The role of individual physical body measurements and activity on spine kinematics during flexion, lateral bending, twist, and squat tasks in healthy young adults – comparing marker(less) data.

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CERTIFICATE

It is certified that the work contained in this thesis, titled "**The role of individual physical body measurements and activity on spine kinematics during flexion, lateral bending, twist, and squat tasks in healthy young adults – comparing marker(less) data.**" by **Harsh Sharma**, has been carried out under my supervision and is not submitted elsewhere for a degree.

Date

Adviser: Dr. Kavita Vemuri

I would like to dedicate this thesis to my parents

Mrs. Mamta Sharma and Mr. Rajesh Sharma

All My Gods

and

My Sister, Miss Mansi Sharma

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Abstract

Physical exercises and gross motor skills support the spine and the body's lower extremities. Understanding the relationship between physical characteristics and activity to kinematic properties of the spine has implications for sports, occupational tasks, clinical diagnosis and prognosis. This study aimed to categorize spine kinematics and the lumbopelvic-hip segments from flexion, lateral-bend, twist, and squat exercises by examining the correlations to body-mass index (BMI), waist-to-hip ratio (WHR), and physical activity levels in healthy young adults. The data was collected from a marker-based opto-electronic motion capture setup and a marker-less motion capture with the RGB camera of a standard mobile phone. Comparing the accuracies of the two techniques on the same data set is important to develop inexpensive (RGB camera) diagnostics. Sixty-two participants (40 Male, 22 female) participated in the study. The angular displacement of the spine and knee/hip for each exercise was extracted by vector analysis using a single reference node/marker. The analysis showed no significant correlations of angular displacements values for the four movements with BMI or WHR. The physical activity level of male participants is significantly correlated with angular displacements for the flexion ($p<0.001$) and lateral-bend (p-value ranges from 0.001-0.04) and weakly correlated (but not significant) for twist exercises. The physical activity level shows a significant correlation for only flexion ($p<0.001$) in female participants. BMI is negatively correlated in male participants for the squat movement, while WHR and physical activity show positive associations. In the female cohort, a negative correlation with BMI, WHR, and physical activity level is observed for the squat movement. The findings emphasize the critical role of physical activity on musculoskeletal flexibility in young, healthy adults. The angles estimated using both techniques were comparable and significantly correlated across participants and exercises.

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Chapter 1

Introduction

1.1 Spine and knee Kinematics

The spinal column is a vital part of the human trunk and the core section of the body. The anatomy and the forces/load applied result in a range of motion (ROM) (Punjabi & White,1980). Height and weight, the first anthropometric measures, have been used extensively to understand body flexibility, with waist circumference as a better measure of adiposity. ROM studies are crucial to understanding the mechanisms supporting gross motor tasks like bending, moving, sitting, etc.- to complex and fine movements required in sports, gymnastics, yoga, or dance. Measurement of ROM also provides insights into the loss of movement due to hemiplegia caused by a stroke, Parkinson's, spine injury, and osteoporosis (Savic et al., 2018). A more common clinical condition is lower back pain caused due to spine curvature and body weight; the latter has a strong effect on the kinematics of the spine (Onyemaechi et al., 2016; Vismara et al., 2010; Ghasemi & Arjmand, 2021). Though a few studies did not find conclusive proof of the connection (Leboeuf-Yde, 2000; Youdas et al., 1996; Bible et al., 2008; Zander et al., 2018). An important factor is prolonged inactivity or a sedentary lifestyle, which increases body mass and has been reported to predict non-specific lower back pain in young adults as muscle power and strength decrease (Andersen et al., 2006; Chen et al., 2009). In a case of cause & effect, as pain increases, one tends to reduce activity, further aggravating the condition. Sitting for long hours, even with high recreational physical activity, can alter Lumbar-pelvic kinematics (Zawadka et al., 2022). A higher BMI and larger waist circumference in early adulthood resulted in an uneven spine curvature (Pavlova et al., 2018) and the Lumbosacral angle, but there was no correlation of spine kinematics to WHR in non-obese males (Oyakhire et al., 2021). Hence, the correlation between BMI, WHR, and physical activity with the kinematics of the entire spine column as a unit needs further exploration.

In addition to the spine, the hip and knee ROM is essential for body-balance and load-bearing. The knee joint bears a lot of stress from daily activities like lifting, kneeling to high-impact sports, jogging, and aerobics. A multi-joint movement supported workout is squat, which activates the appropriate muscle groups with a single manoeuvre (Kim et al., 2021; Wallace et al., 2002; Gabel et al., 2018). This technique applies strain on the knee bones, the hip joints and ankles, with improper methods leading to lower back pain (Fry et al., 2003; List et al., 2013). But the body-mass squat exercise also strengthens the muscles after injuries (Stuart et al., 1996), helps diagnosis of age-related degradation of the pelvic and knee bones (example: osteoporosis) or in measuring muscle strength, especially the quadriceps femoris (Fujita et al., 2011) in sports training. Hence, the displacement of the hip segment to identify the role of the lumbo-pelvic-hip-knee system needs to be studied.

In our study, we measure the angular displacement of the three spine segments (cervical, thoracic & lumbar) in flexion, lateral-bend, and twist exercises and hip/knee joint angular displacement executed by normal healthy young adults (with no reported lower-back pain). Correlation analysis with BMI, WHR, and physical activity level is applied. We follow the standard marker set proposed by List et al. (2013) and other studies from the Institute of Biomechanics ETH Zurich. An single RGB camera data was also analyzed by extraction of 2D poses (key-points) for all frames using the openpose model (Cao et al., 2017), followed by generation of the 3D skeleton using the ProHMR model (Kolotouros et al., 2021) as the marker-based system has some limitations - portability, cost, higher calibration time, customized space requirement, and trained personnel. We compare the same group's RGB and marker-based motion capture data for accurate estimates and measurement error ranges. The comparative analysis is significant for clinical/human movement science applications with the marker-based data as a reference model. Deriving from earlier observations (for example, Vismara et al.,2010; Ghasemi, M., & Arjmand, N., 2021), we hypothesize that BMI, WHR, and physical activity affect spine ROM in the age group of the cohort recruited for this study.

1.2 Aim of the Study

Although spinal column studies have been reported for individual spine segments, very few studied intersegmental motion of the spine. A 2016 meta-analysis of spine biomechanics studies (Negrini et al., 2016) showed limited studies on the whole trunk focused on inter-intra segmental motion of the cervical, thoracic, and lumbar segments. The lumbar segment has been investigated extensively followed by thoracic, but only limited studies on the whole trunk focused on inter-intra segmental motion of the cervical, thoracic, and lumbar segments. Furthermore, prolonged inactivity or a sedentary lifestyle, which results in weight gain and has been associated with the occurrence of non-specific lower back pain in young people due to a loss of muscular power and strength, is a major risk factor (Andersen et al., 2006; Chen et al., 2009). It is a classic instance of cause and effect: when pain increases, individuals tend to slow down, further aggravating the condition. Regardless of high recreational physical activity, sitting for lengthy periods of time might still affect Lumbar-pelvic kinematics (Zawadka et al., 2022). Therefore, more research is required to determine whether or not body mass index, WHR, and physical activity all influence the kinematics of the spine. Understanding spine biomechanics is important for preventing and managing conditions that affect the spine, such as herniated discs, spinal stenosis, and degenerative disc disease. By understanding the mechanical principles that govern the spine, healthcare professionals can develop effective treatment plans and rehabilitation programs to help patients recover from spinal injuries and maintain optimal spinal health.

The biomechanics of the hip, thigh muscles and the knee/ankle joints are also essential in analyzing daily activities in addition of spine biomechanics. Studying knee kinematics is essential for understanding knee joint function, developing effective treatment and rehabilitation strategies, and preventing knee injuries. knee kinematics can provide valuable insights into the biomechanical factors that contribute to knee injuries which can also help in the development of effective rehabilitation strategies for knee injuries. Understanding knee kinematics can aid in the design of prosthetic knees that closely mimic the natural knee joint.

The current study focuses on the study of whole spine with respect to intra- and inter-segment motion and hip/knee segment while employing marker-based and marker-less motion capture techniques. To develop a any kinematics model, a comprehensive analysis requires data from the, a) spine alignment and inter/intra segment kinematics with hip/knee segment, b) ROM of the segments, c) body physiological parameters, and d) a non-invasive robust technique. We performed the correlation analysis of angular displacement of spine and knee with the physical parameters such as BMI, WHR, and physical activity level.

When it comes to biomechanical applications, human motion detection, animations, and even for military use, motion capture systems (Opti Track motion capture systems & Vicon) (Nagymáté et al., 2018) are the gold standard. There are various limitations to using this technique, including its inflexibility, expense, lengthy calibration process, need for dedicated space, and need for specially trained personnel. Analysis of marker-based mechanics can be very complex with correlations between muscle markers and those on spine. Therefore, this work introduces a novel technique/method of measuring spine angles, as incorrect skin marker positioning affects curve measurement and kinematic variability (Severijns et al., 2021). Furthermore, an important extension in past studies, the angular displacement of the spine is extracted using multiple reference frame, which can introduce errors in measurement due to incorrect segment identification. With the current study, we have attempted to resolve there errors by introducing an design independent model using single reference frame.

1.3 Scope of the study

The study was conducted on healthy individuals in the 19-33 years (40 males and 22 females) age group. The original plan to collect data from both healthy and lower back pain patients was put on hold due to the Covid-19 pandemic. The main focus of our research is the study of spine and knee kinematics from the angular displacement of the three spine segments and the lumbo-pelvic-hip segments in flexion, lateral-bend, twist and squat exercise executed by normal healthy young adults. To generate a reference chart/model, the angular displacement is correlated to an individual's physical parameters such as height, weight, BMI, waist-to-hip ratio, and physical activity level. Our study followed the standard marker set proposed by List et al (2013) and other studies from the Institute of Biomechanics ETH Zurich. Comparing the data collected from the same group of participants from two techniques (RGB & marker-based motion capture) would help in better accuracy estimates, error corrections if required, and, significantly, for clinical/human movement science applications with the reference models thus generated. Importantly, the comparison of RGB with motion capture allows for applications of an inexpensive marker-less system for use in clinics backed by robust models.

1.4 Thesis Organization

- This thesis is divided into 6 chapters, and each chapter contains sections aligned to it. The content of ***this chapter*** covered the elementary studies of spine and knee kinematics, the aim of the study and the scope of the study.
- ***Chapter 2***, The study of the structure and mechanics of the spine and knee, including their anatomical structure, biomechanical properties, and mathematical principles.
- ***Chapter 3***, Techniques to measuring movement of the truck: encompassing both marker-based and marker-less approaches.
- ***Chapter 4***, Spine and knee kinematics analysis using marker-based motion capture system using opti-track opti-electonic cameras.
- ***Chapter 5***, Spine and knee kinematics analysis using marker-less motion capture system via single RGB camera.
- ***Chapter 5***, Conclusions, summarizes this thesis. It covers practical applications, corresponding limitations, and possible extensions of this work.

Chapter 2

Anatomy of Human Spine and Knee

2.1 Spinal Structure

The spinal column is a vital part of the human trunk and the core section of the body. The spine's flexibility is attributed to elastic ligaments in the spinal column. It comprises of 33 bones called vertebrae divided into five sections: Cervical, Thoracic, Lumbar, Sacrum, and Coccyx, of which cervical, thoracic, and lumbar are well-investigated. A healthy spine has strong muscles and bones, flexible tendons and ligaments, and sensitive nerves. An adult spine exhibits a natural S-shaped curve when viewed from the side. The cervical (neck) and lumbar (low back) areas are slightly concave, whereas the thoracic and sacral regions are gently convex Fig 2.1. The curves absorb shock, maintain balance, and allow a range of motion (ROM) across the spinal column, much like a coiled spring. The spinal muscles play a crucial role in facilitating movement, stability, and proper posture. A good posture is achieved when a balance is struck between reducing the load on the spine and minimizing muscle activity. The upper trapezius and sternocleidomastoid muscles are primarily responsible for movement and stabilization of the neck, while the erector spinae, rectus abdominis, internal and external obliques, psoas major, iliacus, gluteal, and hamstring muscles are primarily responsible for maintaining posture in the lumbosacral region (Standring et al., 2005). Standing, walking, sitting, and lying with good posture puts the least strain on your spine during movement or weight-bearing activities. Excess body weight, weak muscles, and other factors can cause the spine to misalign, such as an improper curve of the lumbar spine is lordosis, also known as swayback; an irregular curve of the thoracic spine is kyphosis, also known as a hunchback, and an abnormal curve from side to side is called scoliosis.

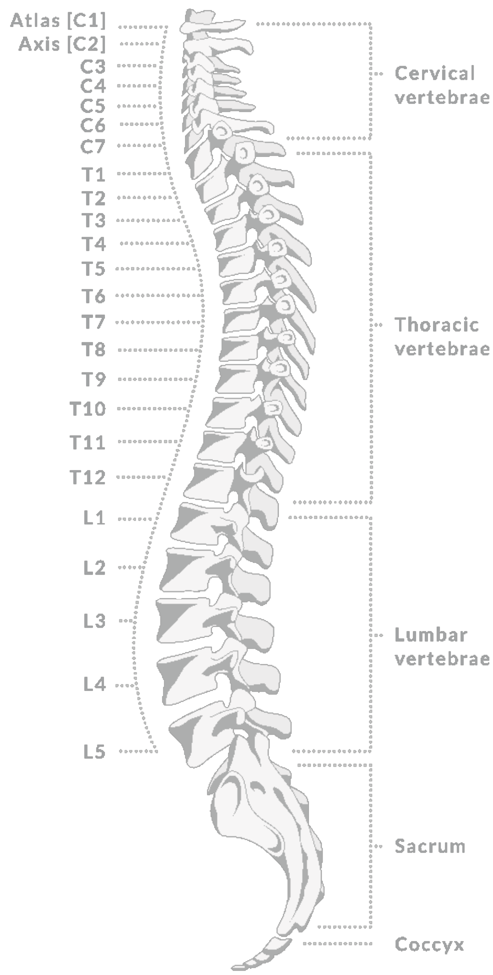

Figure 2.1: Lateral view of human Spine structure

2.1.1 Muscles

The spine muscles are a group of muscles that play a critical role in facilitating movement, stability, and proper posture. These muscles work together to support the spine and enable a range of physical activities, from simple movements like bending and twisting to more complex movements like running and jumping. Extensor and flexor muscles are among the two important groups of muscles which play a vital role in facilitating movement and providing stability in the body. The extensor muscles are responsible for extending or straightening joints, while the flexor muscles are responsible for flexing or bending joints. These muscles work together to enable a wide range of physical activities, from simple movements like walking and reaching to more complex movements like weightlifting and gymnastics. Maintaining strength and flexibility in both the extensor and flexor muscles is essential for preventing injury, improving posture, and enhancing overall physical performance.

2.1.2 Cervical Spine

The cervical spine segment structure refers to the seven vertebrae that make up the cervical spine or neck. Each of these vertebrae is numbered and labeled C1 to C7, starting at the top of the spine near the skull and ending at the base of the neck. The cervical spine is responsible for providing mobility, stability, and support to the head and neck, while also protecting the spinal cord and associated nerves. The cervical spine segment structure includes a range of important structures, such as intervertebral discs, facet joints, ligaments, muscles, and nerves, that work together to facilitate movement and prevent injury. Understanding the structure and function of the cervical spine segment structure is crucial for preventing and managing conditions that affect this area, such as herniated discs, spinal stenosis, and degenerative disc disease.

2.1.3 Thoracic Spine

The thoracic spine segment structure refers to the twelve vertebrae that make up the middle portion of the spine, located between the cervical spine (neck) and the lumbar spine (lower back). These vertebrae are labeled T1 to T[12-15] (depending on the mammal) and are responsible for providing support and stability to the upper body while also protecting the spinal cord and associated nerves. The thoracic spine segment structure also includes important structures such as intervertebral discs, facet joints, ligaments, muscles, and nerves that work together to facilitate movement and prevent injury. Unlike the cervical spine, the thoracic spine is relatively immobile, allowing for more stability but less flexibility. Understanding the structure and function of the thoracic spine segment structure is crucial for preventing and managing conditions that affect this area, such as herniated discs, scoliosis, and osteoporosis.

2.1.4 Lumbar Spine

The lumbar spine segment structure refers to the five vertebrae that make up the lower portion of the spine, located between the thoracic spine (middle back) and the sacrum (pelvis). These vertebrae are labeled L1 to L5 and are responsible for supporting the weight of the upper body, allowing for a wide range of movement, and protecting the spinal cord and associated nerves. The lumbar spine segment structure also includes important structures such as intervertebral discs, facet joints, ligaments, muscles, and nerves that work together to facilitate movement and prevent injury. Due to its weight-bearing function and mobility, the lumbar spine is particularly susceptible to injury and conditions such as herniated discs, spinal stenosis, and degenerative disc disease. Understanding the structure and function of the lumbar spine segment structure is crucial for preventing and managing these conditions and maintaining optimal spinal health. Normal lumbar lordosis ranges from 30 to 50 degrees.

2.1.5 Sacrum

The sacrum is a triangular-shaped bone located at the base of the spine, between the two hip bones of the pelvis. It is made up of five fused vertebrae that form a single structure, labeled S1 to S5. The sacrum plays an important role in supporting the weight of the upper body, transmitting it to the pelvis and lower extremities, and providing attachment points for various muscles and ligaments. It also protects the nerves that exit the lower part of the spinal cord and travel to the legs and feet. Conditions that affect the sacrum, such as fractures or arthritis, can cause pain, stiffness, and mobility issues.

2.1.6 Coccygeal

The coccyx, also known as the tailbone, is a small, triangular bone located at the bottom of the spine, below the sacrum. It is made up of three to five fused vertebrae and provides attachment points for various muscles and ligaments. The coccyx also plays a role in supporting the body's weight while sitting and providing protection for the internal organs in the pelvic region. Injuries to the coccyx, such as fractures or dislocations, can cause pain and discomfort, particularly when sitting.

2.1.7 Intervertebral disc

Intervertebral discs are gel-like cushions that sit between adjacent vertebrae in the spine, acting as shock absorbers to distribute forces and allow for movement in the spine. They consist of a tough outer layer called the annulus fibrosus, and a softer inner layer called the nucleus pulposus. The annulus fibrosus helps to contain the nucleus pulposus and withstand compressive forces, while the nucleus pulposus helps to absorb shock and distribute forces throughout the disc. The intervertebral discs play a crucial role in spine kinematics by allowing for controlled and smooth movement between vertebrae, while also protecting the spinal cord and nerves. However, they are also vulnerable to injury and degeneration, which can lead to conditions such as herniated discs and degenerative disc disease. As we get older, our discs lose their ability to reabsorb fluid and become brittle and flatter, which is why as we grow older, we get shorter. Bone spurs (osteophytes) can also be caused by diseases such as osteoarthritis and osteoporosis. Discs can expand or herniate due to injury or strain, causing the nucleus to push out through the annulus, compressing the nerve roots, and causing back discomfort and lower back pain.

2.2 Clinical terminologies in spine kinematics

Some terminologies often used by doctors/researchers in the literature are defined in this thesis to better understand anatomical positions and to define spine biomechanics. These terminologies differ from standard language and scientific definitions in several cases. Specific body planes are frequently used by spine surgeons to simplify three-dimensional (3D) problems into two-dimensional (2D) planes. The spine is divided into vertical and horizontal parts by three main planes (Fig 2.2).

- The Sagittal Plane (also known as the Frontal Plane) divides the spine into two parts: left and right.
- The Coronal Plane (or Median Plane) divides the front and back parts of the spine.
- The axial plane (or transverse plane) divides the upper and lower parts of the spine.

