4.63E - 06x^5 - 1.57E - 08x^6$

Similarly the R-squared value can be generated for the minimum curve as well which is 0.9661317264. Since it's very closer to 1, this can be concluded as the best fitting curve for the observed values.

Min and Max threshold for Females

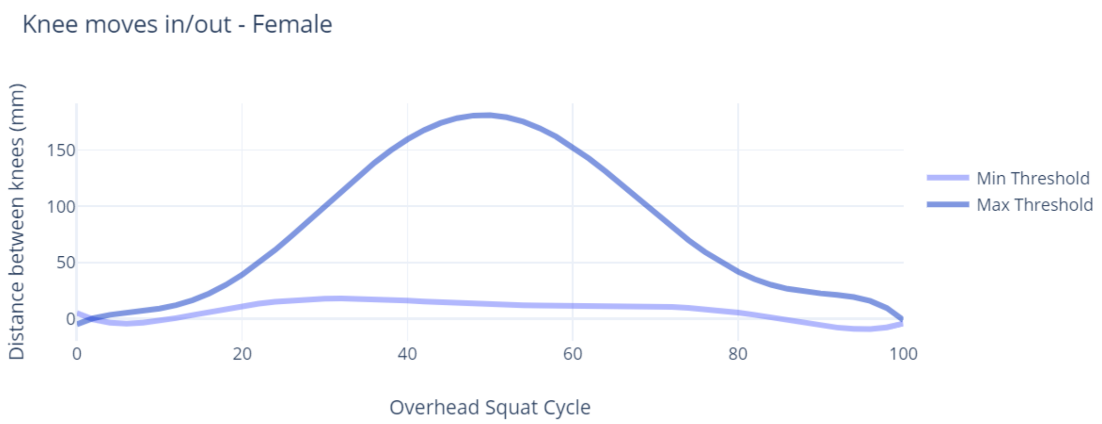

Figure 4.2: Minimum and maximum threshold values in Knee distance variation of an healthy female athlete

Equation for knee distance maximum curve - female : $y = -4.65E + 00 + 3.50E + 00x - 4.75E - 01x^2 + 3.37E - 02x^3 - 8.04E - 04x^4 + 7.77E - 06x^5 - 2.66E - 08x^6$

The R-squared value generated for the above equation is 0.9963832761. Since it's very closer to 1, this can be concluded as the best fitting curve for the observed values.

Equation for knee distance minimum curve - female : $y = 5.19E+00-3.60E+00x+4.36E-01x^2 - 1.73E - 02x^3 + 3.14E - 04x^4 - 2.68E - 06x^5 + 8.72E - 09x^6$

Similarly the R-squared value can be generated for the minimum curve as well which is 0.94225849. Since it's very closer to 1, this can be concluded as the best fitting curve for the observed values. Figure 4.2 shows the minimum and maximum threshold variation for knee distance along a single squat cycle for females.

4.1.2 Lateral view compensations; Excessive forward lean

Excessive forward lean is the first compensation observed in the lateral view. The graphs are generated by comparing the knee angle and the respective hip angle to observe if those two angles are aligned. Since these angles needs to be equal or nearly equal to each other, the difference of these two angles (Hip angle - Knee Angle) are taken into consideration when creating the acceptable movement pattern. Total number of 20 male and female athletes were taken as the healthy sample for the graph generation. The subject distribution is showed in table 4.2.

Males	Females	Total
10	10	20

Table 4.2: Healthy Subjects for excessive forward lean

Min and Max threshold for Males

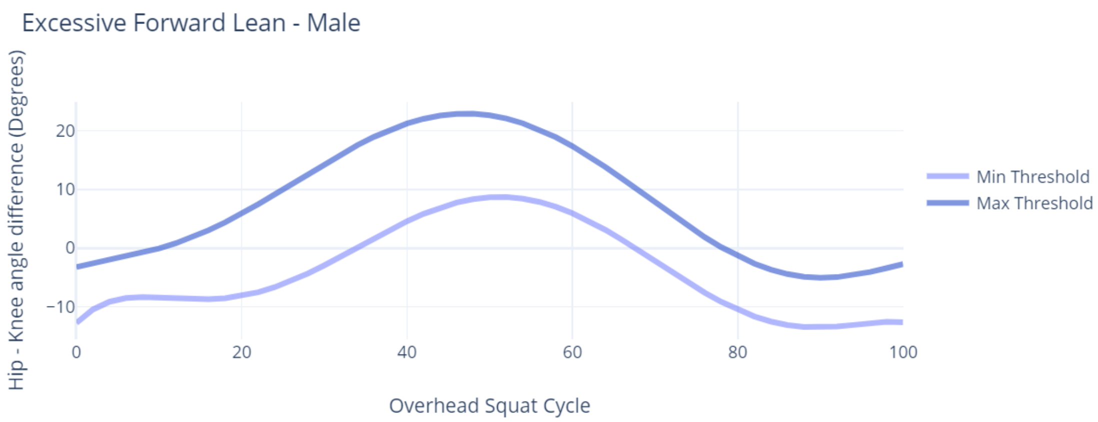

Figure 4.3: Hip and knee angle difference variation of an average healthy male athlete

Equation for excessive forward lean maximum curve - male : $y = -3.26E + 00 + 3.78E - 01x - 2.63E - 02x^2 + 2.66E - 03x^3 - 7.04E - 05x^4 + 6.93E - 07x^5 - 2.33E - 09x^6$

The R-squared value generated for the above equation is 0.9967426569. Since it's very closer to 1, this can be concluded as the best fitting curve for the observed values.

Equation for excessive forward lean minimum curve - male : $y = -1.28E + 01 + 1.45E + 00x - 1.66E - 01x^2 + 7.89E - 03x^3 - 1.57E - 04x^4 + 1.36E - 06x^5 - 4.32E - 09x^6$

Similarly the R-squared value can be generated for the minimum curve as well which is 0.9916375561. Since it's very closer to 1, this can be concluded as the best fitting curve for the observed values. Figure 4.3 shows the minimum and maximum threshold variation for hip and knee angle difference along a single squat cycle for males.

Min and Max threshold for Females

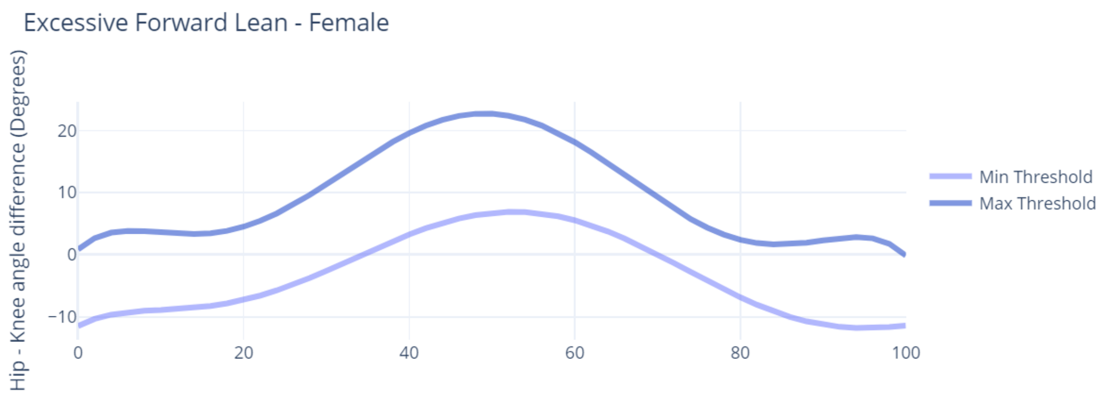

Figure 4.4: Hip and knee angle variation of an average healthy Female athlete

Equation for excessive forward lean maximum curve - female : $y = 8.76E-01 + 1.19E+00x - 1.60E-01x^2 + 8.52E-03x^3 - 1.83E-04x^4 + 1.69E-06x^5 - 5.68E-09x^6$

The R-squared value generated for the above equation is 0.9827946496. Since it's very closer to 1, this can be concluded as the best fitting curve for the observed values.

Equation for excessive forward lean minimum curve - female : $y = -1.15E+01 + 7.04E-01x - 7.64E-02x^2 + 3.91E-03x^3 - 7.88E-05x^4 + 6.73E-07x^5 - 2.06E-09x^6$

Similarly the R-squared value can be generated for the minimum curve as well which is 0.9721368409. Since it's very closer to 1, this can be concluded as the best fitting curve for the observed values. Figure 4.4 shows the minimum and maximum threshold variation for hip and knee angle difference along a single squat cycle for females.

4.1.3 Lateral view compensations; Arms falling forward

The second compensations observed in the Lateral view is Arms falling forward. Total number of 14 males and 8 females were taken as the healthy sample for the graph generation as listed in 4.3. Each subject has done a series of 5 squats, which result in overall 70 squats for male category and 40 squats for female category. As mentioned before, a healthy athlete's arms are extended straight up along the line of the spine throughout the overhead squat. Thus, the variation in the shoulder angle was considered when identifying if the arms fall forward during the span of a squat. Minimum and maximum threshold values are generated from the healthy sample of subjects.

Males	Females	Total
14	8	22

Table 4.3: Subject distribution for Arms falling forward

Min and Max threshold for Males

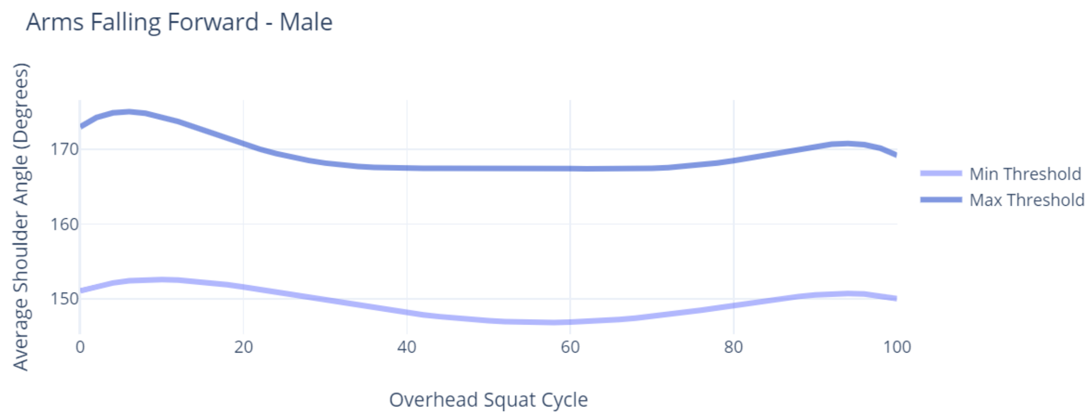

Figure 4.5: Shoulder angle variation of an average healthy male athlete

Equation for Arms falling forward maximum curve - male : $y = 1.73E + 02 + 8.05E - 01x - 9.84E - 02x^2 + 3.72E - 03x^3 - 6.54E - 05x^4 + 5.49E - 07x^5 - 1.77E - 09x^6$

The R-squared value generated for the above equation is 0.9445507344. Since it's very closer to 1, this can be concluded as the best fitting curve for the observed values.