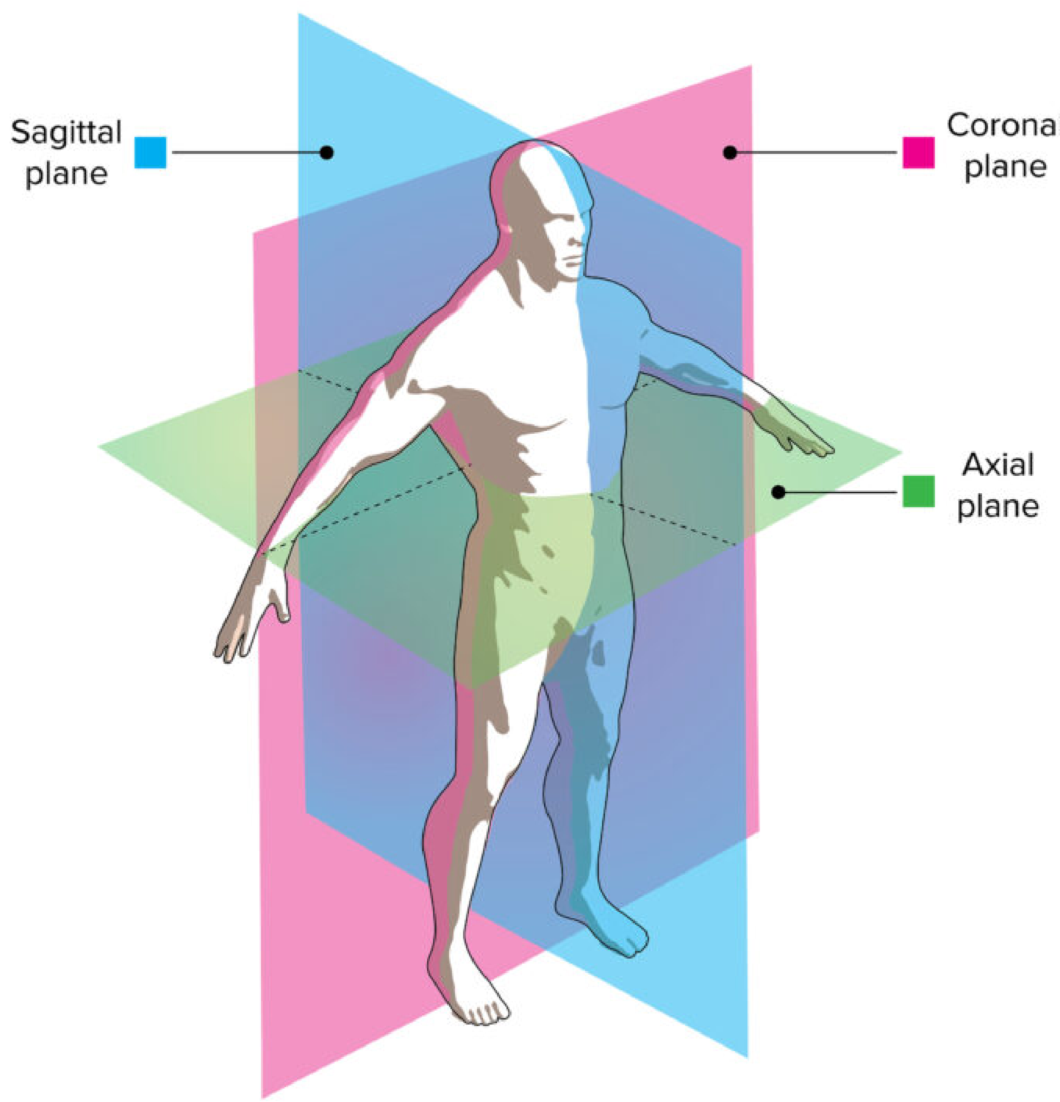

Figure 2.2: Three anatomical planes

In recognition of the superposition of Junghanns' intervertebral mobile segments, the vertebral column can be compared to the flexibility that acts in three perpendicular axes: X, Y, and Z. Translations along these axes, particularly rotations defining the three movements of the vertebral column, are pathogenic when they are over-developed:

- rotation around the transverse X-axis: flexion–extension
- rotation around the vertical Y-axis: true right and left rotation
- rotation around the anteroposterior Z-axis: right and left lateral inclination

As a result, the intervertebral joint has six degrees of freedom (DOF), three DOF in translation, and three DOF in rotation (Lavaste et al., 1997). To fully characterize the spine's location and motion in 3D, there are six degrees of freedom (6DOF), three translational, and three rotational. Furthermore, each DOF's location/motion can be positive or negative about a reference, hence to fully explain the location/motion, twelve terms are required.

DOFs in rotation:

- Forward bending is flexion.
- Backward bending (extension)
- Left/right lateral bending: Bending on the left or right side.
- Torsion/axial rotation (left/right): Left/right twisting (or rotation)

The movements arise in the disc and articular facet joints, which are assimilated into three coaxial joints with no locking position. Ligamentous structures, including the intervertebral disc, and osseous restrictions, are stabilizing mechanisms that can be exceeded under challenging situations, particularly in micro- or macro-trauma.

According to Panjabi, 1978, applying a load to a functional unit of the spine will result in a range of motion that passes through a neutral zone and an elastic zone before peaking. The neutral zone is the region of the intervertebral mobility area closest to rest, where the joint has the largest capacity for movement with the least amount of resistance to intervertebral mobility. Between the end of the neutral zone and the ROM limit, the elastic area correlates to the magnitude of intervertebral mobility. It's important to note that as disc degeneration progresses, the neutral zone and translations expand, indicating instability.

2.3 Spine biomechanics

Spine biomechanics (kinetics & kinematics) is crucial to study as it plays a significant role in human activities from gross motor tasks in daily life – bending, moving, sitting, etc.- to complex movements accomplished in sports, gymnastics, yoga, or dance. The spine is a complex and highly adaptable structure that serves many important functions in the human body, including supporting the weight of the upper body, protecting the spinal cord and nerves, and allowing for movement and flexibility. A 2016 meta-analysis of spine biomechanics studies (Negrini et al., 2016) showed that only a few studies investigated the whole trunk independently and none focused on spinal segments specifically with an emphasis on intersegmental motion involving the cervical, thoracic, and lumbar segments. Understanding the movements as supported by different trunk segments (Leardini et al., 2011), the range of motion (ROM), the coordination between the lumbar-pelvic system, the inter-vertebral and intersegmental movement in the spine are essential for clinical diagnosis (Robertson & Roby-Brami, 2011; test with Aspen collar: Nicholas Rhys Evans et al., 2013; lower back pain meta-analysis: Laird et al., 2014; Bauer et al., 2015; Scholtes et al., 2009; Lateral bending: Gombatto et al., 2007). For medical research, many in-vivo and in-vitro procedures have been utilized to explore and study spinal segments. Both inter-vertebral and intersegmental motion in the spine is seen in general exercises/combined movements, which are motions that occur in tandem with the primary motions, such as flexion-extension, lateral bending, and side-twisting. The range of motion for each spinal segment depends upon the contribution of that segment to support the desired movement and hence investigating the contributing factors is of interest to both clinical intervention and daily-life kinematics. Widmer et al (2019) also suggested that experimental factors such as ROM should be examined. Coupled movements are important in detecting intersegmental motion because it might be affected by spinal problems (Lansade et al., 2009). To study coupled motion it should be quantified as angular displacements of spinal columns. The range of spinal motion or degrees of freedom can be estimated by finding the correlation between the physical parameters and the spine flexibility of an individual.

The kinematics of the lumbar (Wong et al., 2004; Li G et al., 2009; for stooping: Zhu X et al., 2013), thoracic & lumbar (Ignasiak et al., 2017), cervical (Bible et al., 2010; Anderst et al., 2014; rotation/lateral bend: Ishii et al., 2004; 2006) has been investigated extensively. Understanding spine dynamics is also crucial for medical conditions affecting motor movements, like hemiplegia caused by a stroke, Parkinson's, lower back pain, spine injury, osteoporosis (Savic et al., 2018), and obesity (Onyemaechi et al., 2016). Less spinal movements in lumbar and thoracic region were found in chronic low back pain patients performing sit to stand exercise (Christe, G. et al., 2017) and lower lumbar spine movement was observed in participants with low back pain during a step-down functional task (Hernandez, A. et al., 2017). Weak correlations were found in upper/lower lumbar during lifting/sit-to-stand and strong correlations during walking and lifting (Papi, E. et al., 2019) . In addition, upper lumbar angle and greater frontal plane range of motion was found in dancers for the upper lumbar and lower thoracic segments, and no lower back pain was found in any kind of kinematical motion (Swain, C. T. et al., 2019). Another study on the effect of age on thoracic segments of spine (Ignasiak et al., 2017) found that there was simultaneous motion of regions and segments of spine in elderly subjects as compared to the young who flexed the lower spine and hips before thorax and distal thoracic segments before proximal. Wong et al., 2004 analyzed the difference in lumbar spine motion profiles in different genders and age groups by dividing the participants into four groups and observed that the intervertebral flexion-extension (IVFE) curves showed a linear-like pattern in different genders and age groups and there were no statistically significant difference in mobility patterns across genders. However, at all lumbar levels, statistically significant differences in the slope of IVFE curves were found in participants 51 years and older. Zhu X et al. (2013) quantitatively analyzed the effects of various biomechanical response of prolonged stooping in lower back viscoelasticity under more work-related and unrestrained stooped work postures and loading circumstances, and found that after the stooping work period, the range of lumbar flexion and myoelectric activity of the low back muscles increased significantly ($p < 0.05$). The low back extensor muscles did not show flexion–relaxation during stooping work.

Vertebral motions are widely assumed as a biomechanical factor of spinal pathology. Cervical spine segments exhibit complex motions in flexion extension, lateral bending, and axial rotations (Ishii et al., 2004; 2006). As the thoracic spine, which serves as a transitional zone between the cervical and lumbar segments, has received less attention in 3D spine kinematics, its examination is essential to have a better understanding of how symptoms appear and the pathophysiology of spinal illnesses. The range of motion of the thoracic segment is less than the range of motion of other spine sections (Fujimori et al., 2014). Intervertebral motion during exercises such flexion-extension, left-right bending, and left-right twisting has been studied for the Lumbar segment (Li G et al., 2009). Spine flexion can be done in both free motion and with a pelvic constraint. According to Larson et al. (2019), the pelvic constraint did not affect any specific lumbar intersegmental level. Furthermore, they discovered that the differences in whole lumbar spine ROM in the pelvic constrained condition were not statistically significant, implying that spine motion was similar in both movement conditions because the pelvic constraint did not affect lumbar intersegmental spine ROM during spine flexion. Similarly, Beaudette et al. (2020) found that changes in gaze and head orientation while performing spine flexion movement, have similar effects on the ROM of the spine regions, independent of the movement constraints involved. As a result, the current study did not include a pelvic constraint condition in the spine flexion exercise. Despite significant advances in our understanding of the individual segments of the human spine during dynamic motions, the intersegmental vertebral motion during dynamic human body activities remains unclear. Except for Zhu X et al. (2013), who investigated the kinematics and muscular activity for the lumbar spine in stooping postures, very few research studies has evaluated realistic and more natural work situations with human volunteers to investigate their biomechanical responses.

2.4 Knee/hip joint anatomy and biomechanics

Knee biomechanics is the study of the mechanical principles that govern the movement, stability, and load-bearing capacity of the knee joint. Knee biomechanics is a complex field that has been the subject of extensive research over the past several decades. One area of interest has been the role of the knee joint in dynamic movement, such as running and jumping. Research has shown that during dynamic movements, the knee joint experiences large forces and moments that can lead to injury if not properly controlled (Besier et al., 2009).

The knee is a complex joint that connects the thigh bone (femur) to the shin bone (tibia) and is supported by many different ligaments, tendons, and muscles. The ability to carry out daily activities is facilitated by the knee joint which is a complex structure made up of multiple components that function collectively to enable proper movement of the knee. The capacity of the knee joint to withstand heavy loads is mainly due to the bones involved in its formation. The quadriceps and hamstrings are the primary muscles responsible for controlling the movement of the knee joint during dynamic movements. Several studies have investigated the role of these muscles in knee biomechanics. For example, Fukuda et al. (2010) used motion capture and electromyography to study the activation patterns of the quadriceps and hamstrings during jumping and landing. They found that the hamstrings played an important role in controlling knee flexion during landing, while the quadriceps were more active during the propulsion phase of jumping.

The knee joint is a complex structure that can be affected by various factors, including muscle weakness, degeneration, ligament damage, and osteoarthritis. The degeneration of knee cartilage is becoming increasingly common in our modern society, and this can be attributed to a range of factors, including age, diet, genetics, injury, and lifestyle. Additionally, the constant strain placed on the knee during physical activity can lead to the gradual breakdown of cartilage over time (Driban et al., 2017). However, restoring damaged cartilage is not an easy task, as the knee joint's intricate anatomy makes it challenging for patients, surgeons, and physical therapists to facilitate cartilage regeneration once it has been lost (Sophia et al., 2009). Overall, the study of knee biomechanics is important for preventing and managing knee injuries and conditions. By understanding the mechanical principles that govern knee movement and stability, healthcare professionals can develop effective treatment plans and rehabilitation programs for individuals with knee injuries or conditions.

From a clinical standpoint, measuring knee joint angle is a fundamental and crucial approach for both diagnosing knee deficits and tracking treatment progress. Kneeling and squatting are examples of common actions that require deep knee flexion (D'Lima et al., 2007). A multi-joint movement supported workout is squat, which activates the appropriate muscle groups with a single manoeuvre (Kim et al., 2021; Wallace et al., 2002; Gabel et al., 2018). This technique applies strain on the knee bones, the hip joints and ankles, with improper methods leading to lower back pain (Fry et al., 2003; List et al.,2013). Squat exercises are widely used in sports and rehabilitation settings for lower extremity strengthening and conditioning. Several studies have investigated the knee kinematics during squat exercises to better understand the joint mechanics and injury risks associated with these movements. Kim et al., 2015 used kinematic analysis to examine the relationship between the range of motion of the hip, knee, and ankle joints and the capacity to execute squats of different depths with heels lifted from the ground. Fry et al. (2003) analyzed knee kinematics during the back squat exercise using motion analysis. They found that the knee joint underwent substantial flexion and extension throughout the movement, with the greatest knee flexion occurring at the bottom of the squat. They also observed significant differences in knee kinematics between the high-bar and low-bar squat variations. In the past, studies have explored various attributes of deep squat exercises. For instance, Butler and colleagues (2010) examined whether there were unique biomechanical approaches used by individuals who scored differently on the deep squat test of the Functional Movement Screen. Flanagan et al. (2008) investigated the effects of squat depth on knee kinematics and muscle activation patterns. They found that deeper squat depths resulted in greater knee flexion and quadriceps muscle activation, while shallower squat depths resulted in greater knee extension and gluteal muscle activation. Paoli et al. (2009), compared front and back squat exercises and found that, the back squat resulted in significantly greater knee flexion, while the front squat resulted in significantly greater knee extension. They also observed that the front squat placed more demand on the quadriceps muscles, while the back squat placed more demand on the gluteal muscles. These all past studies demonstrate that knee kinematics during squat exercises vary depending on the specific exercise variation, depth, and experience level of the subject. Proper form and technique during squats are essential for minimizing knee injury risks and maximizing training benefits.

2.5 Different angle extraction method in spine kinematics or Kinematics

In this section, two approaches to calculating spine angular displacement have been discussed, with their advantages and disadvantages. Kinematics is the study of objects' motion without considering the masses or forces that cause the motion. Linear kinematics is the simplest form, whereas rotational kinematics is a little more difficult to implement. Kinematics involving translation and rotation can be used to describe the state of a rigid body (rigid-body kinematics). Human movements are generally modeled with multi-segmental models, which consist of rigid bodies joined by joints with variable degrees of freedom.

In general, the rotation and translation of a rigid body in space can be used to characterize its movement relative to a global reference system. The 3D rotation matrix, R, defines the rotation, and the 3D translation vector v, defines the translation. There are various techniques available to break down the physical properties of R and v into an interpretable representation. Instead of using a global reference system, body segment movements are usually measured relative to each other. For example, the movement of the upper arm in relation to the upper body is described in terms of flexion and extension. In clinical settings, the Euler method is commonly employed to analyze R, which breaks it down into angles that describe flexion-extension, abduction-adduction, and internal-external rotation. To determine joint translation, the helical axis method is frequently used. This technique describes the movement of a segment using a rotation angle around an axis, along with a scalar translation along the same axis that can move in space. (Zatsiorsky, 1998: Kinematics of Human Motion. Pennsylvania: Human Kinetics Pub.)

Sagittal, frontal, and transverse planes are the three anatomical planes in which the spine moves. The cervical, thoracic, lumbar, and sacral are spinal regions that are separated based on their curvature. Flexion/extension refers to spinal rotations that occur in the sagittal plane. The range of lumbar flexion/extension is from kyphotic to lordotic, with a neutral posture being slightly lordotic. Left/right lateral bending is lumbar rotation in the frontal plane, while left/right axial rotation is lumbar rotation in the transverse plane.

2.5.1 Angle Calculation method: Euler Angles and Euler/Cardan Sequences

A multitude of approaches can be used to describe three-dimensional joint motion. A few standard methods include Euler angles, helical axes, and projection planes. Even while standards for kinematic analysis are being established, the choice of kinematic analysis method varies across research studies and groups. Despite the limitations of other methods, Euler angles continue to be the most popular method in biomechanics due to their simple numerical description and reduced susceptibility to noise. Euler angles are a set of three angles that describe how the orientation of an object changes relative to a fixed coordinate system. These three angles are determined by a sequence of three rotations around the axes of the fixed coordinate system to express the change from the initial orientation to the final orientation. A YXZ sequence, for example, describes an orientation change by first rotating the local coordinate axis around its y-axis by R_y, followed by R_x rotation around the reoriented x-axis, and finally R_z rotation around the final z-axis. Roll, pitch, and yaw are the most commonly used terms for these angles. In human motion studies, these angles are typically defined as flexion/extension in the sagittal plane, lateral rotation in the frontal plane, and axial rotation in the transverse plane. Rotation matrices are used to model rotation around each axis as,

$$R_x = \begin{pmatrix} 1 & 0 & 0 \\ 0 & cos\alpha & -sin\alpha \\ 0 & sin\alpha & cos\alpha \end{pmatrix} \quad R_y = \begin{pmatrix} cos\beta & 0 & sin\beta \\ 0 & 1 & 0 \\ -sin\beta & 0 & cos\beta \end{pmatrix} \quad R_z = \begin{pmatrix} cos\gamma & -sin\gamma & 0 \\ sin\gamma & cos\gamma & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{2.1}$$

The 3x3 matrix obtained from the ordered multiplication of the three rotation matrices is used to extract Euler angles,

$$R_{xyz} = \begin{pmatrix} cos\beta\ cos\gamma + sin\alpha\ sin\beta\ sin\gamma & sin\alpha\ sin\beta\ cos\gamma - cos\beta\ sin\gamma & cos\alpha\ sin\beta \\ cos\alpha\ sin\gamma & cos\alpha\ cos\gamma & -sin\alpha \\ sin\alpha\ cos\beta\ sin\gamma - sin\beta\ cos\gamma & sin\alpha\ cos\beta\ cos\gamma + sin\beta\ sin\gamma & cos\alpha\ cos\beta \end{pmatrix}$$

from which the values for Euler angles α, β, and γ may be extracted:
For α,

$$\alpha = -sin^{-1}(R_{xyz}(2,3))$$

For β,

$$\frac{(R_{xyz}(1,3))}{(R_{xyz}(3,3))} = \frac{cos\alpha\ sin\beta}{cos\alpha\ cos\beta} = tan\beta$$

which leads to,

$$\beta = tan^{-1}\frac{(R_{xyz}(1,3))}{(R_{xyz}(3,3))}$$

Similarly for γ,

$$\frac{(R_{xyz}(2,1))}{(R_{xyz}(2,2))} = \frac{cos\alpha\ sin\gamma}{cos\alpha\ cos\gamma} = tan\gamma$$

which leads to,

$$\gamma = tan^{-1}\frac{(R_{xyz}(2,1))}{(R_{xyz}(2,2))}$$

The Cardan sequences represent a specific category of Euler sequences. While the Euler angles can be produced by any combination of the three axes, the Cardan angles are created by strict combinations of rotations around three perpendicular axes. Therefore, there are only six Cardan sequences available, such as XYZ, XZY, YXZ, YZX, ZXY, and ZYX. The selection of different Euler/Cardan sequences (Crawford et al., 1996; Skalli et al., 1995) can lead to variations in angular motion values. Some efforts have been made to standardize Euler/Cardan sequences for different joints, but the adoption of these standards is not uniform across the field. Furthermore, different definitions of coordinate axes add to the confusion and inconsistency among recommendations and studies. Using this method, Euler/Cardan sequence(s) and coordinate axes definitions must thus always be reported in kinematic studies.

Aside from the effect of sequence selection, another flaw associated with the use of Euler angles is the occurrence of a gimbal lock. When one axis crosses another parallelly, the gimbal lock effect causes an axis description to be lost. Gimbal lock occurs most frequently when the middle rotation approaches 90° (Crawford et al., 1996; Skalli et al., 1995). According to kinematics studies of the output Euler angles, this appears to be an instantaneous jump of a multiple of ±90°: common values of gimbal lock jumps include ±90°, ±180°, and ±360°. As a result, to avoid gimbal lock situations, you must orient the local references systems. It is crucial to align the reference system accurately with the body segments to avoid the overlapping of abduction/adduction and inward/outward rotation in the calculated flexion. In addition, one limitation of utilizing Euler angles is that the handling of translation is separate from the handling of rotation. To overcome this limitation, the helical axis transformation can be utilized to combine the treatment of translation and rotation within the model.

2.5.2 Angle Calculation method: Helical axis method

To describe the movement of a body in three dimensions, it can be separated into two parts: rotation around and translation along the instantaneous axis of rotation. The helical axis is identified by a unit direction vector, n, and a point c on the axis that satisfies $c^T n = 0$. This axis is not stationary but is defined by its direction and point, and it's known as the screw axis or the axis of motion. The movement can be characterized by the angle of rotation, θ, around the helical axis, and a scalar translation, t, along it. This method of describing movement is known as the helical axis method and has been studied by various researchers, including Spoor et al. (1980), Woltring et al. (1985), and Woltring et al. (1994).

A method of extracting helical axis characteristics from the R and v values involves defining a matrix U that satisfies the condition $U = R^T - R$ (Söderkvist, 1990). This relationship can be demonstrated to hold true:

$$n = \frac{1}{\sqrt{U_{23}^2+U_{31}^2+U_{12}^2}} \cdot \begin{bmatrix} U_{23} \\ U_{31} \\ U_{12} \end{bmatrix}$$

$$\theta = \begin{cases} cos^{-1}(\frac{R_{11}+R_{22}+R_{33}-1}{2}) \\ sin^{-1}(\sqrt{U_{23}^2+U_{31}^2+U_{12}^2}) \end{cases}$$

$$c = \frac{1+cos\theta}{2sin^2\theta} \cdot (I - R^T)v$$

$$t = n^T v$$

The method of helical axis can be advantageous in analyzing joint translations, as it enables the axis to have the flexibility to move throughout space. This provides an opportunity to examine the actual movement of the joint's center by identifying the intersection of at least two instantaneous helical axes from two different points. However, a disadvantage of this method is that errors in the orientation and location of the helical axis are significant for small rotations because they are inversely proportional to the rotational magnitude (Woltring et al., 1985). Another disadvantage is that interpreting the movement clinically, such as determining the amount of flexion, is more challenging than when using the Euler representation.

Chapter 3

Techniques for measuring trunk motion kinematics

Inclinometers, goniometers, and motion capture devices can all be used to measure spinal and knee/hip range of motion (ROM) at the skin's surface. Lower back pain can be diagnosed with the help of these measurements in the clinical setting. However, they do not provide information on the vertebrae's locations or rotational orientation; they can only measure motion in a specific body region (Fritz et al. 2005; Burdett et al. 1986). Individual vertebral positions and orientations can only be determined by measuring the individual vertebrae. Measurements are classified as in vivo or in vitro. In vitro measurements use a piece of the original anatomy extracted from a cadaveric specimen, whereas in vivo measurements are carried out on living subjects. Vitro measurement has the apparent advantage of removing obstructing tissues and bones, allowing direct access to the anatomy of interest. This allows for direct measurements at the points of interest. To better understand mechanical and tissue properties, in vitro measurements can be used to isolate and alter specific anatomical regions in controlled conditions (Brown et al. 2002).

In vivo measurements, while limiting access to the vertebrae, provides motion parameters that have not been affected by dissection or loss of active muscle contribution and can be categorized as invasive or noninvasive. Currently, there aren't many examples of noninvasive in vivo measurements due to practical and ethical constraints and limitations. Kaigle et al. (1992) performed invasive in vivo vertebral measuring by inserting bone pins into neighboring vertebral spinous processes via the skin. While this approach provides for a more direct examination of human joint motion, the research settings may produce anomalous findings due to pain and discomfort and increased motion resistance caused by the interaction of the bone pins and the tissue at the insertion location.

An overview of several methods for collecting the static and dynamic spine-knee/hip kinematics data is provided in this chapter. The reliability and validation tests and the benefits and drawbacks of each approach will be examined.

3.1 Marker-based motion capture techniques

3.1.1 Radiographic imaging

Planar radiography pictures were previously used to study the trunk's kinematics (Dvorák et al.,1991). Spinal measurements can be made via medical imaging, which provides comprehensive images of the anatomical components beneath the skin. Radiographic methods, such as traditional x-ray imaging, create images by sending an electromagnetic radiation beam through the object of interest. The fraction of the beam that is not absorbed or dispersed by the object produces an exposure image on the object's opposing side. Radiography is particularly useful for examining bone geometry, but it exposes individuals to ionizing radiation, which is a known health concern. Planar radiographs have been widely utilized to assess sagittal plane vertebral rotation and translation (Allbrook 1957;Pearcy & Bogduk 1988). The analysis was confined to one plane of motion, and the motion was determined by tracing a vertebra and comparing it to other images captured from different angles. Coupled motions were not observable since this approach only gave data about one plane of motion at a time. Pearcy et al.(1985) integrated two radiographs to generate three-dimensional information on spinal ROM, although only static data were evaluated. Cineradiography and videofluoroscopy (Harada et al., 2000) have been used to evaluate dynamic trunk movement (Adams et al., 1988).

However, limitations include picture distortion effects caused by radiography beam divergence, which must be addressed during data processing (Frobin et al. 1996). The most significant consequence of radiographic techniques is radiation exposure, especially in multiple planar radiography and cineradiography, when participants are exposed to relatively high levels of radiation. The amount of radiography tests and/or treatments performed over time may be connected to the risks of radiation exposure. Fluoroscopy is a modification of traditional planar radiography that allows for dynamic real-time imaging by focussing a continuous x-ray beam onto a fluoroscopic screen. Fluoroscopy has been employed in various studies to measure vertebral kinematics, even though it offers a higher cumulative dose of radiation and needs extensive data processing work due to the increased volume of imaging data, which degrades picture quality (Teyhen et al. 2007; Ahmadi et al. 2009).

3.1.2 Computed tomography (CT)

Computed tomography (CT) is a medical imaging technique that uses X-rays to produce detailed images of the body's internal structures. CT has been used for many years in the study of spine kinematics. It can provide high-resolution images of the spine in different positions, allowing for detailed analysis of vertebral motion. One of the advantage of CT for spine kinematics analysis is its high spatial resolution, which allows for accurate measurements of small changes in vertebral position and angle. CT can also provide images in multiple planes, allowing for analysis of motion in different directions. Additionally, CT can be used to generate three-dimensional (3D) models of the spine, which can aid in the visualization and analysis of complex spinal motion patterns from bone and soft tissues. The capacity to evaluate non-planar motion is a crucial advantage of collecting three-dimensional (3D) spinal data. CT involves more ionizing radiation than standard x-ray imaging, limiting its usage in elective research (Brenner Hall 2007). To prevent unnecessary radiation exposure, computed tomography (CT) has fewer applications in clinical research than traditional x-rays (Brenner Hall 2007). CT's high spatial-resolution capabilities are useful for examining minor displacements during axial lumbar rotation, despite its limited usage for measuring bony spine anatomy (Ochia et al., 2006).

3.1.3 Magnetic Resonance Imaging (MRI)

A magnetic field is used in MRI to produce three-dimensional anatomical images. A magnetic field of intensity 0.3-3 Tesla is directed across the area of interest, causing polar magnetic alignment within the field's atomic nuclei. The magnetically aligned states revert to lower energy equilibrium states once the magnetic field is removed (relaxed) and generates radio-frequency waves. Tissues with various relaxation times emit various frequencies, allowing the bone and soft tissues to be visually distinguished. The 3D location and orientation of all the vertebrae in vivo have been widely studied using MR imaging. Participants must lie prone or supine for the duration of the imaging process in order to comply with traditional MRI image gathering requirements, which restricts the range of motion and changes the natural direction of gravity compared to standing postures. Fujii et al. (2007) built a rotating hip device that allowed imaging at fixed axial rotations to approximate natural rotations in the prone position. This arrangement, however, is incapable of accounting for gravitational influences. Traditional MRI's inability to record spine images in an axial loading posture is addressed by adding a non-restrictive image capture volume in the weight-bearing MRI technique. Weight-bearing magnetic resonance imaging can be obtained when the person is standing and under normal gravity loads. Furthermore, an increased field of view allows for a wide range of motion for most joints. Weight-bearing MR images, like conventional MRI, are confined to static positions, and participants must stay motionless during collection since movement generates artifacts in the image. Weight-bearing MRI has less imaging power than conventional MRI, resulting in a poorer degree of detail.

MRI provides 3D information through a sequence of planar image slices that span the volume of interest. Image slices may be segmented into volumes of interest called segmentation. Each image slice must be analyzed to find the regions of interest that match those in the previous one. The quality and clarity of the images have a significant role in the speed and accuracy of segmentation. The selection of areas of interest in high-contrast images with well-defined boundaries can be automated with identification algorithms. However, segmenting the vertebrae is particularly difficult since the soft tissues surrounding the bone reduces contrast and definition along the bone's edge. MR images generated by 1.5 Tesla or more equipment have often been segmented using automated methods (Carballido-Gamio et al.,2004;Huang et al.,2009).

MR images produced by lower-powered MRI equipment sometimes need manual region identification. Manual segmentation is time-consuming and susceptible to rater error. However, investigations have proven the ability of expert raters to correctly rebuild vertebral bodies based on visual recognition

(Cargill et al., 2007). The difficulty of quickly and precisely segmenting low-quality MR images limits data analysis capabilities. Active research is being conducted to develop noise-insensitive segmentation capabilities. Both Schmid and Magnenat-Thalmann (2008) and Strickland et al. (2011) used shape recognition to improve border detection approaches for automatic segmentation. Manual segmentation will be required until these approaches are developed and sufficient for low-energy devices. Manual segmentation was superior to two automated approaches in Cargill et al. (2007)'s study.

3.1.4 Electromagnetic motion capture system

The kinematics of the spine can be measured in three dimensions using an electromagnetic motion tracking device, which is portable and easy to use. This system is a combination mostly of two components: the transmitter and the receiver, both of which are coupled to an electronic system unit. When a transmitter generates an electromagnetic field, the receiver uses it as a point of reference for its location. Detecting the field created by the transmitter, the receiver emits a signal that is used in a mathematical algorithm to compute the receiver's position. Also, detecting the position of more than one receiver at once is possible. According to reported data, this particular technique has a static accuracy of 0.8 mm for position and 0.15º orientations in terms of root mean square (RMS) values. This method has proven to be effective in kinematic investigations, as demonstrated by previous research (An et al., 1988). Furthermore, Mills et al. (2007) conducted a study on the repeatability of dynamic motion measurements using an electromagnetic system while walking, which demonstrated strong reliability within the same trial, within a single day between different testers, and between different days with the same tester. Burnett et al. (1998) also found high repeatability in spinal motion measurement during fast bowlers in cricket. Finally, Pearcy and Hindle (1989) discovered that the total RMS error for dynamic measurements of spinal rotation was less than 0.2º.

At the level of the first lumbar vertebrae and first sacral vertebrae, sensors were placed to analyze lumbar spine motions (Shum et al.,2005a;2005b,;2007a, Van Herp et al., 2000, Wong and Lee, 2004) In this way, the kinematics of the lumbosacral were studied. Additional data on lumbar spine behavior might be obtained by increasing the number of sensors, but this would make analysis more difficult. One of the system's greatest drawbacks is its limited operational range. Although the manufacturer's report stated that the maximum distance between the receiver and transmitter was 3.05 meters, several studies demonstrated that this functioning zone was substantially narrower, with Milne et al. (1996) result revealing a cubic region about 220-720 mm3 from the source. This value is manufacturer dependant, although validation tests are advised to validate the functioning zone. Another drawback of this method is that it is sensitive to metal-interference. The presence of metal in the testing environment may impact the measurement and limit the functional range (Milne et al., 1996). Compared to radiography techniques, the electromagnetic system was shown to be accurate and less risky for biomechanical research. Furthermore, the technology is less expensive than competing methods, such as video-optical motion capture.

3.1.5 Marker-based motion capture techniques

Motion capture systems (Nagymáté et al., 2018) are widely used for biomechanical applications, human motion detection, animations and military purposes. Three-dimensional camera-based motion capture is broadly acknowledged as the gold standard for capturing and analyzing kinematic performance (McLean, S. G. et al., 2005). Traditional 3D motion capture uses several high-speed cameras that generate 3D coordinates based on point triangulation from distinct two-dimensional (2D) camera projections (Mündermann L. et al., 2006). Active or passive markers are used in the system. Each camera emits IR light at a predetermined pulse frequency in a passive marker system. Each camera captures a two-dimensional image of the light reflected by the markers attached to the body segments. The 2D data from each camera is transformed into 3D coordinate data through a calibration technique. Markers that produce a signal, such as infrared light, are active markers. Each marker has a unique frequency that can be easily detected during movement registration (Nigg et al., 2007). The most common system used is a passive optical system in which infrared cameras track retroreflective markers. Two such motion capture system are Vicon (Vicon, Oxford UK) motion capture system which uses cameras to record up to 120 frames per second (fps) at 16mp (maximum 2000fps) and has an estimated accuracy error of less than 2mm (Merriaux, P. et. al., 2017) and Opti-Track motion capture system which uses cameras capable of collecting 240fps (positional errors less than +/-0.30mm; rotational errors smaller than 0.5 degrees) (Nagymáté, G., et al., 2018). For kinematic studies, optoelectronic tracking (Vismara et al., 2010; Feng et al., 2019; Ghasemi, M., & Arjmand, N., 2021) of the spine in movement is considered highly accurate. Other system for example, active optical systems can record infrared light from 'active' markers (such as those with LEDs). The trunk kinematics of gait analysis can also be analyzed using video optical systems (VOS) (Crosbie et al., 1997). These types of systems have been utilized in various applications such as the assessment of lateral and forward bends in standing (Al-Eisa et al., 2006; Esola et al., 1996) and sitting (Al-Eisa et al., 2006) positions, as well as evaluating balancing strategies while sitting (Van Daele et al., 2009). By incorporating a force platform, a reference position can be used to conduct motion studies and determine joint moment. Manufacturers of these systems claim high accuracy in all three axes of motion, however, Windolf et al. (2008) discovered that the precision is dependent on the task, environment, and set-up, with an inaccuracy of up to 0.42 mm observed during systematic testing. Accuracy was further assessed by comparing radiograph data, which revealed that the optical system had minimal error in all three planes of motion (maximum error of ±2° and root mean square (RMS) error of less than 1°) (Pearcy et al., 1987).

3.1.6 Comparison between methods

3D models are required to determine the angular displacements of each section using 3D motion analysis. Estimation of intersegmental spinal motion used techniques such as Magnetic Resonance Imaging (Saifuddin et al., 2003), CT scan, MRI, X-Ray, and skin-mounted systems (Severijns et al., 2021). Vicon

- Motion Capture systems, Kinect sensors, BTS bioengineering, and optoelectronic systems are some of the sensing systems utilized for motion analysis.

MRI and CT both have their advantages and disadvantages when it comes to studying the biomechanics of the spine. Bony structures may be automatically segmented with better picture quality using CT scans. Human eyes and manual work are still required to segment MR models, which is time-consuming. CT scans' enhanced picture quality of bone structures came at a high radiation expense. This raises ethical concerns about the safety of the subjects being studied. Furthermore, MRI allows for enhanced imaging of the ligamentous and soft tissues surrounding the vertebra and their relationship to significant neurologic structures in this area, which may aid in the evaluation of subject-specific spine health/degeneration. Although radiographic have been used to examine spinal motion, they have proven to be more beneficial for static measurements and carry major health hazards for the participants.

In biomechanics, where kinematics of the human body are investigated, electromagnetic and video-optical systems are becoming popular. It has been proven that all of these methods can accurately evaluate trunk kinematics. However, all of these approaches are limited by various factors that make them useful for different situations.

For intervertebral motion, an in-vitro experiment compared the electromagnetic motion system with lateral radiography, and the findings indicated only minor differences in the sagittal plane rotation (0.47±0.24º) between the two approaches (Zhao et al., 2005). In addition, when compared to radiography methods, Yang et al. (2005) discovered that measuring the spinal angle with an electromagnetic device was reliable. Radiographic images show a relative motion error of less than 8% when compared to skin sensors attached to the back skin of the spine (Yang et al., 2008). Bull and McGregor (2000) discovered an average measuring error of ±1º when they used MRI imaging to examine the error owing to relative motion between the skin (where the sensor is positioned) and the vertebrae in spinal flexion/extension. Video-optical motion systems have also been compared to electromagnetic devices. To test the dependability of optical and electromagnetic motion systems, Hassan et al. (2007) used a mechanical arm. It was found that the three planes of motion differed by 0.15º, -0.32º, and 0.54º between the electromagnetic and video-optical systems, indicating a high degree of similarity between the two techniques. Zwambag et al., 2018 devised a method for recording 3D Intersegmental Angular kinematics during dynamic spine movements with a higher spatial resolution that could be used for detecting intersegmental motion patterns, stiffness, and stability. This study compared the electromagnetic and intersegmental methods and found that both techniques had an excellent agreement. In recent decades, researchers have used optoelectronic motion analysis to examine the neurophysiological and biomechanical underpinnings of human posture and movement to create a biomechanical spine model. Most investigations of coupled motion in the cervical spine focus on intervertebral motion and are confined to MRI and CT imaging. (Feng et al., 2019) demonstrated that optical motion capture techniques for evaluating the cervical range of motion have good repeatability and validity. Different optoelectronic technologies have commonly been used to monitor/record trunk kinematics in various methods, with two to nine cameras being used in most cases. In conclusion, a video-optical method is more useful for research that can be performed in a laboratory environment, for this reason, this method has been used for data collection in our study.

Although, the video-optical method has various limitations, such as portability, expensive, higher calibration time, and physical customized space requirement, in addition to trained personnel. A significant challenge with the marker-based optoelectronic method for the spine is that its structure can be modeled as rigid or deformable as motion is dependent on its adjacent segments. Hence, incorrect skin marker placement impacts the spine's curve measurement and kinematic variability (Severijns et al., 2021). Minute errors in marker misplacements are usually smoothened out using polynomial fit, which quantifies the quality of spine movement and ensures continuity in the arrangement of the spinal column. The internal spinal alignment can be predicted using a cubic polynomial (Zwambag et al., 2018), fourth-order polynomial (Schmid et al., 2021), fifth-order polynomial (Ranavolo et al., 2013; Severijns et al., 2021), and 6th order polynomial (Taylor et al., 2010). The shape estimation of the spinal curve using these polynomial fits investigated the changes due to lower back discomfort (Taylor et al., 2010) and spinal deformity (Severijns et al., 2020). Ignasiak et al. (2017) used cubic polynomial to approximate the S-shaped spinal curve for age-related changes. Zwambag et al. (2018) applied a similar fit to compare the accuracy of the marker-based Opti-track motion capture system and the traditional electromagnetic system.

3.2 Marker-less motion capture techniques

The marker-based technique has various limitations, such as portability, expensive, higher calibration time, and physical customized space requirement, in addition to trained personnel. A significant challenge with the marker-based optoelectronic method for the spine is its structure can be modelled as a rigid or deformable structure as motion is dependent on its adjacent segments. Hence, incorrect skin marker placement impacts the spine's curve measurement and kinematic variability (Severijns et al.,2021). Practicable alternatives and inexpensive instruments are hence required by the health professionals for the motion assessment.

Researchers developed marker-less motion capture techniques that predict motion in broader scenes using multi-view video (Moeslund et al., 2006), with more recent solutions being real-time (Stoll et al., 2011). This was done because commercial systems that required marker suits have usability constraints (Menache, 2000). Recently, markerless solutions that do not require the placing of markers on anatomical landmarks have been developed. These systems provide a more streamlined data capture method and are less prone to measurement error generated by marker movement related to skin movement or soft tissue artifact, a known drawback of marker-based systems (Sati, M. et al.,;, Corazza, S., et al.,). Markerless systems rely on complicated tracking algorithms to provide a 3D representation of the subject (Corazza, S. et al.,).

Applications such as 3D game character control, immersive virtual and augmented reality, and human-computer interaction have led to the development of new real-time full-body motion estimation methods using only a single, easy to install, depth camera, such as with the Microsoft Kinect (Microsoft Corporation 2010, 2013, 2015). Cameras using RGB-D sensors give crucial depth information that substantially helps monocular posture reconstruction and have comparable accuracy (Puthenveetil et al., 2013). Despite this, RGB-D cameras are less common and more expensive with higher power consumption; they have poorer resolution and a lower dynamic range when used outside (due to interference from sunlight).

When working with only a single color camera, it's significantly more difficult to estimate skeletal pose. Body pose estimation in 2D using monocular RGB has been extensively studied, however it only estimates the 2D skeleton pose (Bourdev and Malik 2009; Felzenszwalb et al. 2010; Felzenszwalb and Huttenlocher 2005). 2D pose estimation relies on learning-based discriminative methods, such as deep learning (Insafutdinov et. 2016; Lifshitz et al., 2016; Newell et al., 2016; Tompson et. 2014), and some of these methods have shown real-time estimation (Cao et al. 2016; Wei et al. 2016). These methods are the current state of the art. The 3D skeleton pose estimation in monocular RGB is a significantly more difficult problem that has been solved by a limited number of algorithms (Bogo et al. 2016; Tekin et al. 2016b,c; Zhou et al. 2015, 2016, 2015b). Unfortunately, these approaches are usually offline and commonly reconstruct 3D joint positions for each image, which are temporally unstable. They don't enforce consistent bone lengths, which is a problem. Due to the lack of real-time 3D character control, they are unsuitable for these applications.

Recently, these problems have been solved by Mehta et al. 2020; they used SelecSLS Net convolutional neural network, fully connected neural network, and space-time skeletal model fitting for the real-time analysis of multi-person 3D motion capture using a single RGB camera. Automated marker-less pose estimation systems (Mündermann et al., 2006) used 3D articulated models in multiple 2D image planes (Kolotouros et al., 2021; R.J. Cotton, 2020) and used human mesh recovery techniques for pose estimation. The state-of-the-art deterministic regression models have resulted in increased accuracy and precision-based key points detection, human pose reconstruction (Bogo et al., 2016), and automatic estimation of a 3D human pose from a single image (Kolotouros et al., 2021), model fitting and generating human mesh. Human mesh reconstruction is applied to an image's 2D key points (human body joints) based on training methodology and a simple network design. The mesh is used for RGB analysis to estimate ROM for angular displacements of the three spinal segments. It allows for rotational and translational motion under 3 Degree of Freedom. Cotton (2020) developed a system combining marker-less pose estimation with sensors-based motion tracking for the rehabilitation of patients. Smartphones with embedded (Inertial, accelerometer, and gyroscope) sensors are capable of detecting the joint position, measuring joint ROM, active cervical ROM (Guidetti et al.,2017), and active craniocervical ROM (Pourahmadi et al.,2018) have demonstrated robustness (Sedrez et al.,2020).