Equation for Arms falling forward minimum curve - male : $y = 1.51E + 02 + 3.60E - 01x - 2.67E - 02x^2 + 6.38E - 04x^3 - 8.26E - 06x^4 + 6.44E - 08x^5 - 2.26E - 10x^6$

Similarly the R-squared value can be generated for the minimum curve as well which is 0.915849. Since it's very closer to 1, this can be concluded as the best fitting curve for the observed values. Figure 4.5 illustrates the maximum and minimum threshold variation for shoulder angle along a single squat cycle for males.

Min and Max threshold for females

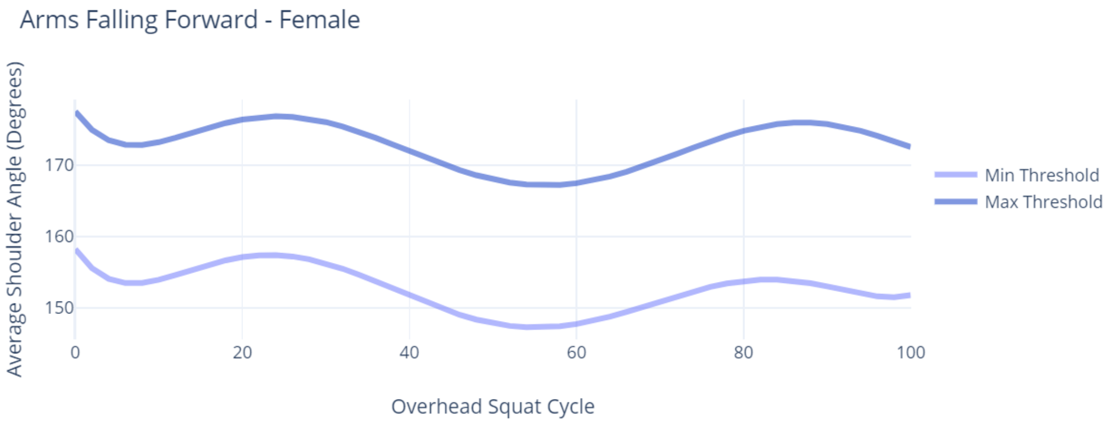

Figure 4.6: Shoulder angle variation of an average healthy female athlete

Equation for Arms falling forward maximum curve - female : $y = 1.77E + 02 - 1.61E + 00x + 1.79E - 01x^2 - 7.20E - 03x^3 + 1.28E - 04x^4 - 1.02E - 06x^5 + 3.05E - 09x^6$

The R-squared value generated for the above equation is 0.9043439409. Since it's very closer to 1, this can be concluded as the best fitting curve for the observed values.

Equation for Arms falling forward minimum curve - female : $y = 1.58E+02-1.69E+00x+1.94E - 01x^2 - 8.13E - 03x^3 + 1.50E - 04x^4 - 1.26E - 06x^5 + 3.05E - 09x^6$

Similarly the R-squared value can be generated for the minimum curve as well which is 0.9160786944. Since it's very closer to 1, this can be concluded as the best fitting curve for the observed values. Figure 4.6 illustrates the maximum and minimum threshold variation for shoulder angle along a single squat cycle for females.

4.1.4 Posterior view compensations; Foot Flattening (Ankle moves in)

Ankle movement is the first compensation observed in the Posterior view. How the distance between the two ankle joints varies in the span of a single overhead squat was taken for graph creation. Total number of 19 males and females were taken as the healthy sample for the graph generation as shown in table 4.4.

Males	Females	Total
11	8	19

Table 4.4: Subject distribution for Ankle movements

Min and Max threshold for Males

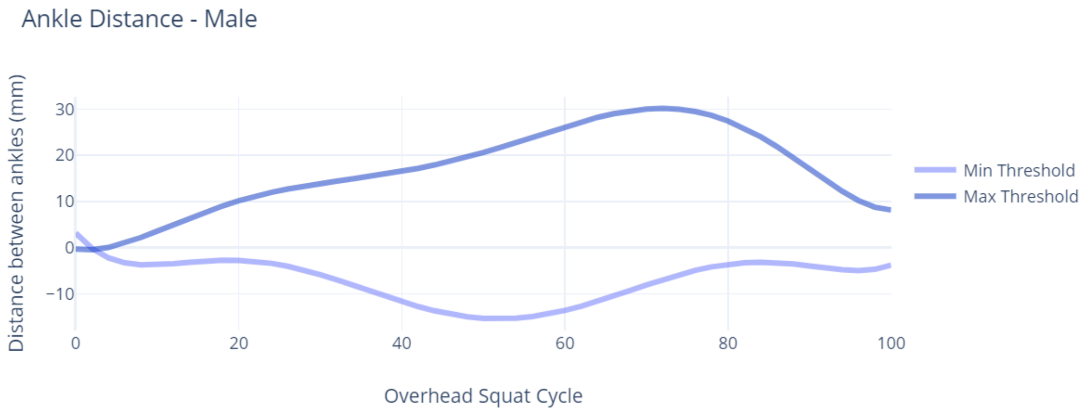

Figure 4.7: Ankle distance variation of an average healthy male athlete

Equation for Ankle distance maximum curve - male : $y = -3.15E-01 - 2.80E-01x + 1.10E-01x^2 - 5.37E-03x^3 + 1.14E-04x^4 - 1.09E-06x^5 + 3.05E-09x^6$

The R-squared value generated for the above equation is 0.9495333136. Since it's very closer to 1, this can be concluded as the best fitting curve for the observed values.

Equation for Ankle distance minimum curve - male : $y = 3.13E+00-2.05E+00x+2.11E-01x^2 - 9.09E-03x^3 + 1.74E-04x^4 - 1.50E-06x^5 + 3.05E-09x^6$

Similarly the R-squared value can be generated for the minimum curve as well which is 0.8891735616. Since it's very closer to 1, this can be concluded as the best fitting curve for the observed values. Figure 4.7 depicts the variation of the minimum and maximum thresholds for distance between ankles for male athletes.

Min and Max threshold for Females

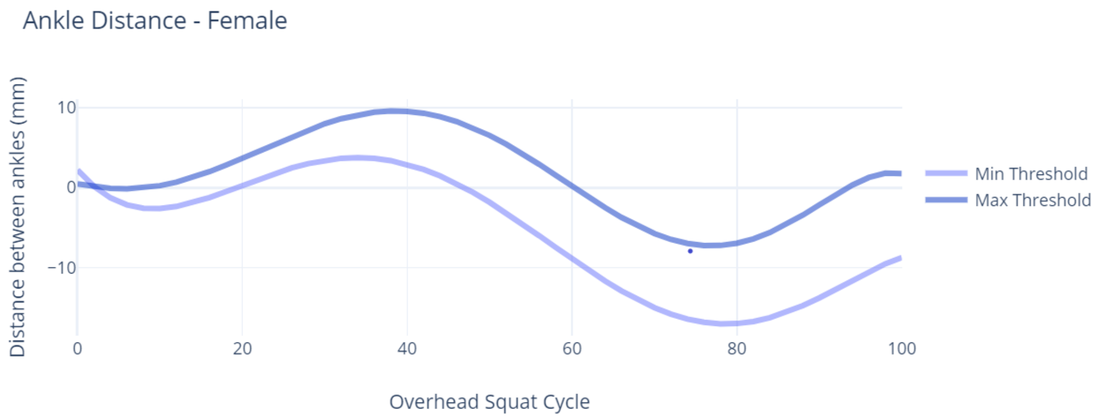

Figure 4.8: Ankle distance variation of an average healthy female athlete

Equation for Ankle distance maximum curve - female : $y = 4.65E - 01 - 1.99E - 01x + 1.14E - 02x^2 + 1.01E - 03x^3 - 4.44E - 05x^4 + 5.50E - 07x^5 - 2.17E - 09x^6$

The R-squared value generated for the above equation is 0.9789519364. Since it's very closer to 1, this can be concluded as the best fitting curve for the observed values.

Equation for Ankle distance minimum curve - female : $y = 2.20E + 00 - 1.21E + 00x + 9.25E - 02x^2 - 2.13E - 03x^3 + 1.32E - 05x^4 + 5.41E - 08x^5 - 5.52E - 10x^6$

Similarly the R-squared value can be generated for the minimum curve as well which is 0.9523222569. Since it's very closer to 1, this can be concluded as the best fitting curve for the observed values. Figure 4.8 depicts the variation of the minimum and maximum thresholds for distance between ankles for female athletes.

4.1.5 Posterior view compensations; Heel lift

The second compensations observed in the Posterior view is the Heel lift. It is observed when either of the heels lift from the ground during the squat. It is calculated as the distance between ankle joints and the floor plane. Total number of 24 males and females were taken as the healthy sample for the graph generation as shown in table 4.5.

Males	Females	Total
13	11	24

Table 4.5: Subject distribution for heel lift

Min and Max threshold for Males

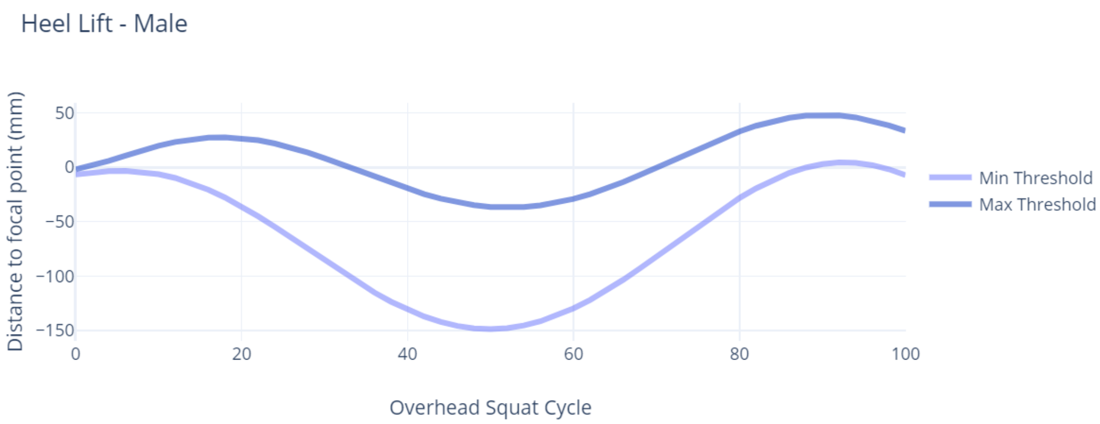

Figure 4.9: Heel lift variation of an average healthy male athlete

Equation for heel lift maximum curve - male : $y = -1.99E + 00 + 1.30E + 00x + 2.22E - 01x^2 - 1.71E - 02x^3 + 3.78E - 04x^4 - 3.35E - 06x^5 + 3.05E - 09x^6$

The R-squared value generated for the above equation is 0.9839251249. Since it's very closer to 1, this can be concluded as the best fitting curve for the observed values.