Chapter 4

Investigating the role of physical activity level and body build characteristics on the kinematics of the spine and knee/hip joint - Marker-based motion capture system

This study aims to investigate the spine and knee biomechanics of young and healthy male and female participants with no reported spinal injury or lower back pain issues and no identified clinical spine deformity. This study investigates spine kinematics by the angular displacement of the three spine segments and the lumbopelvic-hip segments in flexion, lateral-bend, twist, and squat exercise executed by normal healthy young adults. To generate a reference chart/model, the angular displacement is correlated to an individual's physical parameters such as height, weight, BMI, WHR, and physical activity level. Based on the correlation analysis of physical parameters to the angular displacement, we hypothesized the relationship between angular displacements and physical parameters in young and healthy participants. Our study followed the standard marker set proposed by List et al. (2013) and other studies from the Institute of Biomechanics ETH Zurich.

We used two approaches to collect data for this study (marker-based Opti-track cameras and marker-less single RGB cameras). Comparing the data collected from the same group of participants from two techniques (RGB & marker-based motion capture) would help in better accuracy estimates, error corrections if required, and, significantly, for clinical/human movement science applications with the reference models thus generated. Importantly, the comparison of RGB with motion capture allows for applications of an inexpensive marker-less system for use in clinics backed by robust models.

4.1 Methodology

4.1.1 Participants

- Ethics approval was provided by the Human Study Ethics Committee of the institute. Informed consent was obtained from each participant. They were further informed that they could exit the study at any time with no penalty. Forty male subjects (age=19-33 years; mean=21.7 ± 2.97 years) and twenty-two female subjects (age=19-30 years; mean=22.5 ± 3.36 years) pursuing undergraduate and graduate studies at institute (fully residential campus) volunteered for this study. As part of the curriculum, all students undergo 1 hour/day of physical training (exercises, yoga, sports, etc.) in the first year of their 4-year college program. The campus also has an active sports center and a yoga hall with trainers.

- Inclusion criteria:
  - Adults with >=17 and <= 35 years of age (younger people).
  - Adults reported being under no medication, especially for pain, at the time of the experiment.
  - Adults who had no record of any spine/back injuries in the past
- Exclusion criteria:
  - Any spine/knee injury that would limit the ability of the adult to participate in the study.
  - Current pain medication or taking steroids for muscle injury
  - Refusal to give informed consent.

4.1.2 Experimental Paradigm

A three-dimensional marker-based motion capture setup of 6 Opti-track Prime-13w motion tracking cameras capable of capturing 240fps (positional errors less than +/-0.30mm; rotational errors less than 0.5 degrees) which can detect active and passive markers was the studio setup. The cameras detect the infra-red reflectors applied as markers on the body. The Motive Opti-track software controls the cameras to capture 6 Degree of Freedom (3D position and orientation) data as shown in Fig 4.1.

Figure 4.1: The three-dimensional marker-based motion capture setup of 6 Opti-track

The tracking video was captured in a room (20x10 ft). The marker set had 12 infrared reflectors arranged along the spinal column's length. The positioning of the markers is as follows: three on the cervical, five on the thoracic, and four on the lumbar region (as shown in Fig 4.2). Additionally, two reflectors each on the knees (one each on the patella and lateral knee), one on each ankle (Fibula), one each on the palm, two on the shoulders (approximately the trapezius muscle), just above the hips and in line with the last lumbar segment reflector, two on the upper chest. The marker positioning configuration is in accordance with previously reported studies (Suter et al., 2020; Zemp et al., 2014; List et al., 2013). Data collection was preceded by calibration to identify the capture volume by the 'wanding' process to reduce occlusion, setting up of the ground plane and origin as required for the coordinate system in Motive (Optitrack's-software).

Figure 4.2: Marker placement covering the spinal column. A Velcro strip with retro-reflectors affixed was prepared for ease of fixing on the suit.

Participants were positioned at a demarcated position on the floor with maximum capture volume as determined by the calibration stage. Markers directly fixed on skin (either wearing shorts or bikinis by female participants), which is optimal and with less errors would be difficult to get participant consent especially when collecting data from female participants, hence a skin-tight non-reflective bodysuit was worn to minimize the error margin. The instruction was to perform slow (no timer) and gradual movements for each exercise to maximize sensor tracking and minimize detection error. Participants performed spine flexion (Fig 4.3 A), lateral bending (Fig 4.3 D:i,ii,iii), twist (Fig 4.3 D:iv,v,vi), and unrestricted unilateral squat (Fig 4.3 E) exercises, and for ecological relevance, no hip constraint was used (Fig 4.3 E) based on individual comfort with feet to hip-width alignment. Three self-paced trials of each exercise were executed preceded by a warm-up. The BMI and WHR were measured, and self-reported Physical Activity Level scores calculated using a questionnaire on frequency (hours in a week) of participation insports, yoga, jogging, dancing, over the last 2 months from one to five (one as the lowest and 5 as highest). The data was collected during the Covid pandemic between the 1st wave and 2nd wave and hence as most team sports activity was suspended and one was permitted to take walks, jog, or cycle within the campus, the question did not cover sports like basketball, football or cricket.

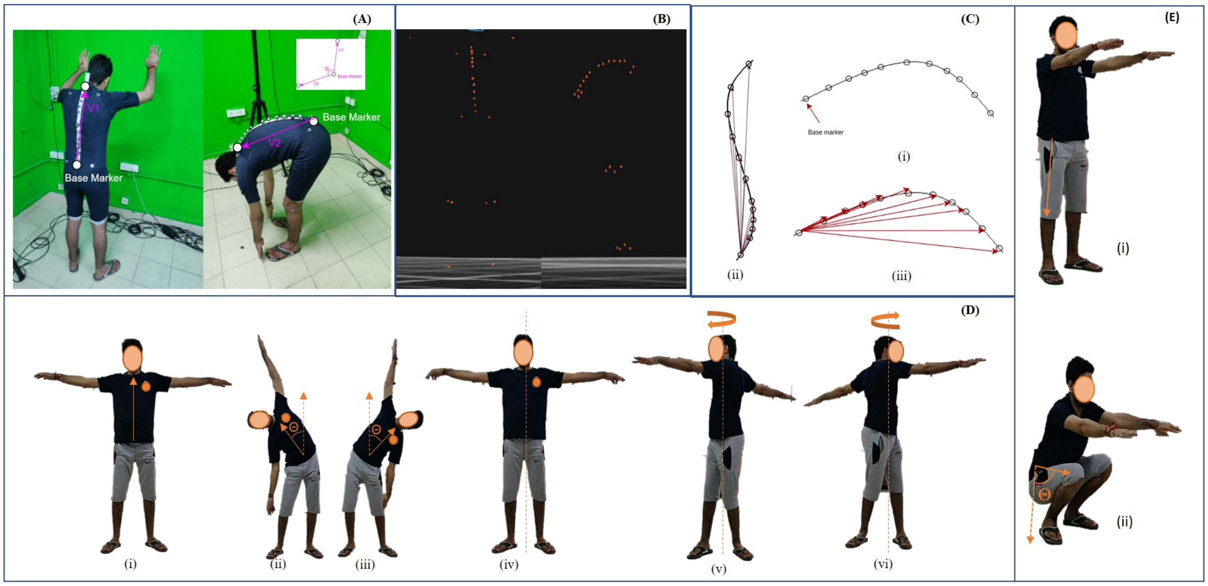

Figure 4.3: (A) Marker placement covering the spinal column. A Velcro strip with retro-reflectors affixed was prepared for ease of fixing on the suit. The vectors from the selected base marker are shown in the inset and the estimated angle "θ" between both positions. (B) A sample screen shot of the point light capture the initial position and the flexion exercise. (C) Approximation of S-shaped spine curvature using vector analysis. Subset images: (i) Last sensor on the lower back as reference (Base) marker (ii) Position vectors formed by connecting all the markers with the base marker as the origin for the first frame (upright position) (iii) Position vectors in the maximum angular displacement frame relative to the first frame in spine flexion exercise with the base marker as the origin (bent position). (D) Spine lateral-bend with angle notation and axial-rotation exercise, with intermediate base position. (E) Squat exercise with angle notation and intermediate base position.

4.1.3 Data Analysis

The pre-processing steps for the motion capture include the 2D Object Filtering (Filter Type: Size & Roundness;Min threshold pixels: 4;Max threshold pixels: 2000;circularity: 0.60) on the image captured by all six cameras to filter marker noise, removing frames with sudden non-task movements, identification and labeling of markers. Data gaps in the marker trajectories were filled using the interpolation method.

4.1.3.1 Spine Motion Analysis

The 12th (reference/base marker) marker of the spine (Fig 4.3 (A, C)) was used to construct a 3D Local Coordinate System(LCS) for flexion and lateral-bend exercises as it showed the least amount of angular and translational displacement while performingthe exercises. The position vectors (location and orientation) of all the markers were constructed by keeping the reference/base marker as the origin in the local 3D coordinate system (Fig 4.3 C). The cervical, thoracic, and lumbar spine region angles were estimated by calculating the angle between the current position vector (Fig 4.3 C) and the initial position vector (a vector before initialization; Fig 4.3 A) in the LCS for all the points to approximate the S-shaped spine curvature at each frame. The angles for axial spine rotation were calculated in the global coordinate system with reference to the world origin, as having a single reference is advantageous for correlational analysis. An exercise starts when the marker's displacement (velocity) changes from zero to positive at each segment with respect to the reference marker in the direction of movement. The end was determined when the marker reached 'zero' displacement, corresponding to the spine's initial vertical position and the angular displacement between these two positions represented by the angle "θ", subtended by the position vectors V1 and V2 (shown in Fig 4.3 A and 4.3 D(ii,iii)) calculated using the law of cosine. For each trial, the maximum angular displacement/ROM values of each segmental region were calculated and the average peak value of three trails was considered for further statistical analysis. A representation (one participant) of the temporal sequence of angles/movements (ROM) for the three trials is shown in Figure 4.4.

4.1.3.2 Knee/Hip Motion Analysis

A position vector is drawn from the 12th (reference/base marker) marker to the knee markers for approximating the relative positioning and direction of the knee/hip-joint movement using the estimation of hip segment angle between the current position vector and initial position vector ((Fig 4.3 E(ii))). The position vector V1 at the starting of the exercise and the position vector V2 at the final squat position i.e., at the ending of the exercise and, the angle "θ" subtended by the two vectors is extracted (Fig 4.3 E). The maximum bend displacements of the left and right hip-knee segments from the initial position were noted. Before applying statistical methods, the peak angle values were averaged for three trials and each knee separately. In addition, squat depth is calculated by estimating the 12th/reference marker's displacement on the spine in the axial plane. A representation (one participant) of the temporal sequence of angles/movements (ROM) for the three trials is shown in Figure (Fig 4.3 D).

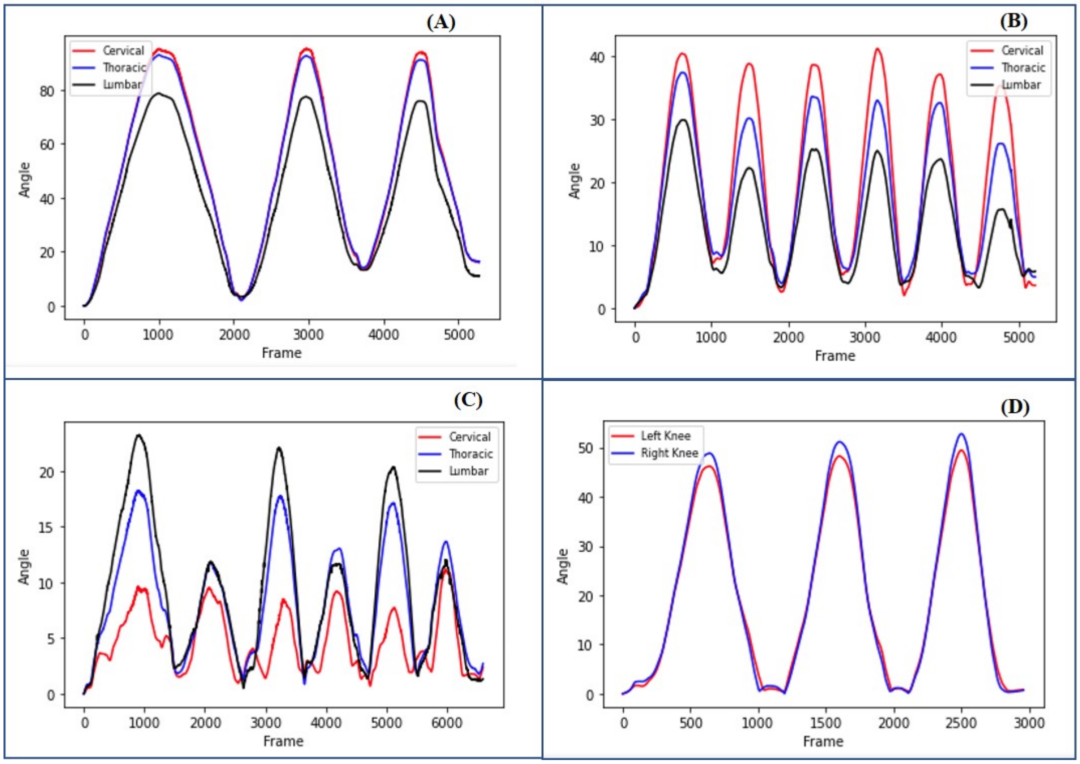

Figure 4.4: Sample of the temporal sequence of the spine movement of a participant for 3 trials with respect to each frame for marker-based motion capture system. (A) Spine Flexion (B) Spine Lateral Bend - left and right- three trails each (C) Spine Side Twist (clock and anticlock wise) -three trails each (D) Squat exercise.

4.1.4 Statistical Analysis

The Shapiro-Wilk test for normality in data showed significance for 7 data sets in both gender groups and hence non-parametric Mann-Whitney U test was applied to examine differences between conditions. The Spearman's rank correlation analysis examined the relationships between BMI, WHR and physical activity level (self-scored on a scale of 1-5 by participants) to angular displacements. A seed-based correlation was applied to test whether subjects with normal and high BMI, WHR, and level of physical activity form a cluster. The statistical significance level for all tests was set at $p<0.05$.

For analysis, participants were further divided as normal (Males: 20 participants; Female: 15) and overweight (Male: 20 participants; female: 7) as per BMI standards (<24.9 is normal and >25 is overweight). Similarly, subjects were categorized into normal and high WHR groups based on established World Health Organization (WHO) waist-to-hip standards for males (0.90 is normal, number = 15 and >0.90 is high, number = 25) and females (0.85 is normal, number = 15 and >0.85 is high, number = 7).

Table 4.1: Descriptive statistics of Physical parameters for both male and female participants.

	Female			Male		
Parameter	BMI	WHR	Physical activity level	BMI	WHR	Physical activity level
min	16.3	0.71	2	18.1	0.83	1
max	29.1	0.89	4	33.6	0.95	4
mean	22.94545	0.819545	3.136363636	24.83	0.91125	2.925
stdev	3.031066	0.054202	0.710161252	3.42249	0.02738	0.693837341

4.2 Analysis of Physical parameters

As shown in Table 4.1, the mean of BMI and WHR is higher for male participants which could be due to the smaller sample size in female participants, but in terms of physical activity level, female participants had higher mean as well as standard deviation (table).

4.2.1 Descriptive Statistics

The Shapiro-Wilk test was significant for BMI ($p<0.01$) and physical activity level ($p = 0.027$) in male participants, while for WHR ($p = 0.474$), it was not significant. A similar trend was observed for female participants, with BMI ($p<0.001$) and physical activity level ($p<0.001$) as significant and WHR ($p = 0.175$) as not significant.

4.2.2 Inferential Statistics

4.2.2.1 Spearman Correlation between BMI, WHR and physical activity level

In male participants, physical activity levels were negatively correlated with BMI (ρ= -0.18; p = 0.266) and WHR (ρ= -0.119; p = 0.463) values (Fig 4.5, i.e., Physical activity increases as BMI and WHR decreases. While for female participants, it was negative for WHR (ρ= -0.114; p = 0.612) but positive for BMI (ρ= 0.29; p = 0.191) (Fig 4.6. For female participants, BMI and WHR were significantly positive correlated (ρ = 0.588**; p = 0.004 (<0.01)) but for male participants, it was negative and not significant (ρ = -0.296; p = 0.063). The detailed correlation matrix with heatmap is shown in Fig 4.5 and 4.6.

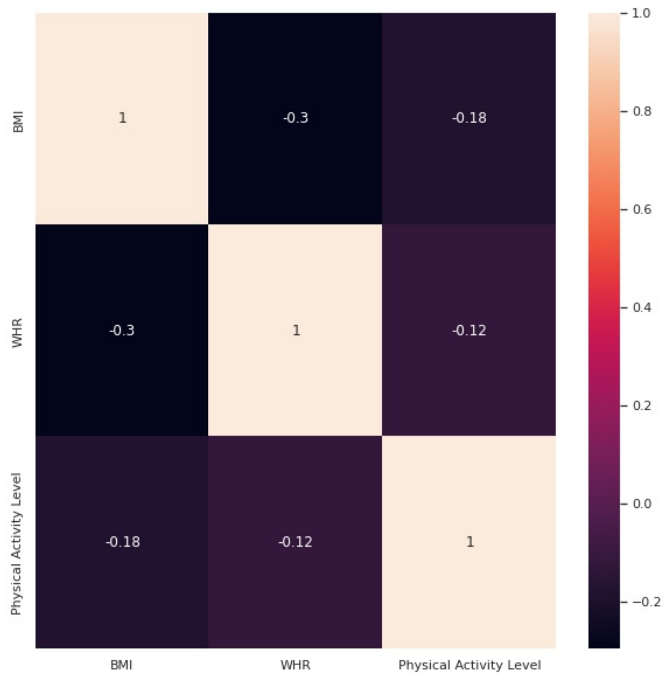

Figure 4.5: Spearman’s correlation heatmap between Physical Parameters for male subjects

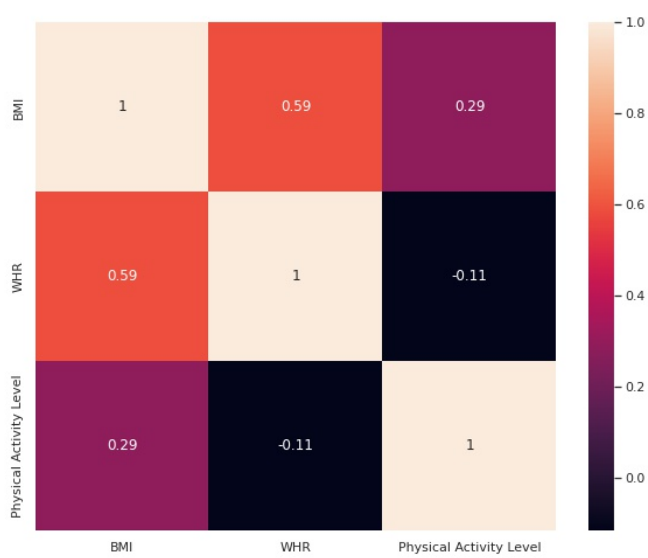

Figure 4.6: Spearman’s correlation heatmap between Physical Parameters for female subjects

4.3 Analysis of spine flexion movement

As expected physiologically for the flexion, the cervical segment (neck) displacement is higher than the other two segments (Fig 4.7 & 4.8) for all participants. The mean values and standard deviations for angles of the flexion exercise were comparable for both genders, but with a wide distribution of angular displacement (minimum $\approx$ 50 deg and max $\approx$ 90deg). Fig 4.8 shows the in-subject variability in angular displacement in flexion exercise for both genders in each spinal region. For both genders, angular displacement in the lumbar region is significantly smaller than in other regions for all subjects (difference of $\approx$ 20 degrees).

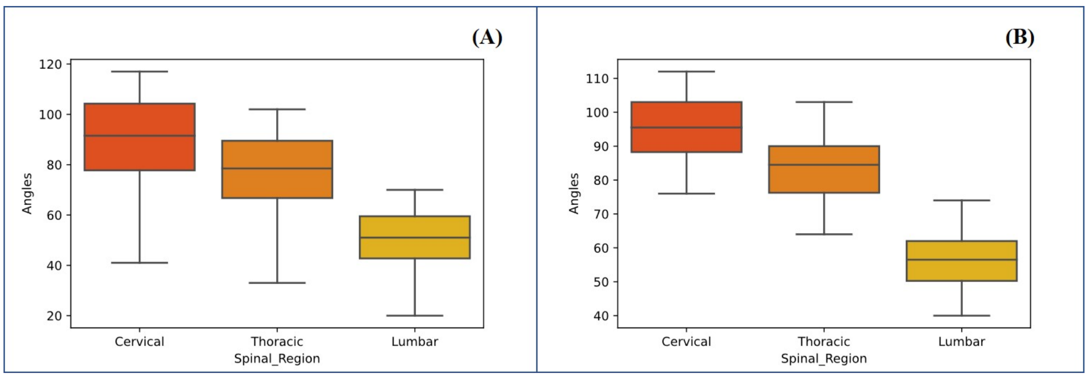

Figure 4.7: Box plot for comparison between angle estimates for the three spine segments in flexion exercise. (a) Box plot of spine segments for male participants (b) Box plot of spine segments for female participants.

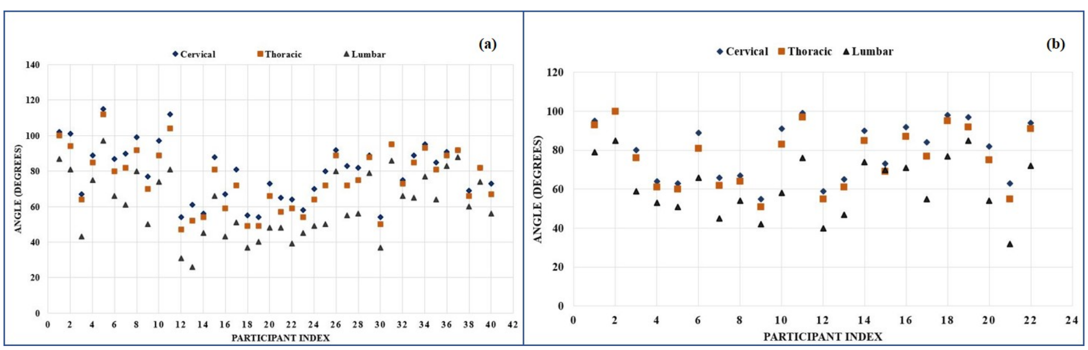

Figure 4.8: Participant wise distribution of spinal column angles using marker-based motion capture for spine flexion exercise in (A) Males (B) Females.

4.3.1 Descriptive Statistics

For male participants, the Shapiro-Wilk test for spinal columns was not significant (p = 0.257 (cervical region); p = 0.328 (thoracic region); p = 0.286 (lumbar region)). While for female participants thoracic (p = 0.17) and lumbar (p = 0.525) were not significant, however cervical region was significant (p = 0.027).

4.3.2 Inferential Statistics

4.3.2.1 Comparative analysis of Angular Displacement in Spine Flexion

In male individuals, cervical angular displacement is similar for both normal (median=83) and overweight (median=82) BMI; however, there are differences in the thoracic and lumbar angular displacement (Fig 4.9 (a)). For all spinal columns, even though angular displacement of the normal BMI group had more dispersion than those in the overweight category (Fig 4.9 (a)), the Mann-Whitney test did not show any significant difference. For females, 31.8% had a high BMI; the medians of the high BMI group were higher than the normal group for all three regions (Fig 4.10 (a)), indicating that the overweight BMI group had more angular displacement. For all three segments, the angular displacement of the high BMI group had more dispersion than the normal group; however, the Mann-Whitney test did not show any significant difference.

High WHR was found in 62.5% of males. The medians of both the groups for the cervical and lumbar regions were comparable (Fig 4.9 (b)), while there were differences in the thoracic region. Although the Mann-Whitney test did not show any significant difference, the angular displacement of the high WHR group had more dispersion than the normal WHR group. In females, the normal WHR group exhibited significantly higher displacement (median) in all three spinal columns than the high WHR group (Fig 4.10 (b)). Still, the Mann-Whitney test did not show any significant difference

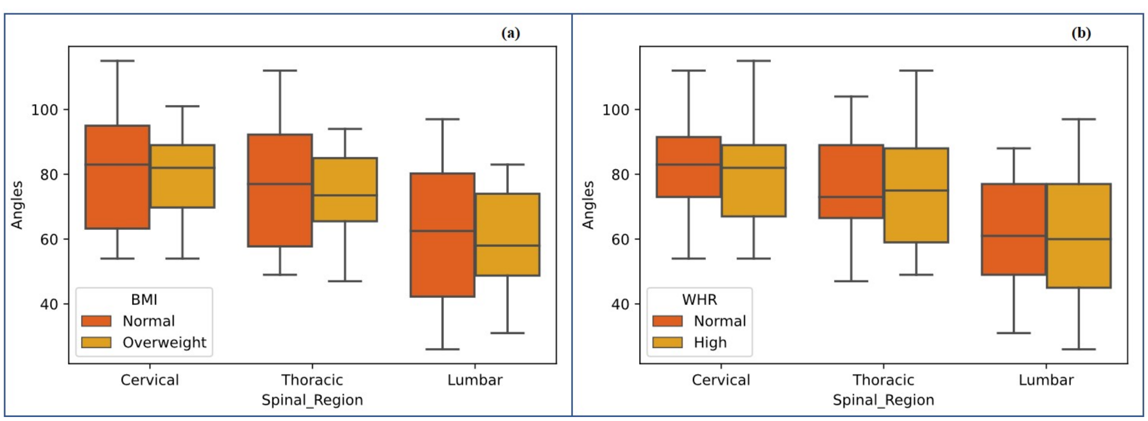

Figure 4.9: Box plot for comparison of angular displacement in all spinal regions for spine flexion exercise. (a) Box plot for comparison of spinal columns' angle distribution in normal and overweight BMI male participants group. (b) Box plot for comparison of spinal columns' angle distribution in normal and high WHR male participants group.

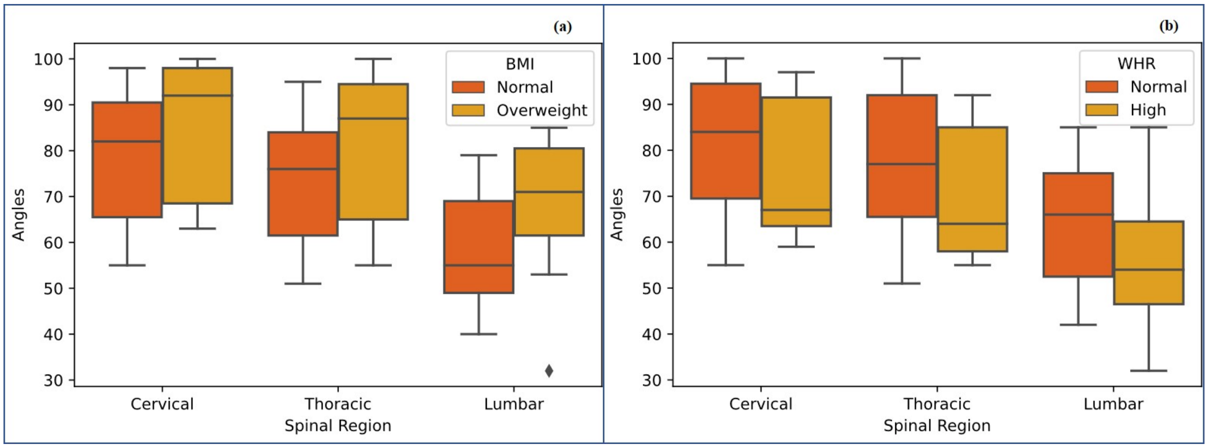

Figure 4.10: Box plot for comparison of angular displacement in all spinal regions for spine flexion exercise. (a) Box plot for comparison of spinal columns' angle distribution in normal and overweight BMI female participants group. (b) Box plot for comparison of spinal columns' angle distribution in normal and high WHR female participants group.

4.3.2.2 Spearman Correlation of BMI, WHR and physical activity level with angular displacements of spinal columns in flexion

In male participants, physical activity level was significantly positive correlated with all three spinal columns (cervical: $\rho = 0.645^{***}$, $p < 0.001$; thoracic: $\rho = 0.643^{***}$, $p < 0.001$; lumbar: $\rho = 0.62^{***}$, $p < 0.001$), i.e., spine flexion angles increase as physical activity level increases. BMI was positively correlated but not significant for all spinal columns. For female cohort, physical activity level was significantly positive correlated with all three spinal columns (cervical: $\rho = 0.874^{***}$, $p < 0.001$; thoracic: $\rho = 0.879^{***}$, $p < 0.001$; lumbar: $\rho = 0.852^{***}$, $p < 0.001$), i.e., spine flexion angles increase as physical activity level increases. BMI was positively correlated but not significant for all spinal columns. The detailed correlation matrix with heatmap is shown in Fig 4.11 and 4.12.

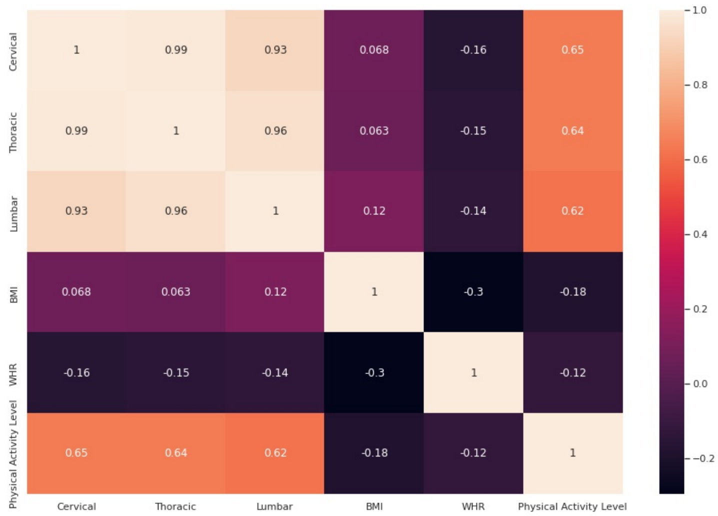

Figure 4.11: Spearman's correlation heatmap between Physical Parameters and Flexion angles for male subjects

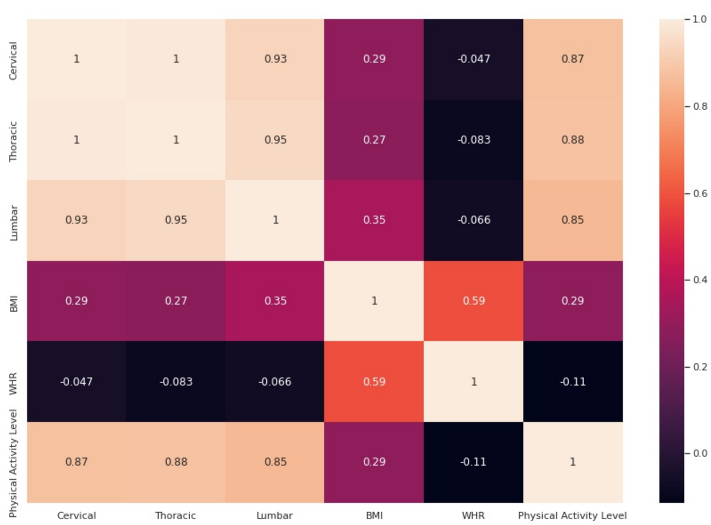

Figure 4.12: Spearman's correlation heatmap between Physical Parameters and Flexion angles for female subjects

4.4 Analysis of spine lateral bend movement

As expected physiologically for the flexion, the cervical segment (neck) displacement is higher than the other two segments (Fig 4.13) for all participants. The dominant side (right, as the majority were right-handed) is evident for both genders (Fig 4.13). The mean values and standard deviation for angles in lateral bend exercise was higher for male participants than female participants. The distribution around the mean is high (stdev $\approx \pm 9$).

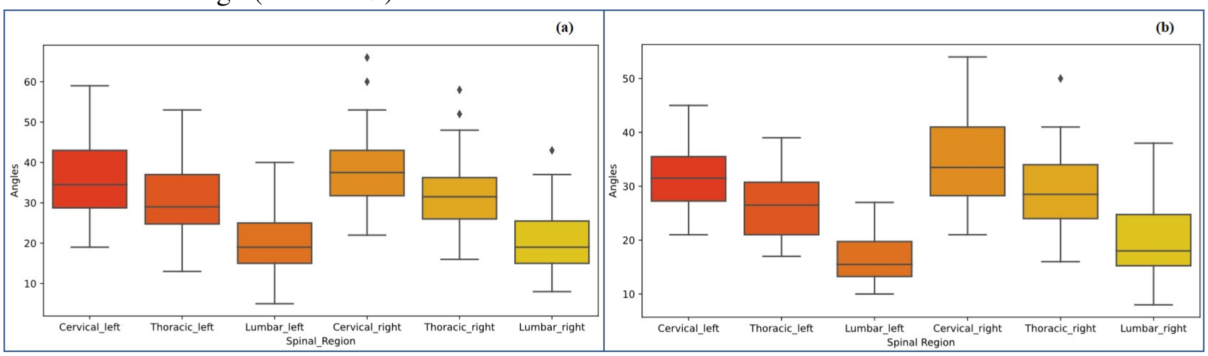

Figure 4.13: Box plot for comparison between angle estimates for the three spine segments in lateral bend exercise. (a) Box plot of spine segments for male participants (b) Box plot of spine segments for female participants.

4.4.1 Descriptive Statistics

For male participants. The Shapiro-Wilk test for spinal columns was not significant ($p = 0.38$ (cervical-left); $p = 0.165$ (cervical-right); $p = 0.426$ (thoracic-left); $p = 0.166$ (thoracic-right); $p = 0.169$ (lumbar-left); $p = 0.068$ (lumbar-right)). For female participants, similar result was found as for male participants, ($p = 0.639$ (cervical-left); $p = 0.622$ (cervical-right); $p = 0.395$ (thoracic-left); $p = 0.369$ (thoracic-right); $p = 0.081$ (lumbar-left); $p = 0.261$ (lumbar-right)).

4.4.2 Inferential Statistics

4.4.2.1 Comparative analysis of Angular Displacement in Spine Lateral Bend

In male participants, the normal BMI group had larger angular displacement in cervical and thoracic regions in the left lateral-bend (Fig 4.14 (a)). By contrast, the overweight group's median angular displacement was higher in the right lateral-bend. The overweight BMI group had more dispersion of angular displacement of all three segments for both sides than the normal BMI group; however, the Mann-Whitney test did not show any significant difference. For females, even though the dispersion of angular displacements for both normal and overweight BMI groups were nearly comparable (Fig 4.15 (a)), the Mann-Whitney test shows significant difference for cervical right lateral-bend (U-value=24, p-value=0.048, n1=15, n2=7, z-score=-1.973, effect-size: -0.543, two-tailed) and lumbar right lateral-bend (U-value=19, p-value=0.0198, n1=15, n2=7, z-score=-2.326, effect-size: -0.638, two-tailed) while thoracic right-lateral bend (U-value=25, p-value=0.057, n1=15, n2=7, z-score=-1.903, effect-size: -0.524, two-tailed) was nearly significant.

In male participants, the high WHR group had higher angular displacement for both left and right lateral-bends than the normal WHR group (Fig 4.14 (b)). The angular displacement of all three segments in the normal WHR group for the left lateral bend had more dispersion than the high WHR group, while the right lateral bend had more dispersion in the high WHR group. Even though the lateral bend showed mixed results in terms of dispersion, the Mann-Whitney test did not show any significant difference. For the female cohort, the normal WHR group had greater angular displacement (median) in all three spinal columns (Fig 4.15 (b)). The angular displacement of all three segments in the normal WHR group for the left lateral bend had more dispersion, while the right lateral bend had mixed results; however, the Mann-Whitney test did not show any significant difference.

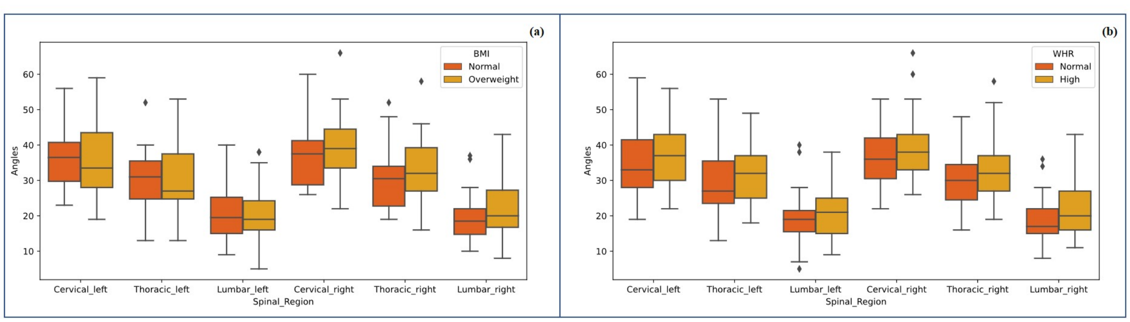

Figure 4.14: Box plot for comparison of angular displacement in all spinal regions for spine lateral bend exercise. (a) Box plot for comparison of spinal columns' angle distribution in normal and overweight BMI male participants group. (b) Box plot for comparison of spinal columns' angle distribution in normal and high WHR male participants group.

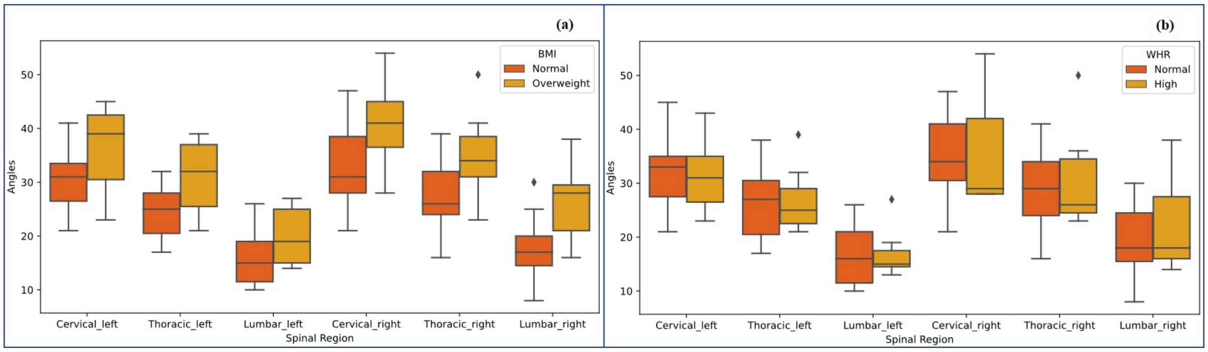

Figure 4.15: Box plot for comparison of angular displacement in all spinal regions for spine lateral bend exercise. (a) Box plot for comparison of spinal columns' angle distribution in normal and overweight BMI female participants group. (b) Box plot for comparison of spinal columns' angle distribution in normal and high WHR female participants group.

4.4.2.2 Spearman Correlation of BMI, WHR and physical activity level with angular displacements of spinal columns in lateral bend

In male participants, physical activity level was significantly positive correlated with all spinal columns (cervical-left: $\rho = 0.372^*$, p = 0.018; cervical-right: $\rho = 0.488^{**}$, p = 0.001; thoracic-left: $\rho = 0.324^*$, p = 0.041; thoracic-right: $\rho = 0.443^*$, p = 0.004; lumbar-left: $\rho = 0.325^*$, p = 0.04; lumbar-right: $\rho = 0.411^{**}$, p = 0.008), i.e., spine lateral bend angles increase as physical activity level increases. BMI was negatively correlated not significant with all the spinal columns when participants bend left side, while positively correlated not significant with all the spinal columns when participants bend right side. WHR was negatively correlated with all the spinal columns except for lumbar region when the participants bend right side. For female cohort, physical activity level was positively correlated but not significant with all spinal columns (cervical-left: $\rho = 0.229$, p = 0.306; cervical-right: $\rho = 0.213$, p = 0.34; thoracic-left: $\rho = 0.268$, p = 0.228; thoracic-right: $\rho = 0.197$, p = 0.378; lumbar-left: $\rho = 0.217$, p = 0.332; lumbar-right: $\rho = 0.147$, p = 0.512). BMI and WHR was also positively correlated but not significant (p > 0.05 for all spinal columns). The detailed correlation matrix with heatmap is shown in Fig 4.16 and 4.17.

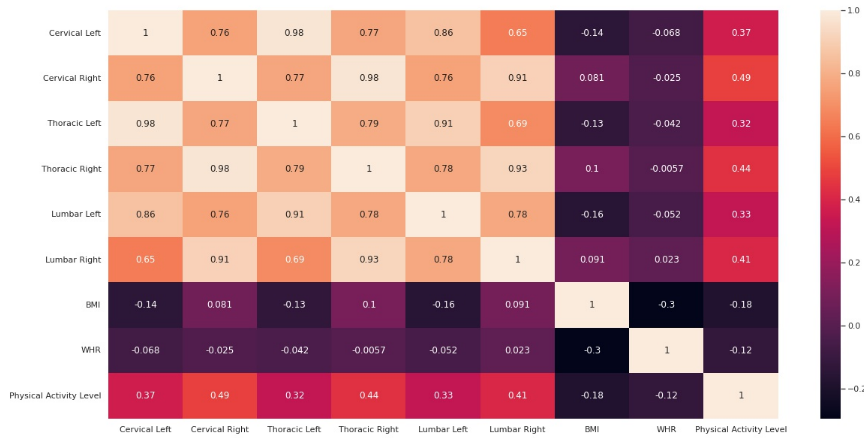

Figure 4.16: Spearman's correlation heatmap between Physical Parameters and Lateral-bend angles for male subjects.

Figure 4.17: Spearman's correlation heatmap between Physical Parameters and Lateral-bend angles for female subjects.