Equation for heel lift minimum curve - male : $y = -6.81E + 00 + 1.03E + 00x - 3.33E - 02x^2 - 9.22E - 03x^3 + 2.85E - 04x^4 - 2.82E - 06x^5 + 3.05E - 09x^6$

Similarly the R-squared value can be generated for the minimum curve as well which is 0.9919761604. Since it's very closer to 1, this can be concluded as the best fitting curve for the observed values. Figure 4.9 depicts the variation of the minimum and maximum thresholds for heel lift from the floor for male athletes.

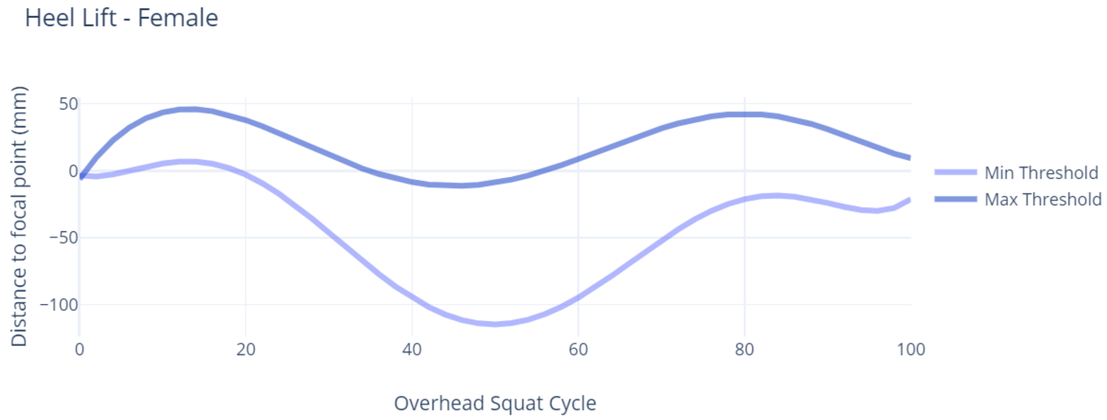

Figure 4.10: Heel lift variation of an average healthy athlete

Min and Max threshold for Female

Equation for heel lift maximum curve - female : $y = -6.32E + 00 + 8.95E + 00x - 4.53E - 01x^2 + 5.09E - 03x^3 + 5.79E - 05x^4 - 1.30E - 06x^5 + 5.76E - 09x^6$

The R-squared value generated for the above equation is 0.9719790921. Since it's very closer to 1, this can be concluded as the best fitting curve for the observed values.

Equation for heel lift minimum curve - female : $y = -3.56E + 00 - 1.23E + 00x + 4.75E - 01x^2 - 3.35E - 02x^3 + 7.84E - 04x^4 - 7.52E - 06x^5 + 2.57E - 08x^6$

Similarly the R-squared value can be generated for the minimum curve as well which is 0.9876781924. Since it's very closer to 1, this can be concluded as the best fitting curve for the observed values. Figure 4.10 depicts the variation of the minimum and maximum thresholds for heel lift from the floor for female athletes.

4.2 Data Evaluation of the Test Sample

The test sample contained male and female athletes that were randomly selected as mentioned in the methodology chapter. A graph comparison was done using the previously generated generic graphs and graphs generated for each compensation category for each subject in the test sample. Total of 41 subjects were included in the sample, but data records of 4 female subjects were discarded because the data files were incomplete due to device errors when recording. 23 males and 14 females were finalized as the test sample for the evaluation as shown in table 4.6.

Males	Females	Total
23	15	37

Table 4.6: Subject distribution of test sample

For each of the joint measurement values collected, graphs were generated against the overhead squat cycle percentage. It was then compared against the maximum and minimum threshold values of corresponding joint measurement (compensation category). If the graph generated for the subject is within the threshold graphs, that person is marked as not having that particular compensation while if the subject graph deviates from the threshold values, it is concluded that subject is having an imbalance in the relevant muscle groups responsible for the compensation. Following are example of graph comparison with respect to each compensation category.

4.2.1 Knee valgus and Knee varus

If the subject graph lies outside (higher than) the maximum threshold graph, it can be concluded as the subject having the knee varus compensation. If the subject graph is lower than the minimum threshold graph, the knee valgus compensation is present in the concerning subject. If these compensations are detected from the graph comparison, the potential overractive and underractive muscle groups responsible for that imbalance can be identified as in the Table 4.7 as per National Academy of Sports Medicine,USA [59].

As shown in the figure 4.11, Subject 19 has knee distance variation graph within the defined maximum and minimum threshold graphs. According to the graph comparison, the subject does not show any imbalance in the knee joint.

The knee distance variation graph of Subject 02 as shown in figure 4.12 has deviated exceeding the maximum threshold graph which means the subject has knee varus compensation.

Figure 4.13 shows how knee distance variates in example healthy female subject.

Compensation	Overractive Muscle Groups	Underractive Muscle Groups
Knee Valgus	Hip Adductors Lateral Gastrocnemius Biceps Femoris (short head) Tensor Fascia Latae Vastus Lateralis	Medial Gastrocnemius Medial Hamstrings Gluteus Maximus Vasus Medialis
Knee Varus	Piriformis Biceps Femoris Gluteus Minimus Tensor Fascia Latae	Adductor Complex Gluteus Maximus Medial Hamstrings

Table 4.7: Potential Overactive and Underactive muscles related to Knee valgus and Knee varus

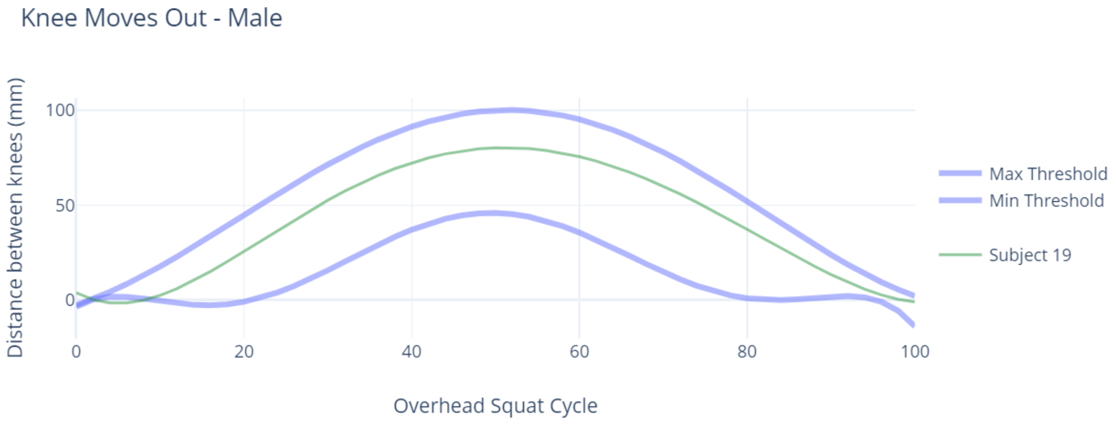

Figure 4.11: Knee distance variation of a healthy male athlete

Figure 4.12: Knee distance variation of an imbalanced male athlete

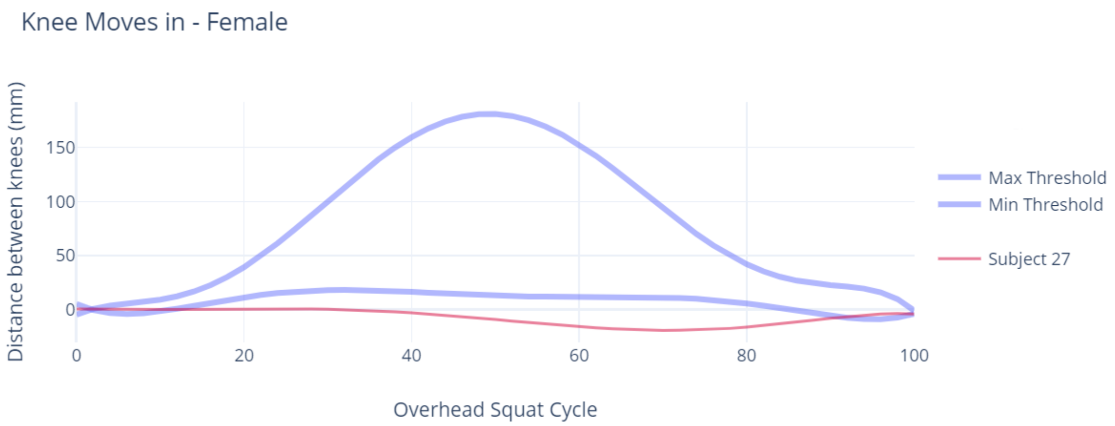

Figure 4.14: Knee distance variation of an imbalanced female athlete

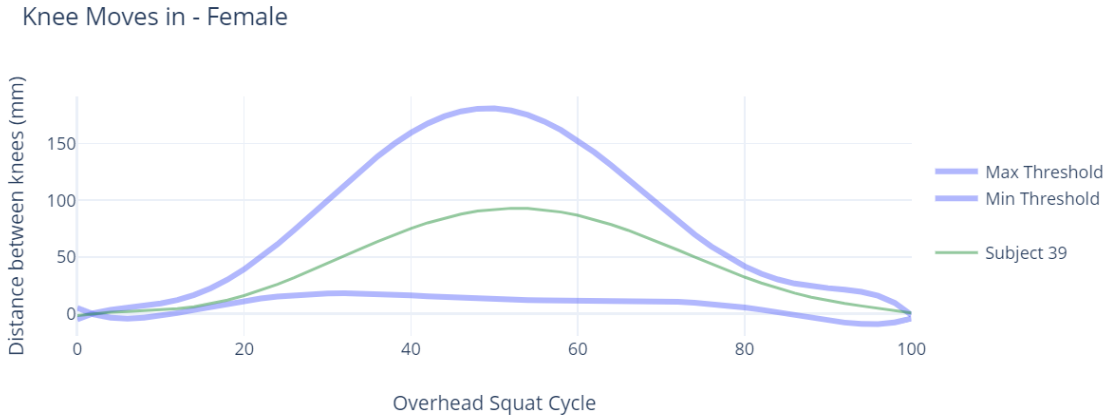

Figure 4.13: Knee distance variation of a healthy female athlete

Subject 27 shows knee valgus compensation since the knee distance variation graph lies underneath the minimum threshold graph represented in figure 4.14.