4.5 Analysis of spine side twist movement

As expected physiologically for sidetwist, the lumbar segment (lower back) displacement is higher than the other two segments (Fig 4.18) for all participants. The mean values and standard deviation for angles in sidetwist exercise was comparable for both male and female participants. The distribution of angular displacements of left and right side axial twist (Fig 4.18 a) is similar for male participants. In contrast, the distribution of angular displacements of thoracic and lumbar segments for the right-side twist had marginally less dispersion than the left-side twist for female participants (Fig 4.18 b).

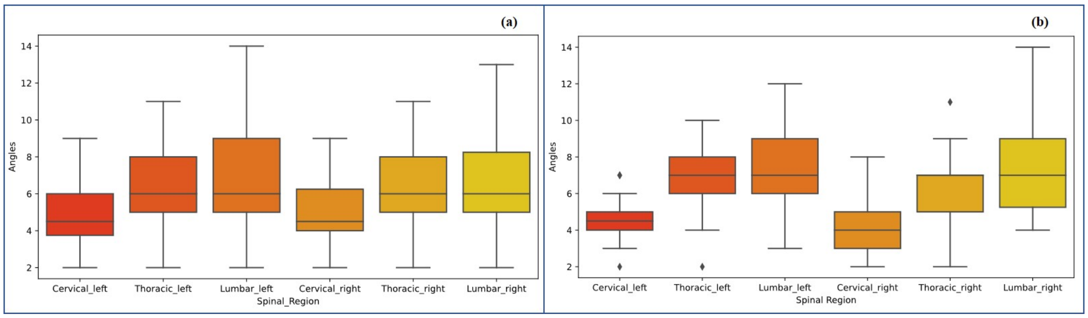

Figure 4.18: Box plot for comparison between angle estimates for the three spine segments in sidetwist exercise. (a) Box plot of spine segments for male participants (b) Box plot of spine segments for female participants.

4.5.1 Descriptive Statistics

For male participants, the Shapiro-Wilk test for spinal column angle data was significant for cervical region (p = 0.005) when participant twist right side and for lumbar region (p = 0.021) when participant twist left side, while not significant for other spinal regions. For female cohort, Shapiro-Wilk test for all spinal column angle data was not significant for all regions.

4.5.2 Inferential Statistics

4.5.2.1 Comparative analysis of Angular Displacement in Spine Side twist

For both BMI groups in the male cohort, relatively equal angular displacement (median) was observed in all three segments ((Fig 4.19 (a)). The dispersion of angular displacement for both groups was comparable in the cervical region, while the overweight group BMI had more dispersion in the thoracic and lumbar region; however, the Mann-Whitney test did not show any significant difference. In females, approximately equal angular displacement (median) was found for all three segments ((Fig 4.20 (a)). The dispersion of angular displacement for both normal and overweight BMI groups was comparable in the cervical region, whereas the overweight BMI group had more dispersion in the thoracic and lumbar region; however, the non-parametric difference test did not show any significant difference.

In the male participants, for the WHR grouping, the angular displacement (median) and dispersion of angular displacement were roughly comparable across all three segments (Fig 4.19 (b)). For females, the dispersion of angular displacement for both the groups was comparable in the cervical region, whereas the normal WHR group had more dispersion in the thoracic and lumbar region (Fig 4.20 (b)); however, the Mann-Whitney test did not show any significant difference.

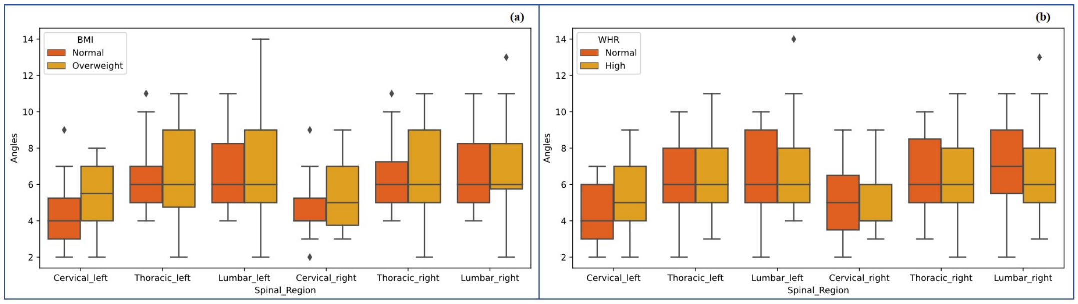

Figure 4.19: Box plot for comparison of angular displacement in all spinal regions for spine sidetwist exercise. (a) Box plot for comparison of spinal columns' angle distribution in normal and overweight BMI male participants group. (b) Box plot for comparison of spinal columns' angle distribution in normal and high WHR male participants group.

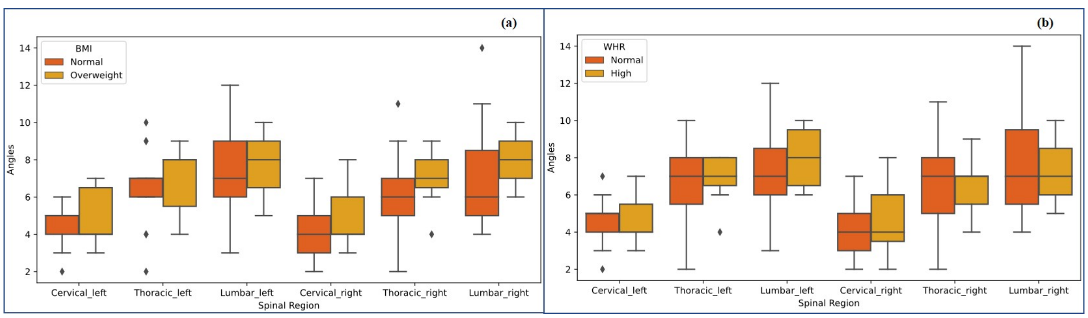

Figure 4.20: Box plot for comparison of angular displacement in all spinal regions for spine sidetwist exercise. (a) Box plot for comparison of spinal columns' angle distribution in normal and overweight BMI female participants group. (b) Box plot for comparison of spinal columns' angle distribution in normal and high WHR female participants group.

4.5.2.2 Spearman Correlation of BMI, WHR and physical activity level with angular displacements of spinal columns in sidetwist

In male participants, physical activity level was weakly correlated with all spinal columns except in thoracic region ($p = 0.038$) when participants twisted in left side and in lumbar ($p = 0.022$) when participants twisted in left side, while BMI and WHR both were not significant with all spinal columns in spine sidetwist exercise. For female cohort, physical activity level, BMI and WHR all three were postively correlated with all the spinal columns in spine sidetwist exercise but not significant ($p > 0.05$). The detailed correlation matrix with heatmap is shown in Fig 4.21 and 4.22.

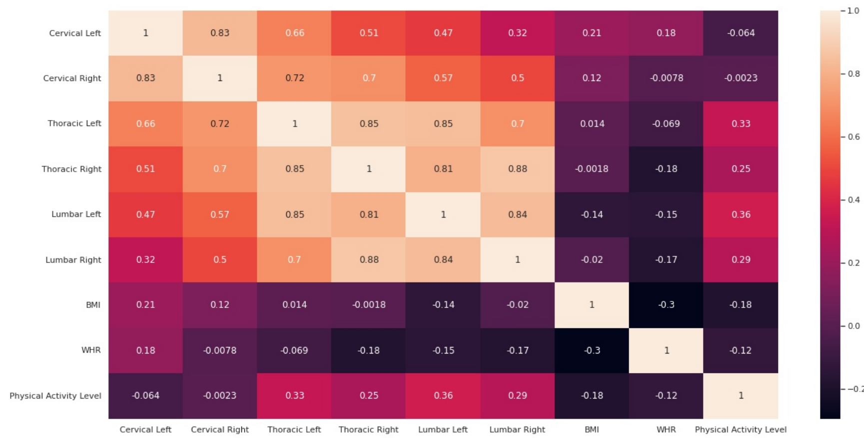

Figure 4.21: Spearman's correlation heatmap between Physical Parameters and Sidetwist angles for male subjects.

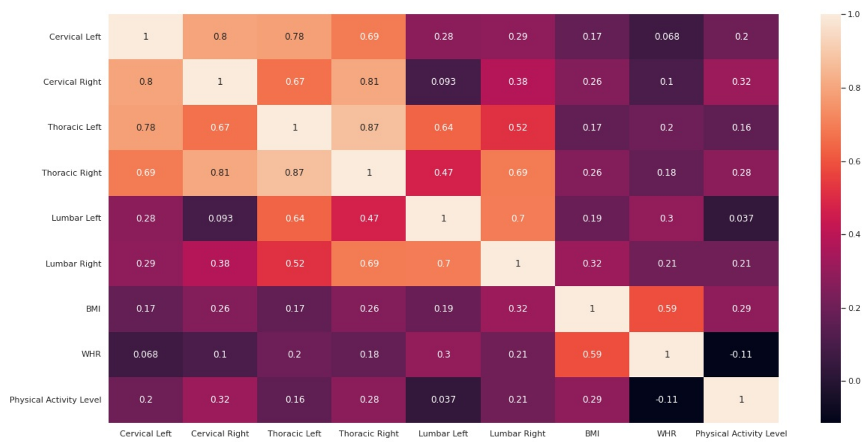

Figure 4.22: Spearman's correlation heatmap between Physical Parameters and Sidetwist angles for female subjects.

4.6 Analysis of squats movement

The squat had approximately similar angular displacement distribution for all the participants. Female participants show significantly higher angles than the male participants (Fig 4.23). The mean and standard deviation of female participants was higher than for the male participants. The distribution of hip-knee segment displacements for both sides was more disperse in female participants ($\approx$ 14) than for male participants (≈10). The squat depth as measured by the reference (12th) marker in male participants was in a range (14.07 - 66.31 cms; average: 32.75 cms), while for female participants, the range was between (15.08 - 65.31 cms; average = 38.5 cms). Fig 4.24 shows the in-subject variability in angular displacement in squats exercise for both genders in each hip-knee segment.

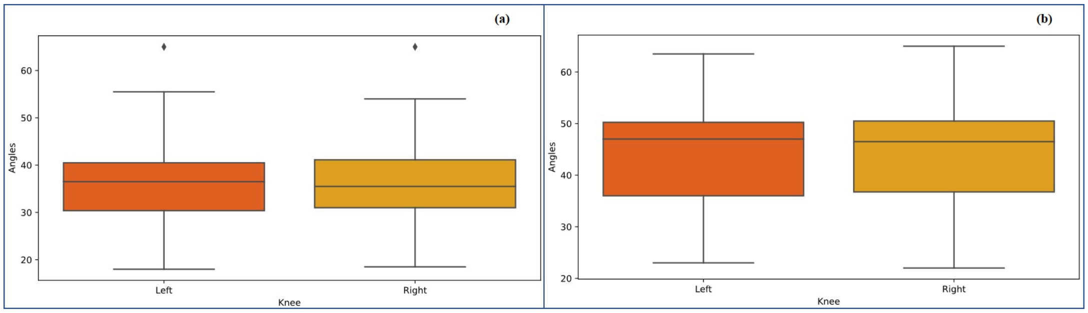

Figure 4.23: Box plot for comparison between angle estimates for the Hip-knee segments in squats exercise. (a) Box plot of hip-knee segments for male participants (b) Box plot of hip-knee segments for female participants.

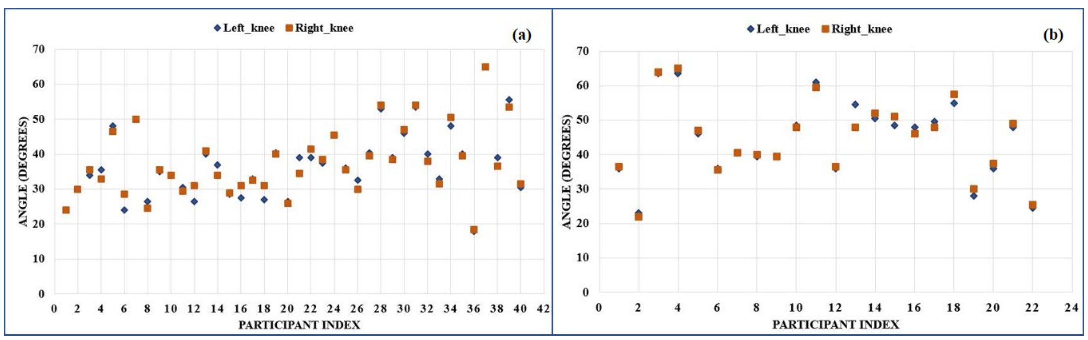

Figure 4.24: Participant wise distribution of hip-knee segment angles using marker-based motion capture for squats exercise in (A) Males (B) Females.

4.6.1 Descriptive Statistics

The Shapiro-Wilk test for hip-knee segment displacement data was not significant for both male and female participants.

4.6.2 Inferential Statistics

4.6.2.1 Comparative analysis of Angular Displacement in Squats

Although the male group in the normal BMI group had more angular displacement (median) and dispersion than the overweight group (Fig 4.25 (a)) and an inverse trend was observed for females (Fig 4.26 (a)), the Mann-Whitney test did not show any significant difference.

For male participants, the high WHR group had more angular displacement (median) than the normal WHR group (Fig 4.25 (b)), while for females, angular displacement for both WHR groups was comparable (Fig 4.26 (b)). For both males and females, the normal WHR group had more dispersion of angular displacement than the high WHR group for both the limbs. Though the differences were not significant.

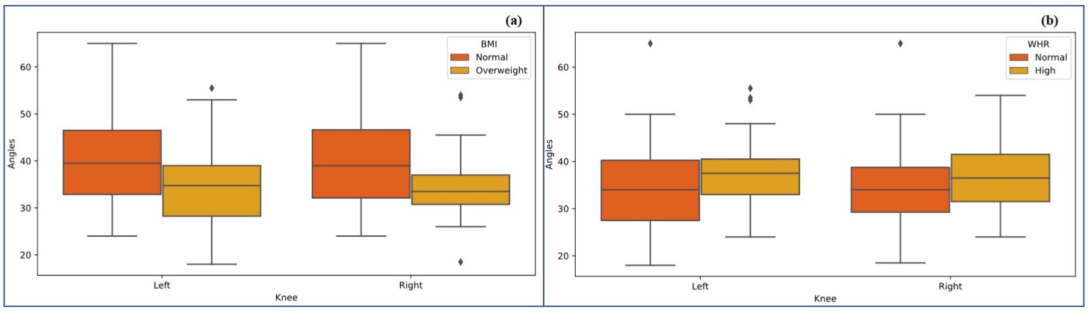

Figure 4.25: Box plot for comparison of angular displacement in both hip-knee segments for squat exercise. (a) Box plot for comparison of knee/hip angle distribution in normal and overweight BMI male participants group. (b) Box plot for comparison of knee/hip angle distribution in normal and high WHR male participants group.

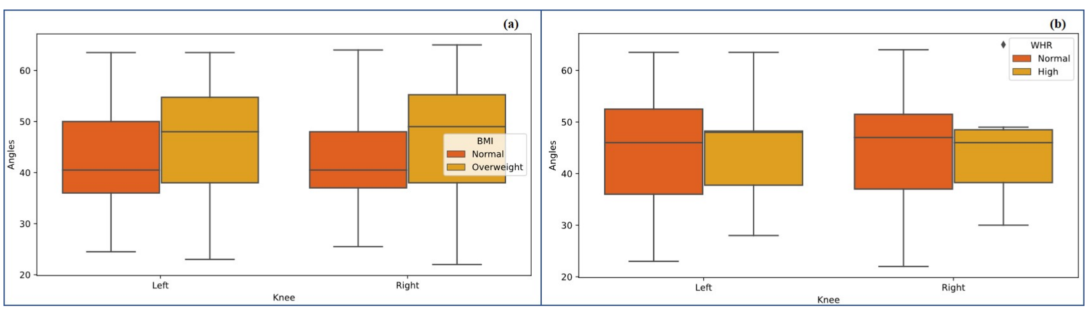

Figure 4.26: Box plot for comparison of angular displacement in both hip-knee segments for squat exercise. (a) Box plot for comparison of knee/hip angle distribution in normal and overweight BMI female participants group. (b) Box plot for comparison of knee/hip angle distribution in normal and high WHR female participants group.

4.6.2.2 Spearman Correlation of BMI, WHR and physical activity level with angular displacements of hip-knee segment in squats

BMI was significantly negatively correlated (p = -.352*) with hip-knee angular displacements for the squat exercise, while WHR showed weak positive correlations (not significant) and physical activity level was positively correlated for male participants (Fig 4.27). The analysis grouped by gender, BMI, WHR and physical activity level in the female cohort were negatively associated with hip-knee angular displacement (Fig 28) but were not statistically significant. The detailed correlation matrix with heatmap is shown in Fig 4.27, 4.28.

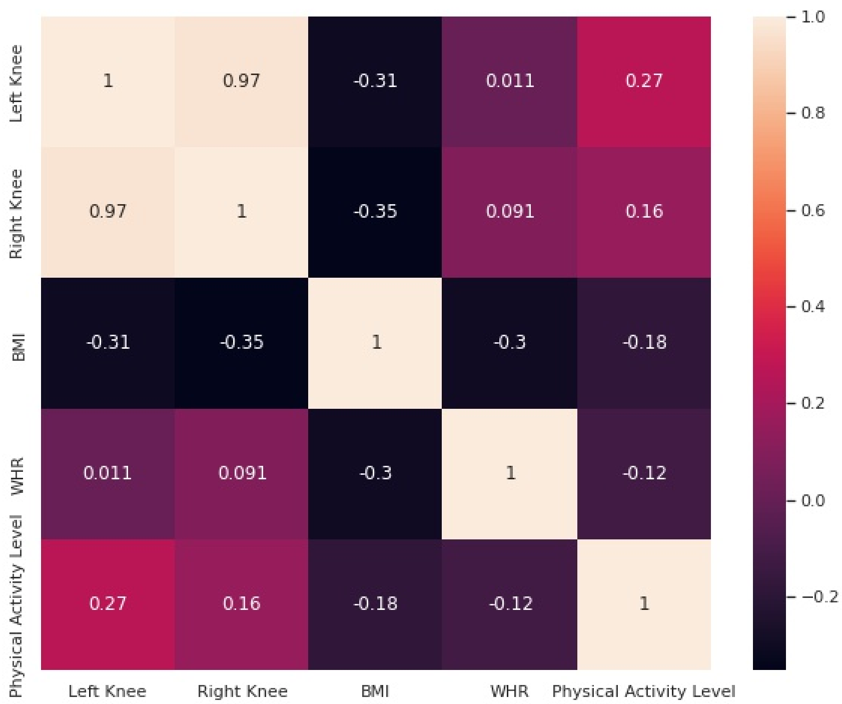

Figure 4.27: Spearman's correlation heatmap between Physical Parameters and knee/hip angles for male subjects. .

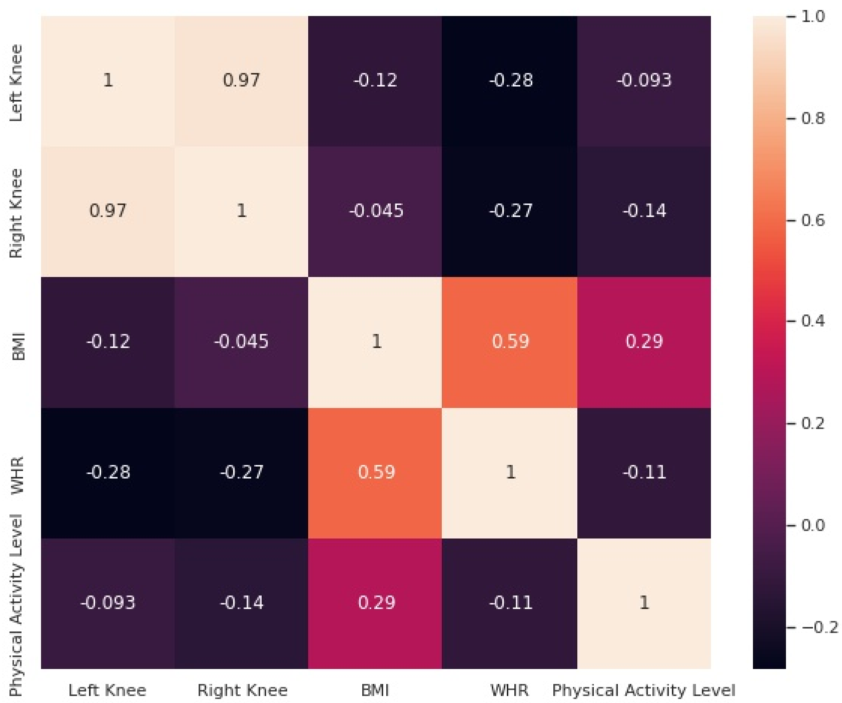

Figure 4.28: Spearman's correlation heatmap between Physical Parameters and knee/hip angles for female subjects.

4.7 Seed-based correlation analysis of participants

We considered a male participant who was a trained dancer and a female participant who does yoga daily, with great flexibility and good angular displacements of the spinal columns, as references for male and female groups. The Spearman seed-based correlation matrix for flexion exercise and both genders resulted in a single cluster; that is, the correlational value (ρ) was greater than 0.90, signifying minimal variation in participants of both genders as a function of flexibility due to specific motor skills.

4.8 Interpretations of Results

4.8.1 Spine Kinematics

The three exercises (flexion in the sagittal plane, lateral-bend in the frontal plane and twist in the transverse plane) confirmed the contribution of all the three segments (Schinkel-Ivy et al., 2015). The angular displacement of the lumbar spine for flexion, twist and the lateral-bend (Lee & Wong, 2002) was within the reported range (Tafazzol et al., 2014; Lee & Wong,2002; Zwambag et al., 2018; review article: Widmer et al., 2019), but show a substantial inter-subject variability (for flexion in males the range was 50-110 degrees for the thoracic) even in healthy subjects recruited for the study. The angular displacement distribution shows higher dispersion in female participants than in male participants. Previous studies have also reported gender-related differences (MRI method: Muriuki et al., 2016; motion capture method: Ignasiak et al., 2017). Though, in our study the range was similar, which may be attributed to the sample size (fewer female participants). In the lateral bending exercise, angles were higher in the right bend, this finding adds to the discussions on the dominant side effect on the lumbar spinal muscles supporting lateral bend (Sung et al., 2004).

Comparative analyses based on grouping as a function of BMI or WHR as between-subject parameters for males and females yielded mixed results. For normal and overweight BMI female groups, significant differences were observed only in cervical and lumbar right lateral bends, while male participants had no significant differences. There was also no significant difference when grouped on WHR. In the participants considered for this study, we observed that a significant number of participants with normal BMI had high WHR, and hence inferences on the effect of each require unique groups (high BMI & High WHR/ Normal BMI & Normal WHR) is required. Further investigation with exclusive categorization is also important to isolate the role of each factor (WHR or BMI or both) on chronic lower-back pain in the younger population (Ganesan et al., 2017). Secondly, our study does not consider spinal load by computing the muscle forces as a function of body weight and waist circumference, which has been shown to affect flexion exercise (Ghezelbash et al., 2016; 2017).

We observed significant correlations between physical activity level and angular displacements in male subjects in all spinal segments for spine flexion, left and right spine lateral-bend, and a few conditions in the spine side-twist. A positive (significant) with physical activity and flexion exercise for all the spine segments was observed in the female group. The absence of statistical significance in the female cohort for certain exercises could be due to the smaller sample size and the role of higher estrogen levels (Chidi-Ogbolu et al., 2019) in the age group considered and, hence, flexibility may be independent of physical characteristics or activity.

Overall, the outcomes from the correlations to spine angles are on expected lines, and it can be inferred that flexibility (as measured by the exercise routines) is primarily attributed to age (18-27 years) and physical activity. The seed-based correlation analysis resulted in a single cluster indicating minimal variation across the participants, indicating a higher effect of age and health (importantly physical activity) and not just on BMI or WHR. For male participants' physical activity levels were negatively correlated with their BMI and WHR values whereas for female participants' there was a negative correlation with their WHR, and a positive correlation with BMI. The positive correlation between BMI and physical activity level could be due to a more uniform BMI range in the female sample or being more sensitive to BMI, leading to physical activity.

4.8.2 Knee/hip joint kinematics

The biomechanics of the hip, thigh muscles and the knee/ankle joints are essential in analyzing daily activities. In particular, the synchronous flexion/extension of several muscle groups (quadriceps, hamstrings, glutes, abdominals and calves) is required for most daily activities (such as walking, stair climbing, kneeling, and squatting). The engagement of the erector spinae in addition to the hamstring muscles was also reported by (Gorsuch et al., 2013) when testing runners. Because parallel squatting exercise demands both movement and stability, it is shown to be effective in developing muscle strength (Escamilla, 2001) and utilized to better understand flexibility by evaluating the ROM. The correlation analysis run on the male participant data showed that BMI was significantly negatively correlated with hip angular displacements, WHR was weakly positively correlated, and physical activity level was positively correlated. While in the female cohort, BMI, WHR, and physical activity level were all negatively correlated with knee angular displacement. There was a difference in male and female's left and right knee angular displacements in the WHR/BMI grouping. This variation could be due to two physiological factors: an individual's center of gravity as a function of body weight and height, and body posture asymmetry. The studies (Hale et al., 2014) on the role of muscles to execute a squat could explain to a degree the surprising findings of normal BMI group having smaller angular displacements and range of motion than the overweight female group. Thomas et al., (1998) reported that women choose hip and knee movement patterns while men choose spine and knee movement pattern during reaching tasks that necessitate some forward bending of the trunk. Also, it is possible that females and males used different movement strategies as was observed during a single leg squat (Graci et al., 2012; Weeks et al., 2015; Zeller et al., 2003).

Chapter 5

Developing a new technique to investigating the role of physical activity level and body build characteristics on the kinematics of the spine and knee/hip joint - Marker-less Single RGB camera motion capture system

This study aims to develop a new technique to investigate the spine and knee biomechanics of young and healthy male and female participants with no reported spinal injury or lower back pain issues and no identified clinical spine deformity. This study investigates spine kinematics by the angular displacement of the three spine segments and the lumbopelvic-hip segments in flexion, lateral-bend, twist, and squat exercise executed by normal healthy young adults. To generate a reference chart/model. The angular displacement extracted from marker-less approach was correlated with the angular displacement extracted from marker-based approach. Based on the correlation analysis, we hypothesized the relationship between marker-less and marker-based methods.

5.1 Methodology

5.1.1 Participants

- Ethics approval was provided by the Human Study Ethics Committee of the institute. Informed consent was obtained from each participant. They were further informed that they could exit the study at any time with no penalty. Forty male subjects (age=19-33 years; mean=21.7 ± 2.97 years) and twenty-two female subjects (age=19-30 years; mean=22.5 ± 3.36 years) pursuing undergraduate and graduate studies at institute (fully residential campus) who volunteered for the markets-based motion capture system study volunteered for this study. As part of the curriculum, all students undergo 1 hour/day of physical training (exercises, yoga, sports, etc.) in the first year of their 4-year college program. The campus also has an active sports center and a yoga hall with trainers.

- Inclusion criteria:

  - Adults with >=17 and <= 35 years of age (younger people).
  - Adults reported being under no medication, especially for pain, at the time of the experiment.
  - Adults who had no record of any spine/back injuries in the past

- Exclusion criteria:
  - Any spine/knee injury that would limit the ability of the adult to participate in the study.
  - Current pain medication or taking steroids for muscle injury
  - Refusal to give informed consent.

5.1.2 Experiment Paradigm

The recording with an RGB camera was captured from the 62 participants wearing track pants and a T-shirt in the mocap studio. The camera angles were adjusted to position the spine in the field view, as shown in Fig 5.1. The subjects performed spine flexion, lateral bend, and squats exercises as the same exercises for marker-less as were executed for the marker-based motion capture paradigm. Each exercise's three self-paced trials were executed, preceded by a warm-up time. In practice, because muscle constraints can cause variations in spine movement across trials of the same exercise, the participants were instructed to warm up before the experiment to relax their muscles and improve flexibility, followed by performing three trials of each exercise to get a better approximation of range of motion values for each movement.

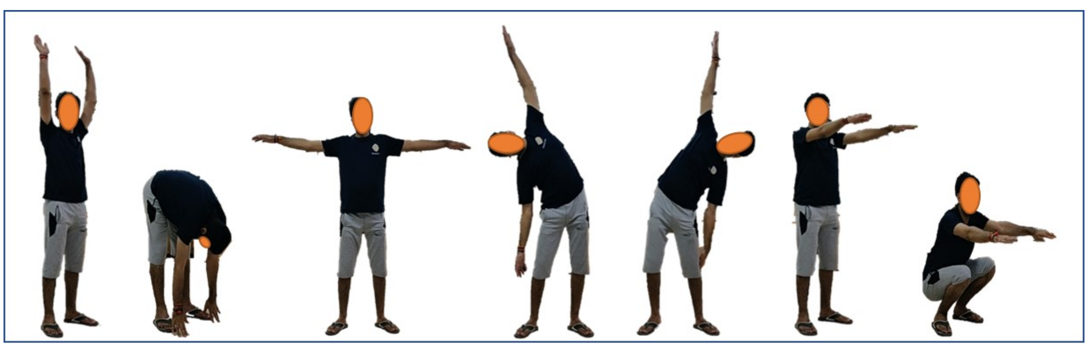

Figure 5.1: Spine flexion, lateral-bend, and squat exercises with intermediate base positions performed via an individual.

5.1.3 Data Extraction

The initial (first frame when the task began) and maximum displacement frames (frames when the participant's spine had the most angular displacement relative to the first frame) for all trials of an exercise for each participant were obtained from the recorded data. Extraction of 2D poses (key-points) for all frames was done using the Open Pose model (Cao et al.,2017), followed by generation of the 3D skeleton using these 2D poses in the ProHMR model (Kolotouros et al.,2021). By visualizing one of the 3D skeletons with the blender tool (open-source 3D visualization tool) and extracting all the spine coordinates for all 3D skeletons using these indices, twenty-seven spine (8 cervical, 14 thoracic, and 5 lumbar) coordinate indices were identified. The 3D skeleton for one participant from the ProHMR model in the analysis sections for each exercise.

5.1.4 Data Analysis

Using the method applied for marker-based motion capture, the angular displacement for the three spinal columns and hip/knee segments was extracted.

5.2 Analysis of Spine, knee/hip movement

In this section, a detailed analysis of the skeleton/mesh extracted using ProHMR model is presented with the correlation analysis of angular displacement estimated via both the techniques to hypothesize the relationship.

5.2.1 Spine flexion

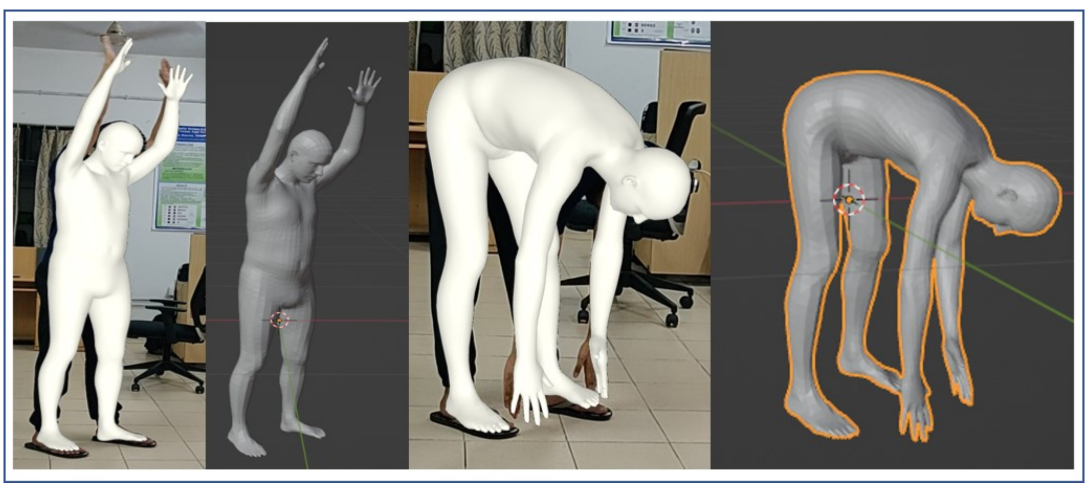

Figure 5.2: Generated 3D Human skeleton for a single participant in spine flexion exercise: Fitted 3D pose from 2D key-points and Consolidated 3D pose visualized in blender tool.

For spine flexion, 3D skeleton for one participant from the ProHMR model is shown in Fig 5.2. For spine flexion, as expected physiologically and through our marker-based model for the flexion, the cervical segment (neck) displacement is higher than the other two segments (Fig 5.3 & 5.4) for all participants. The mean values and standard deviations for angles of the flexion exercise were comparable for both genders (Fig 5.3), but with a wide distribution of angular displacement (minimum $\approx$ 50 deg and max $\approx$ 100deg). Fig 5.4 shows the in-subject variability in angular displacement in flexion exercise for both genders in each spinal region. For both genders, angular displacement in the lumbar region is significantly smaller than in other regions for all subjects (difference of $\approx$ 15 degrees).

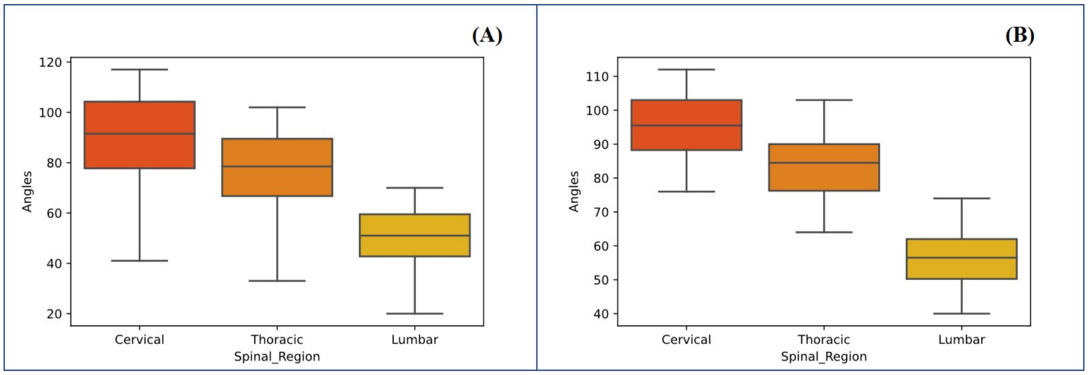

Figure 5.3: The angle estimates for the three spine segments and Flexion exercises (a) Male participants, (b) Female participants.

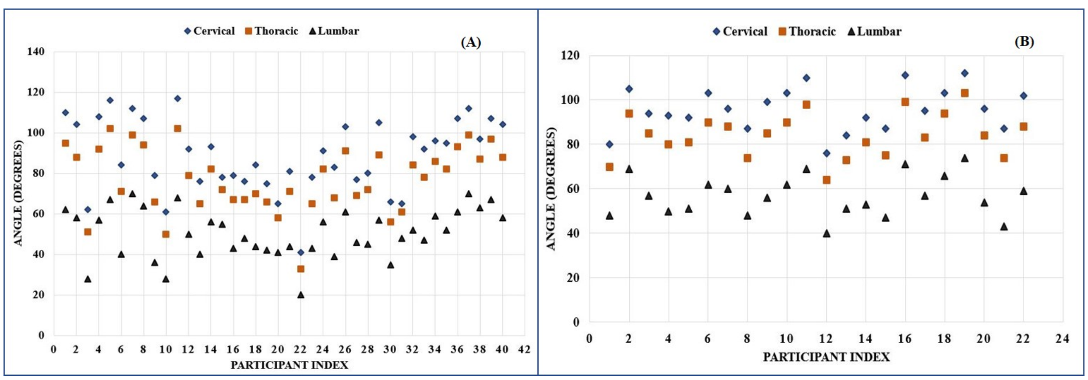

Figure 5.4: Participant-wise distribution of spinal region angles extracted from the RGB camera video for spine flexion exercise in (A) Males (B) Females.

5.2.1.1 Comparative analysis between marker-based and marker-less motion capture system

For male participants, Spearman's correlation analysis revealed that marker-less RGB angular displacement and marker-based angular displacement was significantly positively correlated with all three spine regions ($p<0.001$), i.e., spine flexion angles estimated via both methods are approximately similar. For female cohort, the similar pattern was observed as for male (cervical: $p = 002$; thoracic: $p = 0.002$; lumbar: $p = 0.004$). The detailed correlation matrix with heatmap is shown in Fig 5.5 and 5.6.

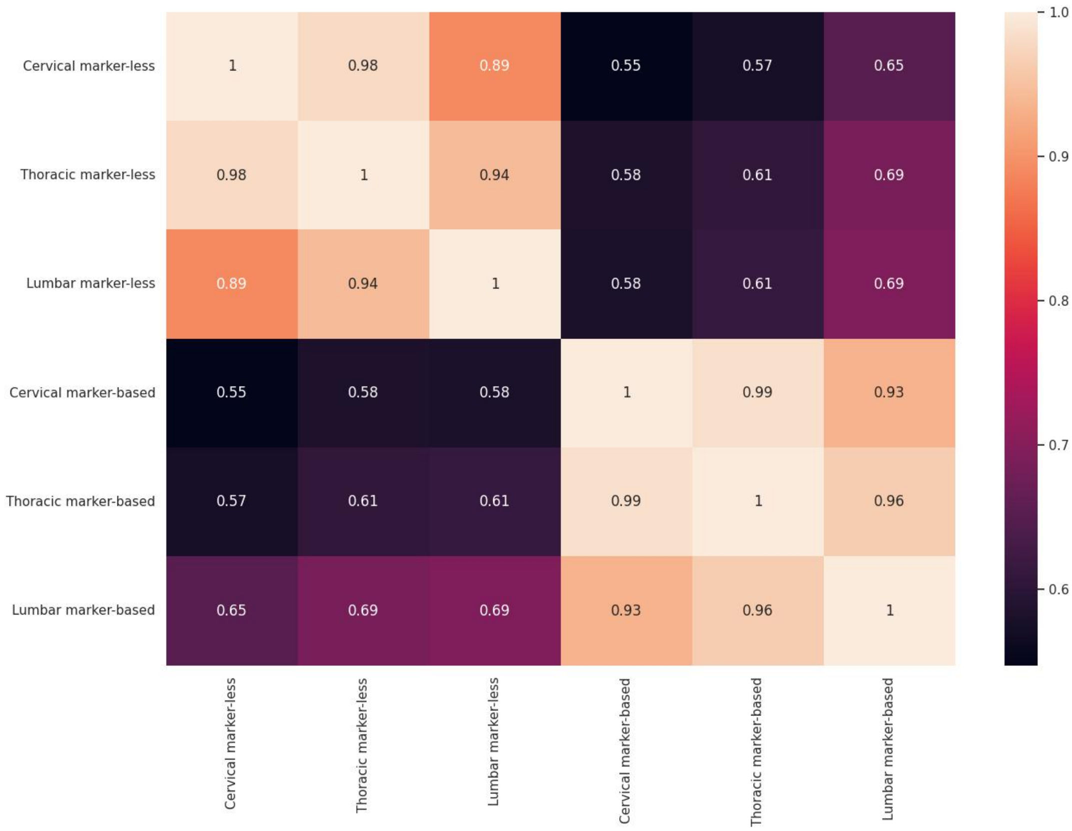

Figure 5.5: Spearman's correlation heatmap between marker-less angular displacement and marker-bases angular displacement for male participants in spine flexion exercise.

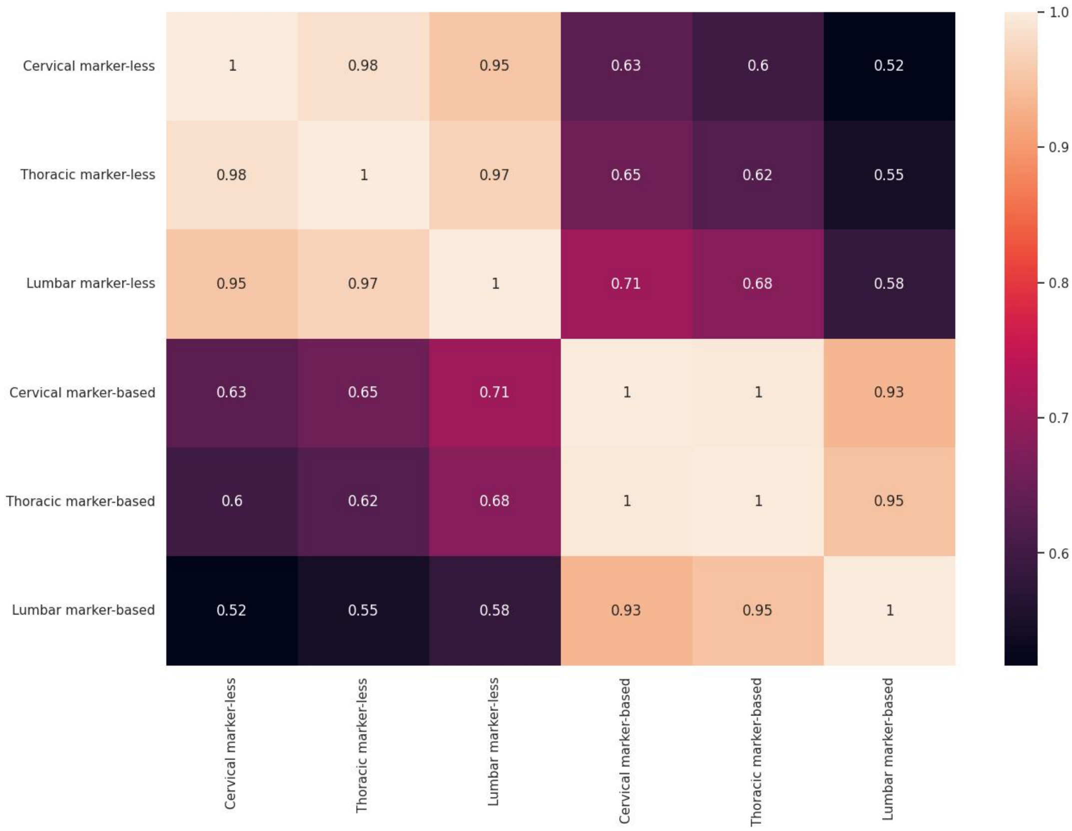

Figure 5.6: Spearman's correlation heatmap between marker-less angular displacement and marker-bases angular displacement for male participants in spine flexion exercise.