4.2.2 Excessive forward lean

The subject graph is created by taking the difference of hip angle and knee angle. If the difference is a positive value (hip angle - knee angle > 0), it means that the subject's back and shin (lower leg) are not in parallel lines as it should be. If the difference is a negative value (hip angle - knee angle < 0), the subject is having the excessive forward lean compensation. If these compensations are detected from the graph comparison, the potential overractive and underractive muscle groups responsible for that imbalance can be identified as in the Table 4.8 as per National Academy of Sports Medicine,USA [59].

Compensation	**Overractive Muscle Groups**	**Underractive Muscle Groups**
Excessive Forward Lean	Soleus Gastrocnemius Hip Flexors Abdominal Complex	Anterior Tibialis Gluteus Maximus Erector Spinae

Table 4.8: Potential Overactive and Underactive muscles related to Excessive Forward Lean

As shown in the figure 4.15, Subject 13 has the hip - knee difference graph within the defined maximum and minimum threshold graphs. According to the graph comparison, the subject does not show the excessive forward lean compensation.

The hip - knee difference graph of Subject 22 as shown in figure 4.16 has deviated going under the minimum threshold graph which means the subject's knee angle is larger

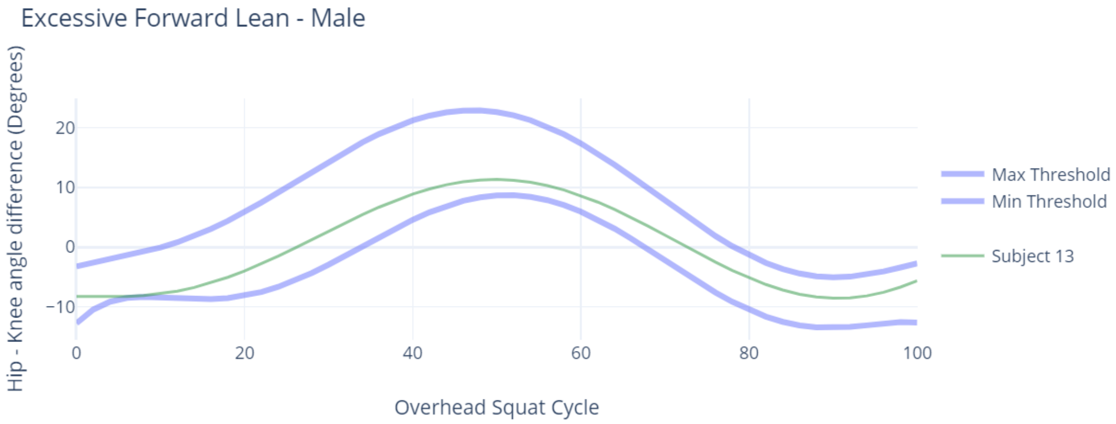

Figure 4.15: Hip and Knee angle difference of a healthy male athlete

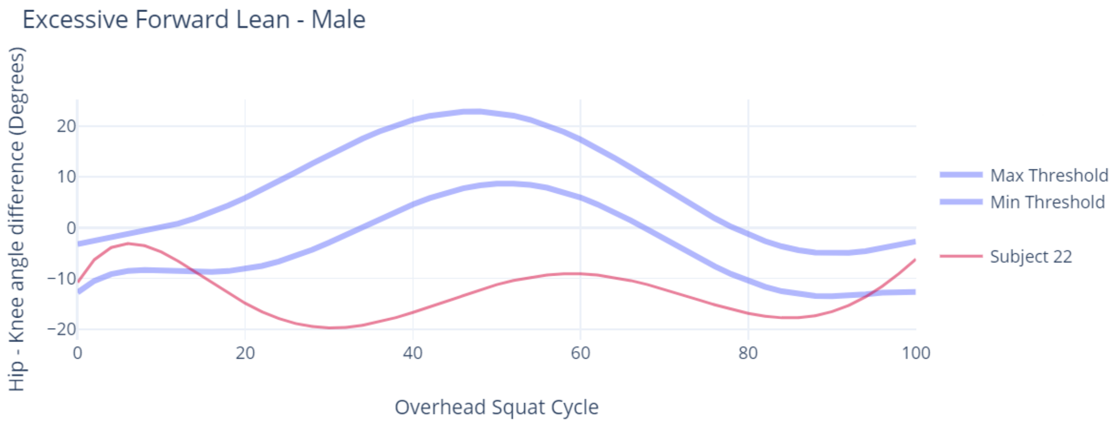

Figure 4.16: Hip and Knee angle difference of an imbalanced male athlete

than hip angle when performing the overhead squat. It concludes as the subject having the excessive forward lean compensation.

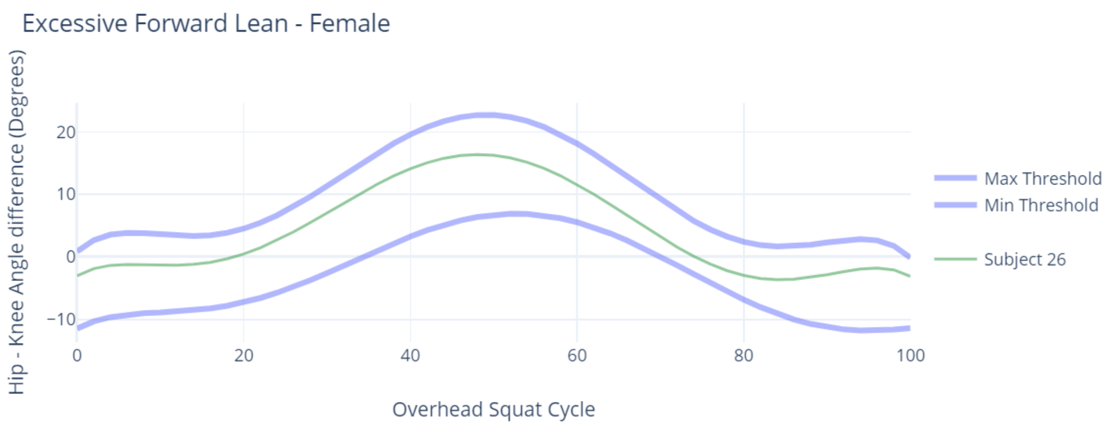

Figure 4.17: Hip and Knee angle difference of a healthy female athlete

Figure 4.17 shows how hip - knee difference variates in an example healthy female subject. Figure 4.18 shows how an imbalanced female subject's graph deviates from the threshold values.

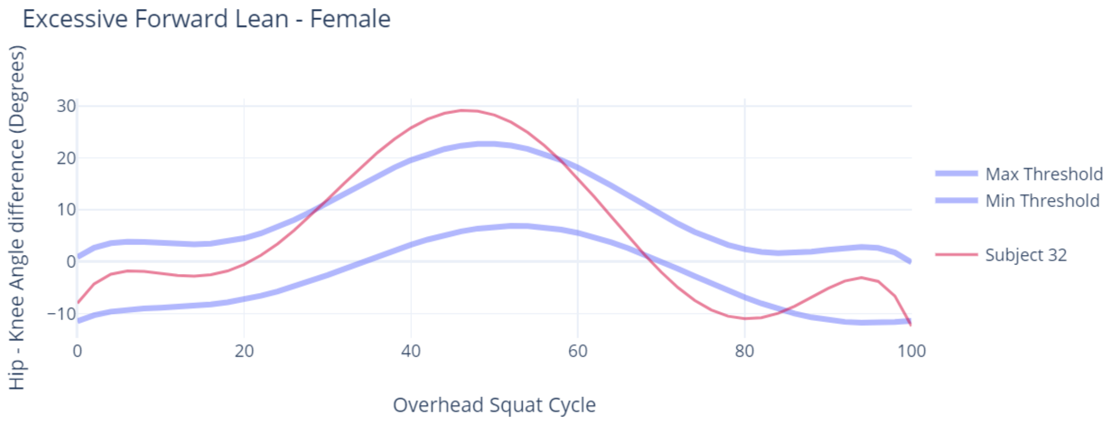

Figure 4.18: Hip and Knee angle difference of an imbalanced female athlete

4.2.3 Arms falling forward

The subject graph is created by taking the shoulder angle when the arms are extended at the start of the overhead squat. If the subject graph lies lower than the defined minimum threshold that means the shoulder angle is lower than a healthy athlete's. It can be concluded as the subject having the Arms falling forward compensation. If this compensation is detected from the graph comparison, the potential overractive and underractive muscle groups responsible for that imbalance can be identified as in the Table 4.9 as per National Academy of Sports Medicine,USA[59].

Compensation	Overactive Muscle Groups	Underractive Muscle Groups
Arms falling forward	Latissimus Dorsi Pectoralis Major Pectoralis Minor Teres Major Coracobrachialis	Middle Trapezius Lower Trapezius Rhomboids Posterior Deltoid Rotator Cuff

Table 4.9: Potential Overactive and Underactive muscles related to Arms falling forward

As shown in the figure 4.19, subject 15 has the hip - knee difference graph within the defined maximum and minimum threshold graphs. According to the graph comparison, the subject does not show the Arms falling forward compensation.

The shoulder angle variation graph of Subject 02 as shown in figure 4.20 has deviated going under the minimum threshold graph which means the subject's shoulder angle is less than the defined healthy minimum angle when performing the overhead squat. It concludes as the subject having the Arms falling forward compensation.

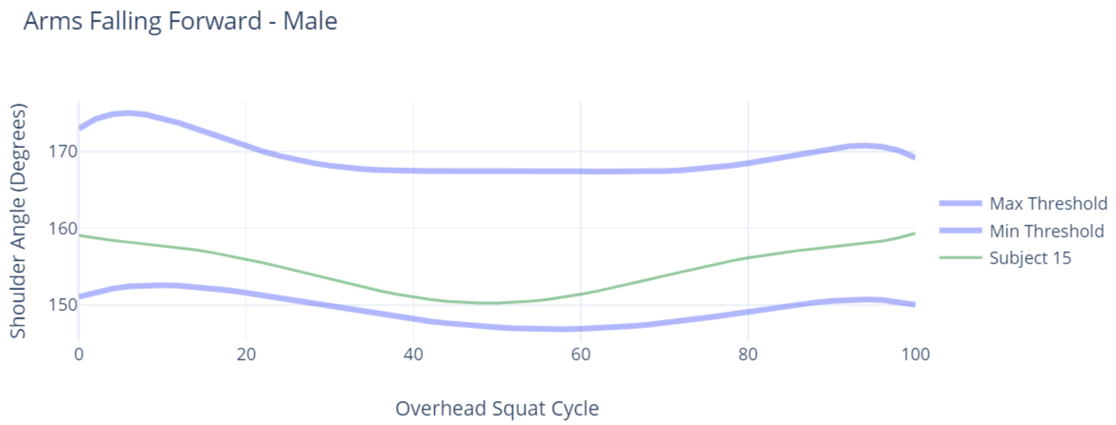

Figure 4.19: Shoulder angle variation of a healthy male athlete

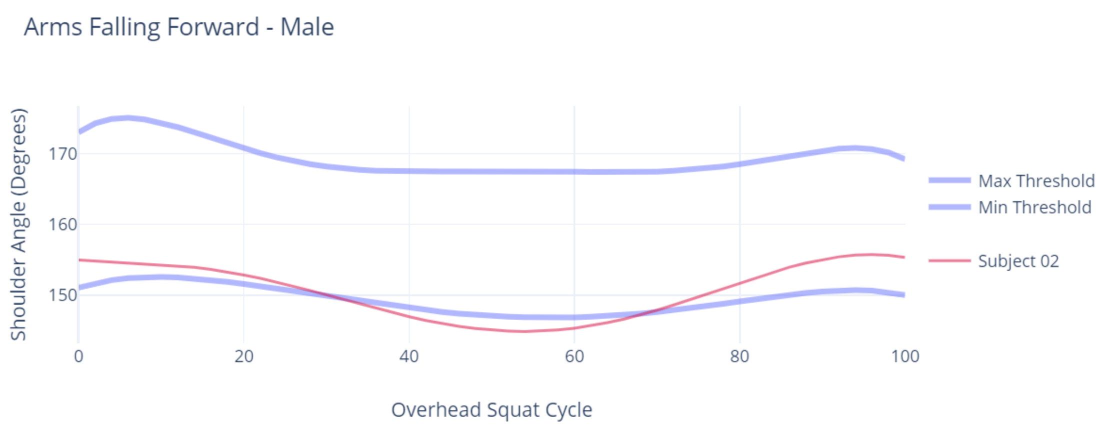

Figure 4.20: Shoulder angle variation of an imbalanced male athlete

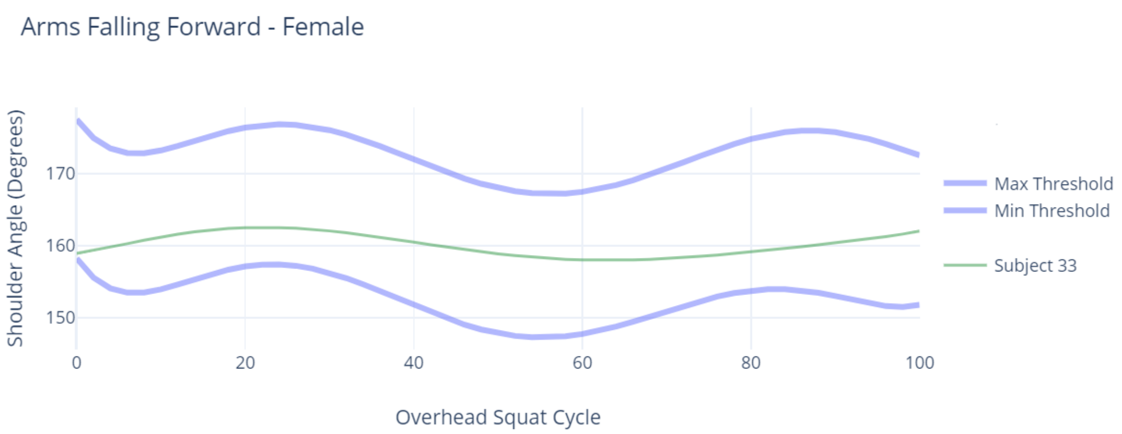

Figure 4.21: Shoulder angle variation of a healthy female athlete

Figure 4.21 shows the shoulder angle variates in an example healthy female subject. Figure 4.22 shows how an imbalanced female subject's graph deviates from the threshold values.

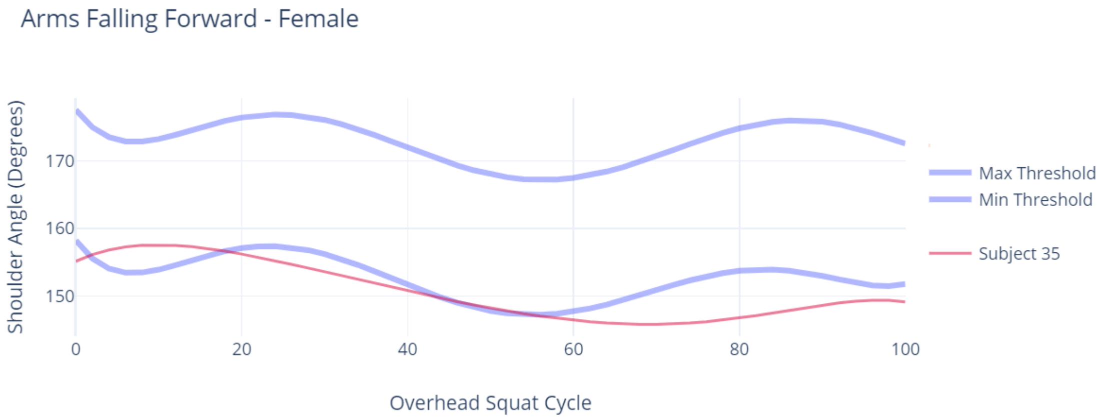

Figure 4.22: Shoulder angle variation of an imbalanced female athlete

4.2.4 Foot Flattening (Ankle moves in)

The subject graph is created by taking the distance between ankle positions during overhead squat cycle. If the subject graph lies lower than the defined minimum threshold that means the subject's ankles move in during the squat. It can be concluded as the subject having the foot flattening compensation. If this compensation is detected from the graph comparison, the potential overractive and underractive muscle groups responsible for that imbalance can be identified as in the Table 4.10 as per National Academy of Sports Medicine,USA [59].

Compensation	Overractive Muscle Groups	Underractive Muscle Groups
Foot Flattening	Peroneus Major Peroneus Tertius Lateral Gastrocnemius Biceps Femoris Tensor Fascia Latae	Posterior Tibialis Anterior Tibialis Medial Gastrocnemius Gluteus Medius

Table 4.10: Potential Overactive and Underactive muscles related to Foot Flattening

As shown in the figure 4.23, Subject 12 has the ankle distance variation graph within the defined maximum and minimum threshold graphs. According to the graph comparison, the subject does not show the foot flattening compensation.

The ankle distance variation graph of Subject 18 as shown in figure 4.24 has deviated from the defined threshold graphs which means the subject's ankle moves outside when performing the overhead squat. It concludes as the subject 18 having the foot flattening compensation.

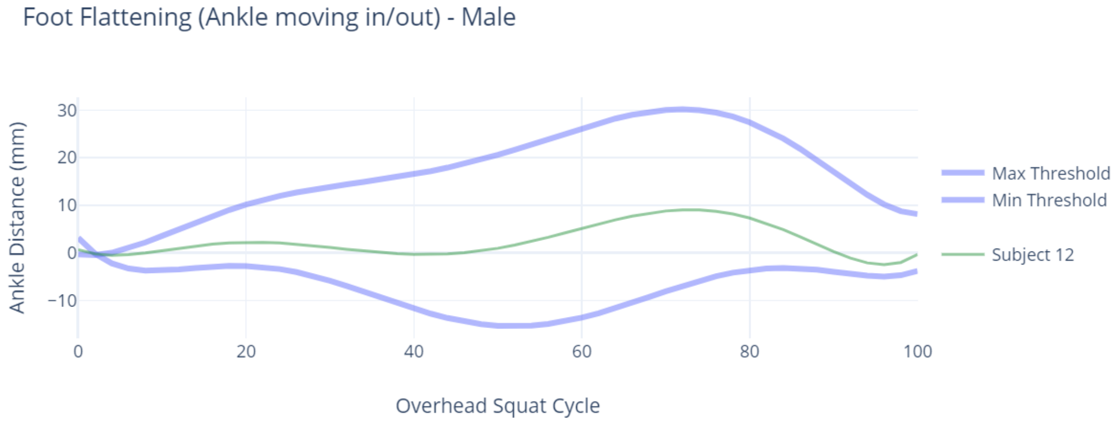

Figure 4.23: Ankle distance variation of a healthy male athlete

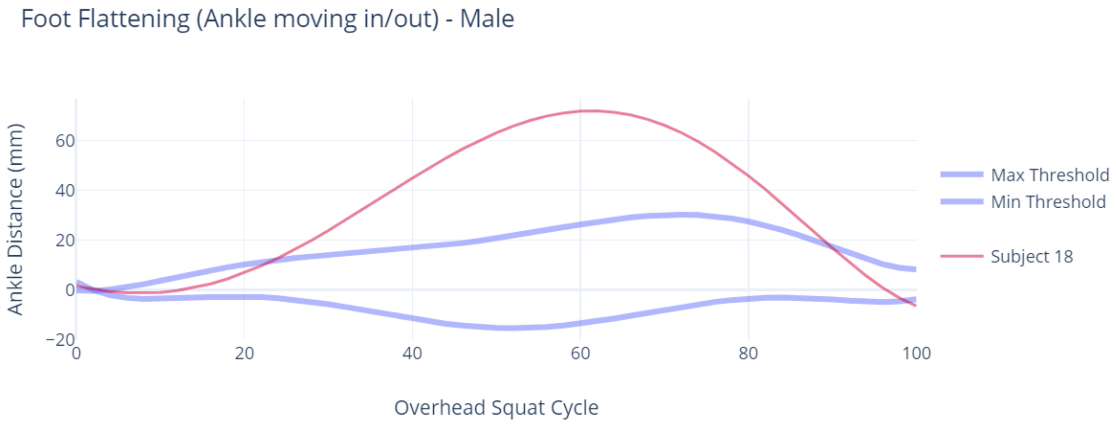

Figure 4.24: Ankle distance variation of an imbalanced male athlete

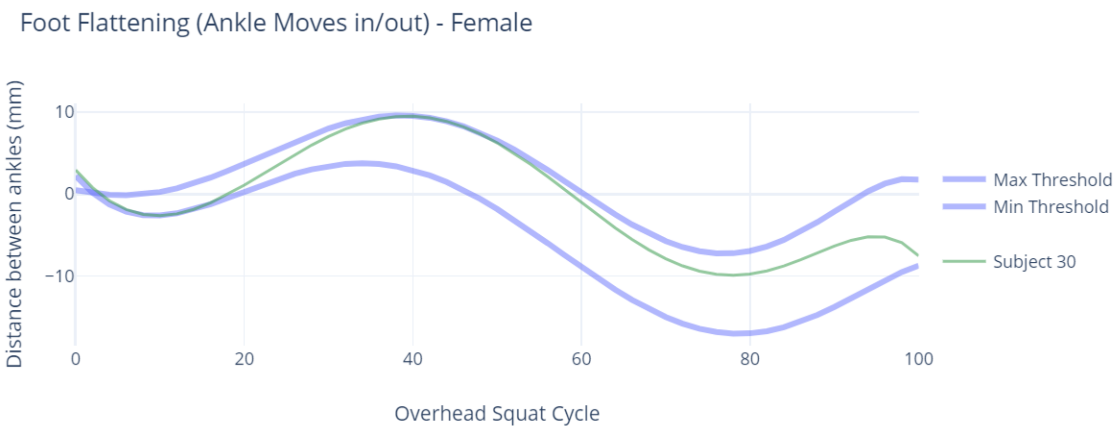

Figure 4.25: Ankle distance variation of a healthy female athlete

Figure 4.25 shows the ankle distance variates in an example healthy female subject. Figure 4.26 shows how an imbalanced female subject's graph deviates from the threshold values.

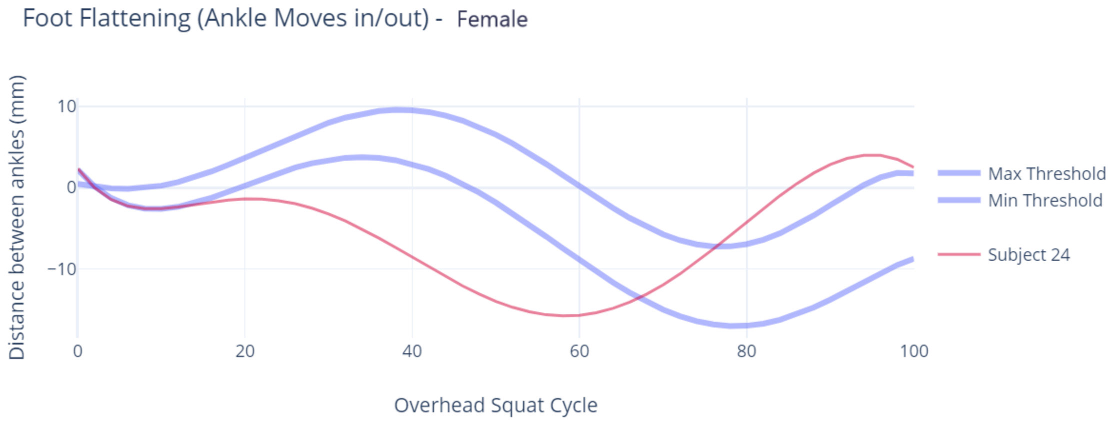

Figure 4.26: Ankle distance variation of an imbalanced female athlete

4.2.5 Heel lift

The subject graph is created by taking the vertical ankle position (Y coordinate) during overhead squat cycle. If the subject graph lies over the defined maximum threshold that means the subject's heels rise off the floor during the squat. It can be concluded as the subject having the heel lift compensation. If this compensation is detected from the graph comparison, the potential overractive and underractive muscle groups responsible for that imbalance can be identified as in the Table 4.11 as per National Academy of Sports Medicine,USA [59].

Compensation	Overractive Muscle Groups	Underractive Muscle Groups
Heel Lift	Soleus	Anterior Tibialis

Table 4.11: Potential Overactive and Underactive muscles related to Heel Lift

Figure 4.27 shows how subject 07's heel lift variation graph lies in between the defined threshold values. According to the graph, subject 07 who is male subject does not have the heel lift compensation.

Figure 4.27: Heel lift variation of a healthy male athlete

A heel lift variation graph of an imbalanced male subject is shown in figure 4.28 which indicates presence on heel lift compensation.

Similarly, figure 4.29 and figure 4.30 shows heel variation graphs of a healthy female subject and an imbalanced female subject respectively.

Figure 4.28: Heel lift variation of an imbalanced male athlete

Figure 4.29: Heel lift variation of a healthy female athlete

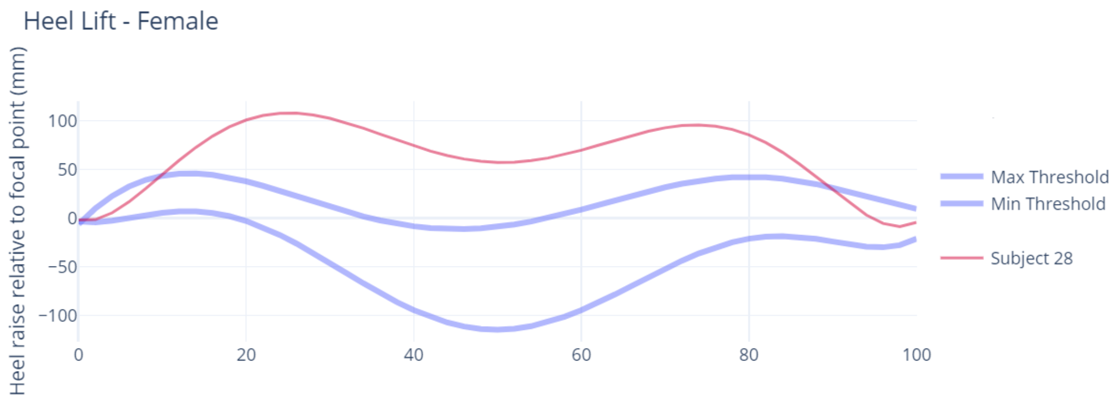

Figure 4.30: Heel lift variation of an imbalanced female athlete

4.3 Accuracy evaluation of the design

The accuracy of the results generated by the proposed solution is measured by consulting a domain expert (physiotherapist). The subjects were evaluated at the same time as they perform the overhead squat by a domain expert to observe and clinically analyze the dysfunctions in musculoskeletal system. Then compared the results of our study against the expert opinion to clarify the accuracy.

The method used in this research to clarify accuracy is by using confusion matrix. It is a two by two matrix that present four possible outcomes derived from a binary classifier. In this research study, we classify each subject as having imbalanced compensation or not. Thus, the confusion matrix can be used to evaluate the performance (accuracy, error-rate) of the proposed system as a suitable method. For each of the compensation category, confusion matrices are developed. The testing sample consisted of overall 41 subjects. Data from 4 female athletes were discarded due to errors in data recording. Thus total of 37 collegiate athletes, including both male and female were taken into consideration for the confusion matrix evaluation. Following are the list of terminology used in the confusion matrix.

- True Positive (TP) - The cases where the system predicts the subjects have an imbalance and the domain expert clarifies the subjects actually do.
- True Negative (TN) - The cases where the system predicts the subjects do not have

an imbalance and the domain expert clarifies the subjects actually do not have.

- False Positive (FP) - The cases where the system predicts the subjects have an imbalance and the domain expert clarifies the subjects actually do not have.
- False Negative (FN) - The cases where the system predicts the subjects do not have an imbalance and the domain expert clarifies the subjects actually do.

For each of the compensation category, we can calculate the following.

- Accuracy : Overall how often is the system correct
- Miscalculation rate : Overall how often the system is wrong
- Sensitivity (True positive rate) : When the subjects actually having an imbalance how often is the system correct
- Specificity (True negative rate) : When the subject is actually healthy, how often is the system correct

4.3.1 Knee valgus and Knee varus

		System Prediction	
Domain Expert Opinion		Positive (Imbalanced)	Negative (Healthy)
	Positive (Imbalanced)	TP = 15	FN = 3
	Negative (Healthy)	FP = 3	TN = 16

Table 4.12: Confusion matrix related to Knee valgus and Knee valgus

Accuracy

(TP + TN)/ Total

= (15 + 16)/37

= 83.78%

Miss-classification rate

(FP + FN)/ Total

= (3 + 3)/37

= 16.21%

Sensitivity (True positive rate)

TP/ (TP + FN)

= 15/ (15 + 3)

= 83.33%

Specificity (True negative rate)

TN/ (TN + FP)

= 16/ (16 + 3)

= 84.21%

4.3.2 Excessive Forward Lean

		System Prediction	
Domain Expert Opinion		Positive (Imbalanced)	Negative (Healthy)
	Positive (Imbalanced)	TP = 19	FN = 3
	Negative (Healthy)	FP = 0	TN = 15

Table 4.13: Confusion matrix related to Excessive Forward Lean

Accuracy

(TP + TN)/ Total

= (19 + 15)/37

= 91.89%

Miss-classification rate

(FP + FN)/ Total

= (0 + 3)/37

= 8.11%

Sensitivity (True positive rate)

TP/ (TP + FN)

= 19/ (19 + 3)

= 86.36%

Specificity (True negative rate)

TN/ (TN + FP)

= 15/ (15 + 0)

= 100%

4.3.3 Arms falling forward

Due to device recording errors, 3 male and 5 female recodes had to be discarded for the evaluation of arms falling forward. Total number of 29 subjects were finalized for the evaluation.

		System Prediction	
Domain Expert Opinion		Positive (Imbalanced)	Negative (Healthy)
	Positive (Imbalanced)	TP = 1	FN = 0
	Negative (Healthy)	FP = 3	TN = 25

Table 4.14: Confusion matrix related to Arms Falling Forward

Accuracy

(TP + TN)/ Total

= (1 + 25)/29

= 89.65%

Miss-classification rate

(FP + FN)/ Total

= (3 + 0)/29

= 10.34%

Sensitivity (True positive rate)

TP/ (TP + FN)

= 1/ (1 + 0)

= 100%

Specificity (True negative rate)

TN/ (TN + FP)

= 25/ (25 + 3)

= 89.28%

4.3.4 Foot Flattening

Due to device recording error, data of one female athlete were discarded when evaluating accuracy. Total number of 36 athletes were considered for the confusion matrix.

		System Prediction	
Domain Expert Opinion		Positive (Imbalanced)	Negative (Healthy)
	Positive (Imbalanced)	TP = 15	FN = 4
	Negative (Healthy)	FP = 3	TN = 14

Table 4.15: Confusion matrix related to Foot Flattening

Accuracy

(TP + TN)/ Total

= (15 + 14)/36

= 80.55%

Miss-classification rate

(FP + FN)/ Total

= (3 + 4)/36

= 19.44%

Sensitivity (True positive rate)

TP/ (TP + FN)

= 15/ (15 + 4)

= 78.94%

Specificity (True negative rate)

TN/ (TN + FP)

= 14/ (14 + 3)

= 82.35%

4.3.5 Heel Lift

		System Prediction	
Domain Expert Opinion		Positive (Imbalanced)	Negative (Healthy)
	Positive (Imbalanced)	TP = 7	FN = 5
	Negative (Healthy)	FP = 4	TN = 21

Table 4.16: Confusion matrix related to Heel Lift

Accuracy

(TP + TN)/ Total

= (7 + 21)/37

= 75.67%

Miss-classification rate

(FP + FN)/ Total

= (4 + 5)/37

= 24.32%

Sensitivity (True positive rate)

TP/ (TP + FN)

= 7/ (7 + 5)

= 58.33%

Specificity (True negative rate)

TN/ (TN + FP)

= 21/ (21 + 4)

= 84%

The accuracy of each category are at a higher level above 75%. Hence we can conclude that the results obtained by the proposed method is adequate enough to identify musculoskeletal imbalances in whole body without the aid of a domain expert. After identifying the existence of each compensation, coaches or athlete themselves can implement suitable interventions.

Chapter 5

Discussion

5.1 Discussion Overview

The primary purpose of this chapter is to address the various aspects of the obtained results in this research study. According to literature, this is a novel approach to detecting muscle imbalances in collegiate athletes. There are a few limitations in carrying out the study, which will be addressed in this chapter. Also the accuracy aspect of the methodology used and the proposed solution will be critically discussed.

As we discussed in the introduction chapter, the injury rate of collegiate athletes are increasing as the number of sport participants increase. We identified that muscle imbalance is one of the common reasons for the manifesting of these injuries over time. Considering the collegiate athletes and their lack of time spent for extra curriculum as sports, we identified that there's a need for a more sophisticated method to routinely analyze their movement patterns.

There are a few issues that can be identified in the current clinical evaluation methods of muscle imbalance as we discussed in detail in the background chapter. The high cost of diagnosing, late identification, excessive time consumption for rehabilitation, the essential presence of a domain expert for evaluations are a few of these issues. This research is carried out to address these issues and suggest a novel approach to identify muscle imbalances in collegiate athletes.

5.1.1 Analysis of the Results

The generation of clinically acceptable models for healthy athletes were done using the data gathered from the device. Overhead Squat observations are categorized into 5 compensations. Overall 10 models were created to represent the correct movement pattern behavior for each of the categories of both male and female athletes. Several deviations and possible reasons for these deviations were identified from the results obtained. We would discuss them relating to each of the compensation category.

Knee valgus and Knee varus

As observed in the captured data, the distance between the left and right knee joints are varied from subject to subject. Normally females have less distance due to their small compared to males. A specific behavior that was identified from the calculation of the distance between knees is that the male subjects have shown the knee varus compensation more often than the knee valgus compensation. Whereas in female subjects, the knee valgus compensation is commonly seen. It was also confirmed by the domain expert that behavior can be seen respectively in males and females differently. The subjects having imbalances and subjects that were not having imbalances were shown equally distributed in the selected sample from the results obtained from the confusion matrix evaluation.

Ideally the difference between knees does not change during the squat. Even so, it's evident that the minimum threshold value graph developed is above 0. Thus, It needs to be noted that only subject graphs consists of negative values are being considered as having knee valgus (knee moving in) rather than the subject graphs below the minimum threshold value. This was observed because of the nature of the selected sample.

Excessive forward lean

Forward lean is detected by comparing the knee angle and the hip angle while doing overhead squat. As shown in the results, they needs to be parallel to be able to identified as healthy. But as the clinician's instructions, the knees should not go beyond the toes. Since we only detect the parallelism of the knee and hip angles, there ought be cases where the knee goes beyond toes while the knee and hip angles are within the defined healthy range. Even though that behavior does not contribute heavily to the detection of muscle imbalances, that can be concluded as a limitation in our research study. Even though we carried out a training session prior to the data collection, there can be cases where the subjects were not doing the overhead squat according to the appropriate technique. Thus, some of the deviations in hip and knee angle difference where hip angle is larger than knee angle may be due to the inadequate technique.

Arms falling forward

Ideally, the shoulder angle should be 180°degrees, though from the results we have observed that none of the athletes' can reach that angle. In the selected sample, the male athletes have maintained uniformity in the shoulder angle throughout the span of squat, however there were a varying behavior in the female results. All subjects except one were able to maintain their shoulder angle within the defined range of angle thresholds. Which can mean that the arms falling forward is a more uncommon compensation found in collegiate athletes.

Foot Flattening (Ankles moving in/out)

The foot flattening compensation was detected using the difference in the distance between ankles. Since there were no detection point in the toes in the Device SDK, we were left with the ankle joint to identify the compensation. Even though the imbalance rate is similar with the healthy rate in the sample, there observed a higher rate of incorrect detection as well. The reason for this deviations may be the cause of ankle joints not being tracked by the device properly.

Heel lift

The ideally the heels should not be raised when performing the overhead squat. We have used the ankle joint positions to detect the heel raise relative to the floor plane. However the data gathered through the device shows that the joint positions fluctuate a little bit off the ground. This behavior is detected in all the evaluated subjects, thus we can conclude that it may be caused by a device error. This is the only compensation that takes the vertical height into consideration. The observations show that the joint position fluctuation is affected by the vertical momentum when performing the overhead squat. Thus, the erroneous results can be due to speed of a subject doing the squat.

Since all subjects' speed will be a fact that affect the vertical height, if the deviation is large compared to others as we discussed in the result chapter, we can say the subject shows a heel lift compensation.

5.1.2 Limitations and Constraints

- The research study was done based on the collegiate athletes which is limited to the sportsmen and sportswomen aged between 20 to 25. Even so, the proposed solution can be applied to those who are following fitness regimes as well.
- The Overhead Squat, the movement pattern used by the study, is specifically used in the clinical field to identify muscle imbalances. It is a basic functional movement that is being used by many complex movement patterns in sports. The model for healthy athletes are generalized in this study, thus it cannot be applied for professional athletes who have developed specific behavior patterns for their respective sports.
- One of the constraints in the device is that the Orbbec Astra uses infrared rays to detect the joint positions. Thus the subjects should not wear any black clothing. It will cause the device not to detect properly.

- Another device constraint is that the capturing of the joint positions should be done in a closed environment to avoid sunlight. The infrared emits from the sun rays can interfere with the infrared rays coming from the device, causing it to give erroneous results.

5.2 Contribution

The research study was able to address the aforementioned issues of current clinical imbalance detection techniques. The following research contributions were done through the research.

- One research paper was accepted and published by the European Journal of Computer Science and Information Technology (EJCSIT) Vol.6, No.5, pp.37-50, November 2018.
- At present time, the overhead squat is used by many physiotherapy and fitness institutions around the world to identify and assess the dysfunctions of the musculoskeletal system. It is mainly used by clinicians to identify muscle imbalances as mentioned in the introduction section. Currently the assessment is entirely based on the evaluator observation and expertise, thus a similar computational method of identifying muscle imbalances have not being introduced as of now.
- The joint angles and joint distance ranges for a healthy subject is not documented in the clinical field. The evaluation is done by the observed behavior through naked eye or recorded video feed. The actual quantified angle/distance values are identified in this research study.
- This is the first research study which was done in local context focused on detecting muscle imbalances on both upper body and lower body to best of our knowledge.
- Orbbec Astra Pro is a motion tracking device that launched recently, which mainly have been used for depth image creation and 3D model creation. We have used this device to identify joint positions, angle and distances in the 3D space, opening a new aspect for utilizing this device for similar projects.

Chapter 6

Conclusion and Future Directions

6.1 Conclusion

Injury prevention in the field of sports is a crucial element that should be looked upon. Once an injury occurs, it may force the athlete to refrain from taking part in training and competitions along with additional costs on rehabilitation treatments. Furthermore, it may reoccur in the future and prevent the athlete from reaching his or her full potential. Thus, the need to identify potential overactive and underactive muscle groups which contribute to biomechanical disadvantages and injuries in the long run was identified. Taking these into consideration, this research contributed to determine an ICT based novel approach to identify muscle imbalances in athletes.

Considering the previous literature studies, a main hypothesis was developed for the research.

Musculoskeletal imbalances of the human body can be identified by joint positional values captured by a motion tracking device.

To address the above hypothesis, three main research questions were established. These questions were addressed under few limitations and constraints which discussed in the previous section 5. First question was to determine a suitable movement pattern and a suitable motion tracking device to identify the movement patterns of athletes. After consulting Dr. Chathuranga Ranasighe of University of Colombo, Overhead squat was chosen as the primary movement pattern to be analyzed. As discussed in the chapter 2 section 2.2, there are several movement patterns used in the clinical field for the Movement Analysis. However, the overhead squat is especially suited to assess muscle imbalance according to domain experts. It is a fundamental movement pattern that assess the entire human body. Overhead Squat contains several key joints that can be used to evaluate the functionality of human body. Considering the ease of training and assessment advantages the overhead squat was chosen as a suitable movement pattern to use in the research study to carry out the movement analysis. The first objective of the study was achieved after choosing the suitable movement pattern.

Motion tracking is a new cutting edge technology that can be easily obtained and used with a low cost than the expensive clinical equipments. Many researches were done using this technology to detect movement patterns in many fields including sports medicine as discussed in the chapter 2 section 2.3. Comparing both maker based and marker less motion tracking techniques, it was proved that marker less motion tracking is more suitable for analyzing movement since it carries less burden to the athlete. Considering the cost, ease of implementation, ease of training and ease of handling, Orbbec Astra Pro was chosen as the suitable marker less motion tracking device to carry out the research study. The second objective of determining a suitable motion tracking device to identify joint positions was completed.

The second main research question is to determine a clinically acceptable criterion to map overhead squat movement pattern. The device is able to detect skeletal joints in the 3D space and output the positional data as numeric point values. These values were being analyzed to determine a suitable way to represent the overhead squat so that the comparisons can be done using the collected data. In previous studies, researches have used graphs to represent how the joint angles change throughout a selected movement pattern which was discussed in the chapter 2 section 2.4. This research also incorporated a similar method to calculate selected joint angles and joint distances that involve in overhead squat in order to represent them as graphs. Dot product was used to calculate the joint angle measurements and point distance in 3D space is used to calculate the distance between joints.

Overhead squat is clinically evaluated based on observations. These observations can be identified as compensations. Having compensations means to have an imbalance in the physiotherapy domain. This research only considers 6 compensations to identify potential overractive and underractive muscle groups that contributes to muscle imbalance. They're Knee valgus, knee varus, excessive forward lean, arms falling forward, foot flattening and heel lift. To detect these 6 compensations, five criterion were developed as graph representations using the mathematical models stated in chapter 3 section 3.2.1. It can be defined as graphs representations of healthy athletes' movement pattern during an overhead squat. The maximum and minimum movement measurements(joint angles and distances) threshold values were identified for each criterion that can fluctuate in between. All graphs were fitted with 6th order polynomial curve to smooth out the errors. For each criterion there are two specific equations for maximum and minimum threshold graphs which were stated in chapter 4 section 4.1. The generic 6th order polynomial curve equation takes the form of following equation.

$$Y = a + bx + cx^2 + dx^3 + ex^4 + fx^5 + gx^6$$

Any athlete's measurement that goes beyond these defined threshold values are identified as that athlete having the respective compensation. The threshold values are determined for both males and females separately. By determining the graph representation of overhead squat, the objective of finding a suitable method to map movement pattern was substantially achieved. The research was carried out in two phases. First phase was to collect data from the healthy sample of athletes in order to develop the criterion graphs with thresholds. Second phase was to test the developed solution with test sample. Experiment was carried out using 37 total number of subjects. Identification of deviations through the determined method was done with an experiment which addresses the third main research question of how to differentiate athletes holding a muscle imbalance with the deviations in the graph representation. Compensations were identified with the visual deviations from the defined criterion graphs as shown in chapter 4 section 4.2. In line with each compensation a set of potential overractive and underractive muscle groups were identified according to the physiotherapy domain.

Evaluation of the conducted research was done using confusion matrix method. Results obtained from the experimental study were compared with decisions of a domain expert to identify the accuracy of the results. Accuracy was calculated for each of the compensation criterion. The sample was consisted of 23 males and 14 females. Accuracy for all the categories were above 75% which can be concluded as the proposed solution was adequate enough to identify muscle imbalance via motion tracking at a satisfactory level.

The findings of this research study will enable athletes to self-evaluate and identify biomechanical imbalances cost effectively as well as minimize the damage caused.

6.2 Future Directions

This research study was focused on identifying imbalances in the musculoskeletal system using a motion capturing device in order to provide a cost effective solution for athletes to self evaluate the condition of their musculoskeletal systems. However, there are several limitations to this study as stated in section 5.1.2. This section discusses on such limitations and potential future directions that this study can be expanded to.

The research study was done focused on collegiate athletes who are not involved in sports at a professional level. Future studies can be conducted involving professional athletes by taking into account the specific movement patterns that are involved with each sport which may cause certain changes in the musculosketal system of such professional athletes. Furthermore, the current study only involved collegiate athletes and the defined threshold graphs are derived from this sample. These threshold values can be tested for accuracy on a sample which consists of fitness enthusiasts (non-athletes but attends to gym on a regular basis to maintain fitness). Such a study can be conducted to determine the applicability of this study to the non- athlete fitness enthusiasts.

The current research study was done based on mathematical models to determine the status of a subject. However, there is a possibility to redo this research using machine learning instead of mathematical models. The main reason for not using machine learning in this study was the lack of data to train the model. To conduct a future study using machine learning, there lies a need to collect a sufficient amount of data before carrying out the study.

At present, there are many wearable devices that athletes can use while engaged in sports without any discomfort such as fitness bands and foot reaction pressure detecting shoes. This research study only implemented a motion tracking device to detect muscle imbalance. Thus, the study do not take muscle strength and length into account when determining whether a subject has an imbalance or not. There is a possibility of implementing similar fitness devices to measure the strength of athletes to improve the accuracy of this solution.

This research study was mainly focused on providing a solution that can be used for athletes to self evaluate muscle imbalances. However, a stand alone application that can be commercially distributed was not developed as an output of the research. Furthermore, as mentioned in section 2.4, there were no previous studies done on standard measurements of the overhead squat. Therefore, precise measurements can be taken using a marker based motion capturing system in a future study which can then be used to improve the accuracy of the solution. Also, the current solution considers each of the compensations independently of each other. There were no studies done to determine the relationship between each of the compensations to observe how one compensation affects the other. Therefore, it possible to carryout future studies to determine the relationships between these compensations.

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Appendices

Appendix 01 -Informed Consent form for the 4th year research project

This consent form is for collegiate athletes who're attending University of Colombo, and those who we invite to participate in this research study.

Title of the research :
Identifying muscle imbalances via motion analysis using sensory inputs

Names of the researchers:
S.S Vithanage | Undergraduate, University of Colombo School of Computing
(Registration No: 2014/IS/087)
M.S Ratnadiwakara | Undergraduate, University of Colombo School of Computing
(Registration No: 2014/IS/069)

Purpose of the research:
We intend to use your data to model a solution that can successfully identify muscle imbalances in collegiate athletes, in a comfortable, cost-effective and a convenient way.

Data requirements:
- Joint positions when doing the overhead squat
- Age, height, weight
- Sport activities engaged in
- Any information, medical records about previous injuries or treatments for research purposes

Your participation in this research is entirely voluntary. It is your choice whether to participate or not. Whether to disclose your private information or not. The data gathered are exclusively only for this study.

Collegiate Athlete ID no:

I have read the foregoing information, or it has been read to me. I have had the opportunity to ask questions about it and any questions that I have asked have been answered to my satisfaction. I consent voluntarily to participate as a participant in this research.

Print Name of Participant :
Signature of Participant :
Date : ____________________
Day/month/year

Appendix 02 - Python script for splitting subject data files

```
import csv
from pprint import pprint
import os

# define filenames here
filename = 'subject_1'

# create folder for each subject
def filecreator(array,folder,count):
    foldersplit = str('/')
    count = str(count)
    with open(folder+foldersplit+folder+count+'.csv', "w") as f:
        writer = csv.writer(f)
        writer.writerows(array)
        print(count+' successful')

# read file and split files
with open(filename+'.csv') as csv_file:
    csv_reader = csv.reader(csv_file, delimiter=',')
    new_array = []
    counter = 0
    time = 1
    if not os.path.exists(filename):
         os.makedirs(filename)
    for row in csv_reader:
        if row[0]=='*':
            filecreator(new_array,filename,counter)
            counter = counter+1
            new_array = []
            time = 1
        else:
            row[0] = time
            new_array.append(row)
            time = time + 1
```

Appendix 03 - Python script for scaling data files

```
import csv
from pprint import pprint
import math


# funtions required
# get the list of xcoordinates based on the data set length
def xcreator(last, i, xcords):
	x = (i*last)/100
	xcords.append(x)

# find the corresponding y value from the data set
def yfinderdirect(data, column, i):
	x = data[i][column]
	x = float(x)
	return x

# find the y value if the x cord is an integer
def yfinder(a,ay,b,by,i):
	y = by - (b-i)*(by-ay)/(b-a)
	return y


def scaler(file):
	data = []
	count = 0
	xcords = []
	ycords = []

	with open(file+'.csv') as csv_file:
		csv_reader = csv.reader(csv_file, delimiter=',')

		for row in csv_reader:
			row[0] = count
			data.append(row)
			count = count +1
		# pprint(data)
		last = len(data) - 1

		for i in range(0,101):
			xcreator(last, i, xcords)

		# pprint(xcords)
		# print(len(xcords))

		for i in xcords:
			if (i).is_integer() or i == 0:
				i = int(i)
				data_row = []
				for x in range(1,9):
					y = yfinderdirect(data,x,i)
					data_row.append(y)
				ycords.append(data_row)
			else:
				data_row = []
				a = int(math.floor(i))
				b = int(math.ceil(i))
				for x in range(1,9):
					ay = yfinderdirect(data, x , a)
```

```
                              by = yfinderdirect(data, x , b)
                              y = yfinder(a,ay,b,by,i)
                              data_row.append(y)
                        ycords.append(data_row)

            # pprint(ycords)
            # print(len(ycords))

            timer = 0

            for x in ycords:
                  x.insert(0, timer)
                  timer = timer + 1

            columns = ['Time', 'Distance between knees', 'Hip angle', 'Knee angle', 
'Right arm angle', 'Left arm angle', 'Distance between ankles', 'Right ankle Y 
coordinate', 'Left ankle Y coordinate']
            ycords.insert(0,columns)

            with open(file+'scaled.csv', "w") as f:
                  writer = csv.writer(f)
                  writer.writerows(ycords)

# function calling
# enter the files in to the array as elements
files = []

for i in files:
      scaler(i)
```

Appendix 04 - Python script for calculating mean of subject data files

```
import csv
from pprint import pprint
import statistics as s

######################################
folder = 'subject_1'
files = ['0','2','3','4']
data = []
meandata = []
######################################
# read the file
def filereader(folder, files, data):
	for i in files:
		file = []
		with open(folder+'/'+folder+i+'scaled.csv') as csv_file:
			csv_reader = csv.reader(csv_file, delimiter = ',')

			for row in csv_reader:
				file.append(row)
		file.pop(0)
		data.append(file)

	return data

######################################
x = filereader(folder,files,data)
filecount = len(x)
######################################
# calculate mean values
def meancal(array, filecount,column):
	fulldataset = []
	for i in range(0,101):
		meanarray = []
		for j in range(filecount):
			meanarray.append(float(array[j][i][column]))
		mean = s.mean(meanarray)
		fulldataset.append(mean)

	return(fulldataset)

######################################
columndata = []

for i in range(1,9):
	cdata = meancal(x,filecount,i)
	columndata.append(cdata)



truedata = []

for l in range(0,101):
	rowdata = []
	for t in range(0,8):
		rowdata.append(columndata[t][l])

	truedata.append(rowdata)
```

```
timer = 0

for row in truedata:
      row.insert(0,timer)
      timer = timer + 1


headers = ['Time', 'Distance between knees', 'Hip angle', 'Knee angle', 'Right arm angle', 'Left arm angle', 'Distance between ankles', 'Right ankle Y coordinate', 'Left ankle Y coordinate']
truedata.insert(0,headers)

# creat new file with mean values
with open(folder+'avg.csv', "w") as f:
                  writer = csv.writer(f)
                  writer.writerows(truedata)

print(folder+'avg.csv created')
```

Appendix 05 - Python script for editing distance value columns of subject data files

```
import csv
from pprint import pprint


# read the csv files
def filereader(file):
      data = []
      with open(file+'avg.csv') as csv_file:
            csv_reader = csv.reader(csv_file, delimiter = ',')

            for row in csv_reader:
                  data.append(row)

      header = data[0]
      data.pop(0)
      return data, header

# edit the columns
def columneditor(data):
      kneedis = float(data[0][1])
      ankledis = float(data[0][6])
      rytankle = float(data[0][7])
      lftankle = float(data[0][8])

      # pprint(data)

      for i in range(101):
      # knee
            kneevalue = float(data[i][1])
            newkneeval = kneevalue - kneedis
            data[i][1] = newkneeval
      #ankle
            anklevalue = float(data[i][6])
            newankleval = anklevalue - ankledis
            data[i][6] = newankleval
      # ryt heel
            rytheelvalue = float(data[i][7])
            newrytheelval = rytheelvalue - rytankle
            data[i][7] = newrytheelval
      #left heel
            lftheelvalue = float(data[i][8])
            newlftheelval = lftheelvalue - lftankle
            data[i][8] = newlftheelval

      return data

# write the data into a file
def filewriter(file,data):
      with open(file+'final.csv', "w") as f:
                  writer = csv.writer(f)
                  writer.writerows(data)

      print(file+'final.csv created')

#enter file names in this array
files = []


for j in files:
```

```
data, header = filereader(j)
newdata = columneditor(data)
newdata.insert(0, header)
filewriter(j, newdata)
```