5.2.2 Spine lateral bend

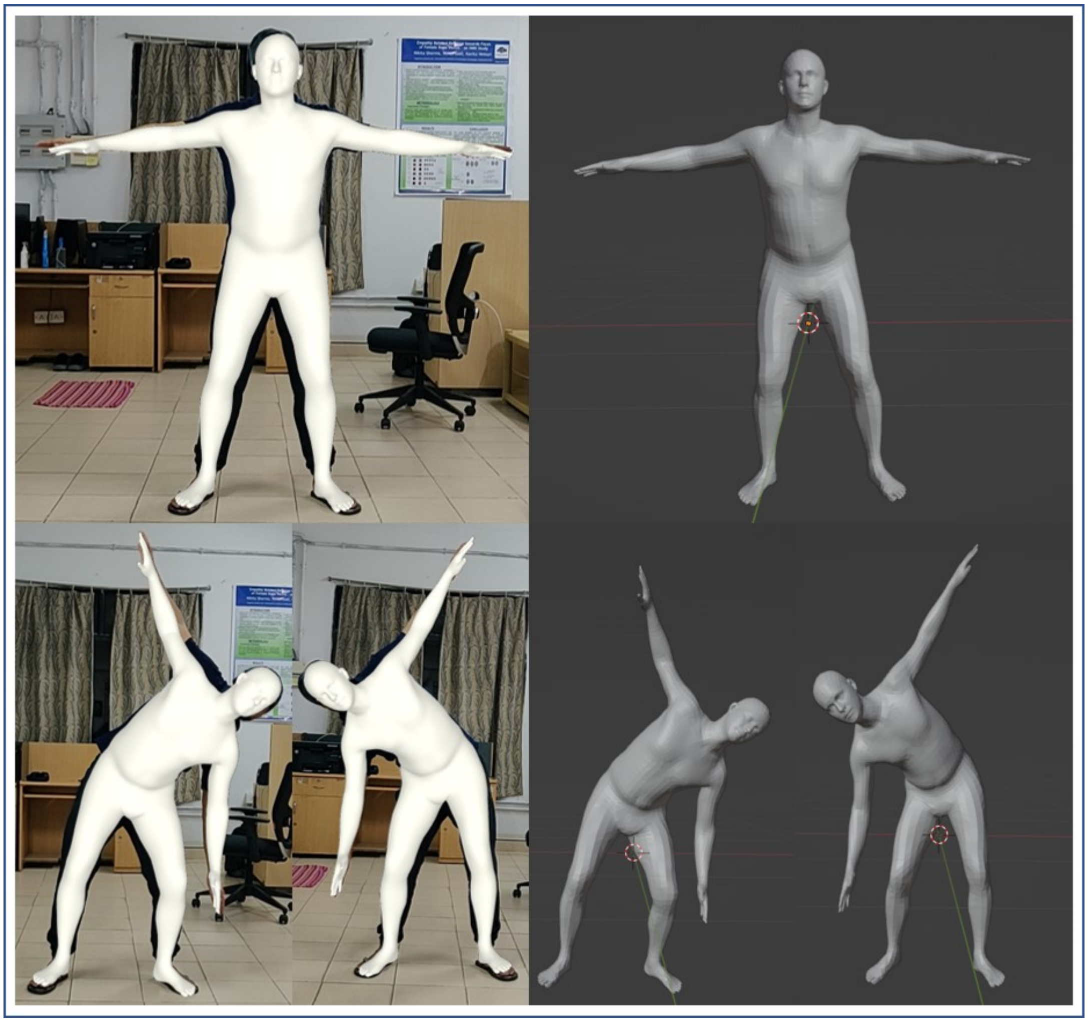

Figure 5.7: Generated 3D Human skeleton for a single participant in spine lateral-bend exercise: Fitted 3D pose from 2D key-points and Consolidated 3D pose visualized in blender tool.

For spine lateral-bend, 3D skeleton for one participant from the ProHMR model is shown in Fig 5.7. As expected physiologically for the flexion, the cervical segment (neck) displacement is higher than the other two segments (Fig 5.8) for all participants. The dominant side (right, as the majority were right-handed) is evident for both genders (Fig 5.8). The mean values and standard deviation for angles in lateral bend exercise was higher for male participants than female participants. The distribution around the mean is high (stdev $\approx \pm 10$).

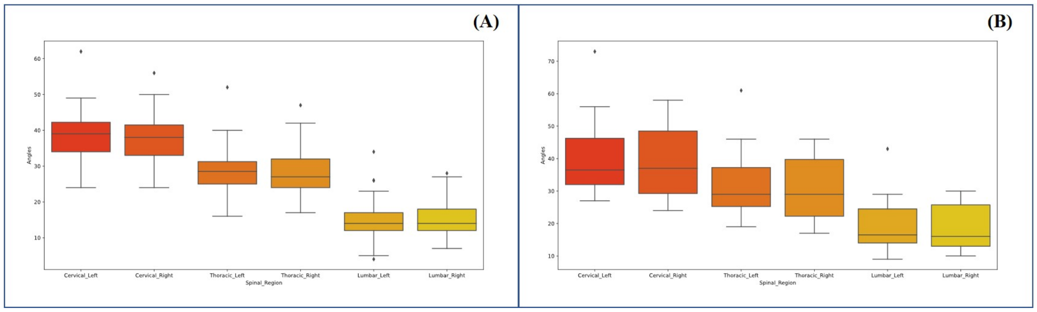

Figure 5.8: The angle estimates for the three spine segments and Lateral bend exercise (a) Male participants, (b) Female participants.

5.2.2.1 Comparative analysis between marker-based and marker-less motion capture system

Spearman's correlation analysis revealed that marker-less RGB angular displacement and marker-based angular displacement that strong positive correlations for spine lateral-bend were observed in female participants, while weak mixed correlations were found in male participants though the maximum difference was 5.825 degrees. The detailed correlation matrix with heatmap is shown in Fig 5.9 and 5.10.

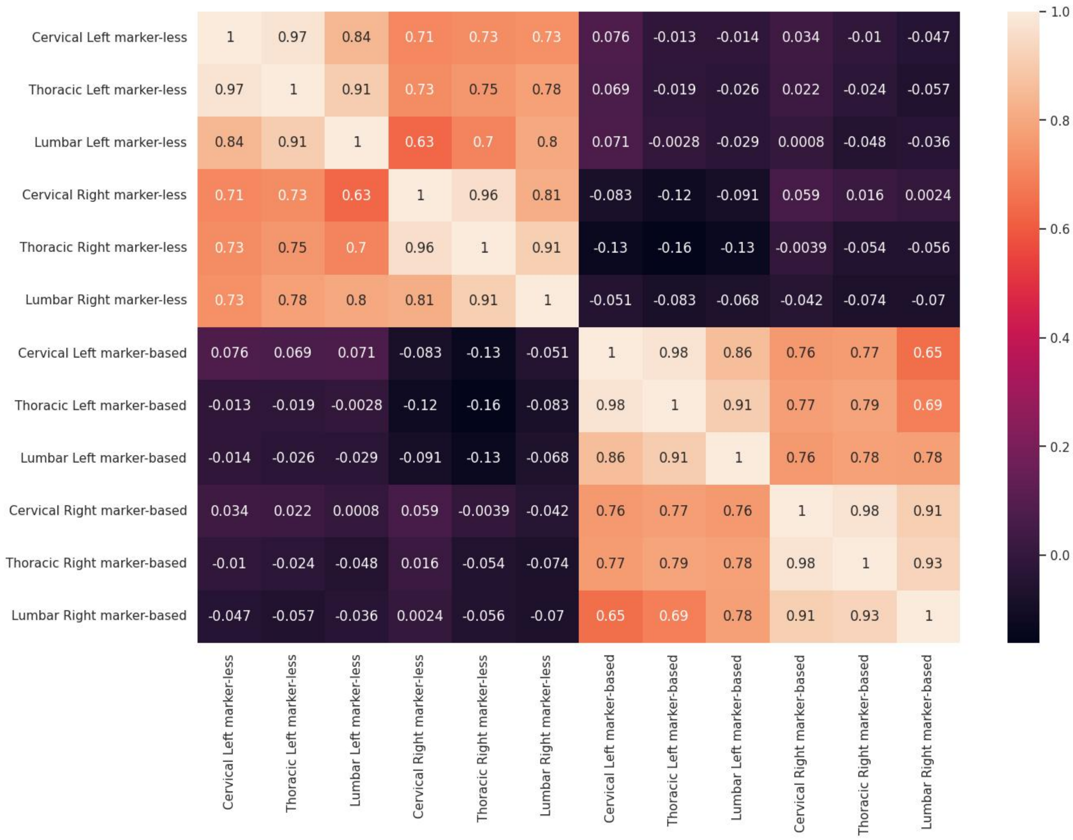

Figure 5.9: Spearman's correlation heatmap between marker-less angular displacement and marker-bases angular displacement for male participants in spine lateral bend exercise.

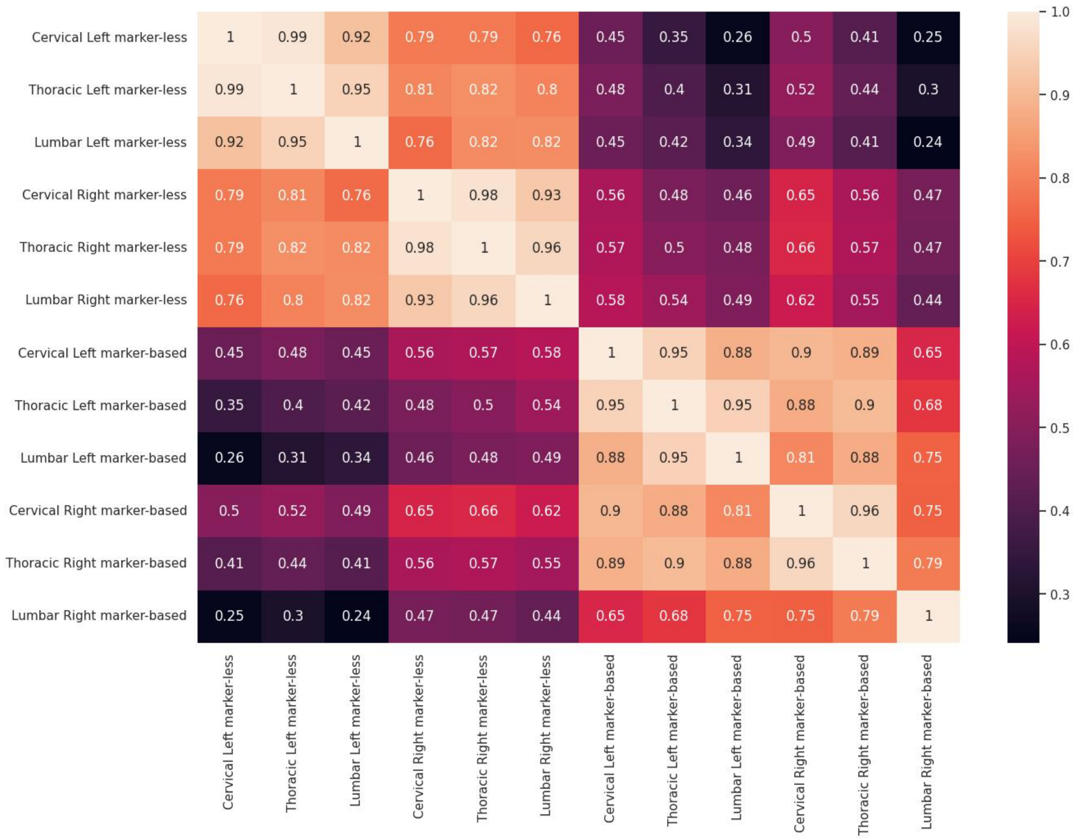

Figure 5.10: Spearman's correlation heatmap between marker-less angular displacement and marker-bases angular displacement for female participants in spine lateral bend exercise.

5.2.3 Squats

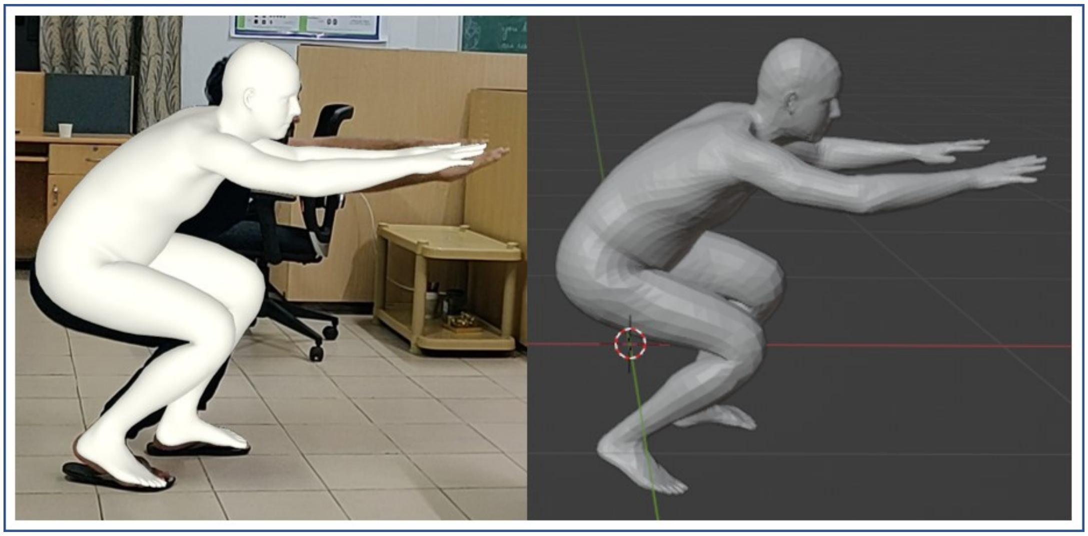

Figure 5.11: Generated 3D Human skeleton for a single participant in squat exercise: Fitted 3D pose from 2D key-points and Consolidated 3D pose visualized in blender tool.

For squat, 3D skeleton for one participant from the ProHMR model is shown in Fig 5.11.The squat had an approximately similar angular displacement distribution for all the participants. Female participants show significantly higher angles than the male participants (Fig 5.12). The mean and standard deviation of female participants was higher than for the male participants. The distribution of hip-knee segment displacements for both sides was more disperse in female participants (≈14) than for male participants (≈10). The squat depth as measured by the reference (12th) marker. Fig 5.13 shows the in-subject variability in angular displacement in squats exercise for both genders in each hip-knee segment.

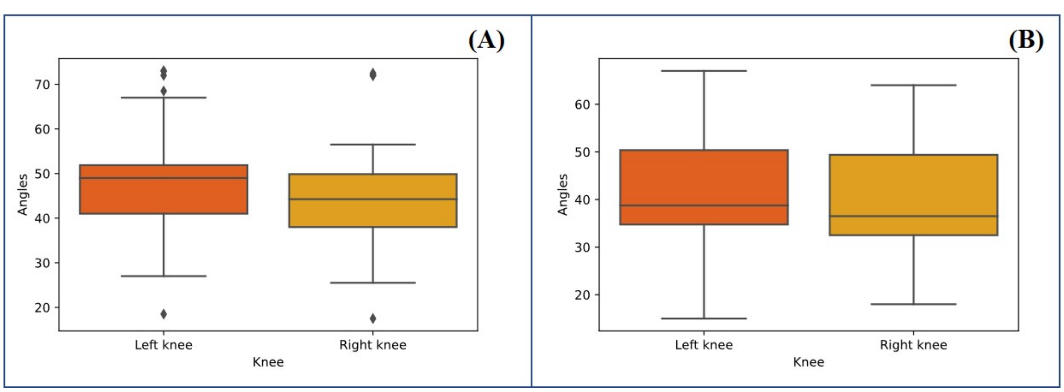

Figure 5.12: The angle estimates for both the knee segment in squat exercise. (a) Male participants, (b) Female participants.

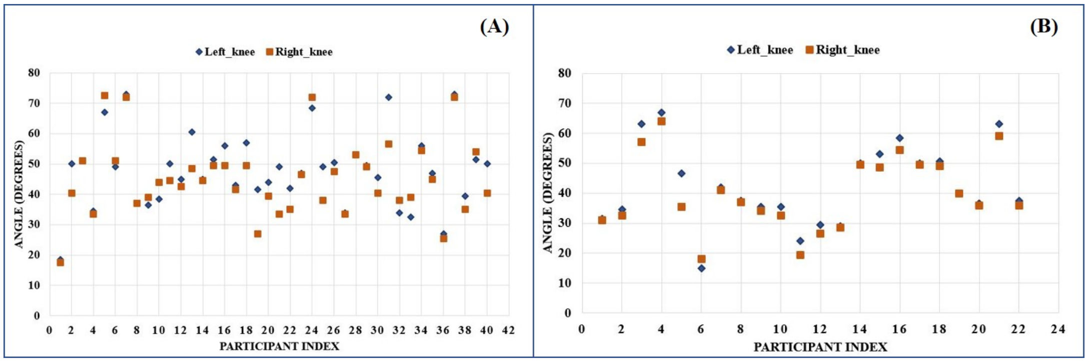

Figure 5.13: Participant-wise distribution of hip-knee segment angles extracted from the RGB camera video for squat exercise in (A) Males (B) Females.

5.2.3.1 Comparative analysis between marker-based and marker-less motion capture system

For male participants, Spearman's correlation analysis revealed that marker-less RGB angular displacement and marker-based angular displacement was significantly positively correlated with both the knee segments ($p<0.01$), i.e., knee-hip segment angles estimated via both methods are approximately similar. For female cohort, the similar pattern was observed as for male ($p<0.01$). The detailed correlation matrix with heatmap is shown in Fig 5.14 and 5.15.

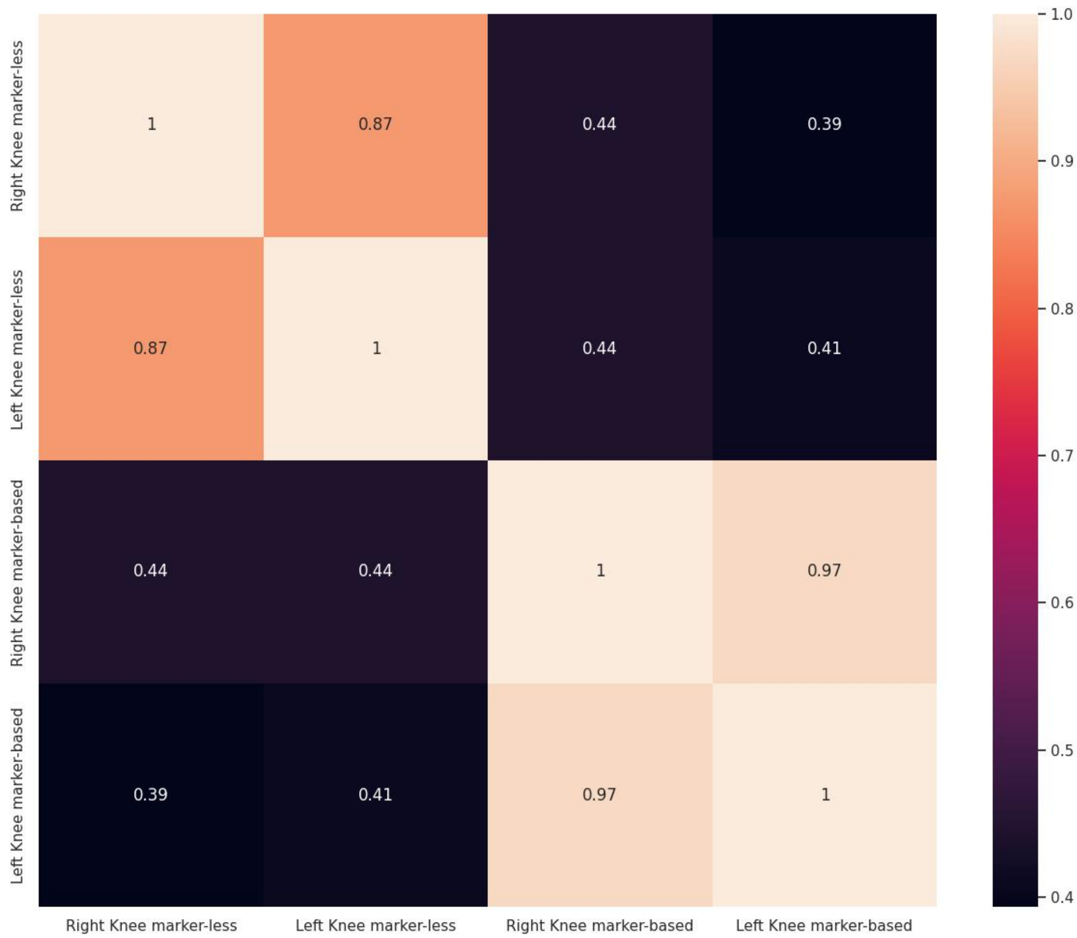

Figure 5.14: Spearman's correlation heatmap between marker-less angular displacement and marker-bases angular displacement for male participants in squat exercise.

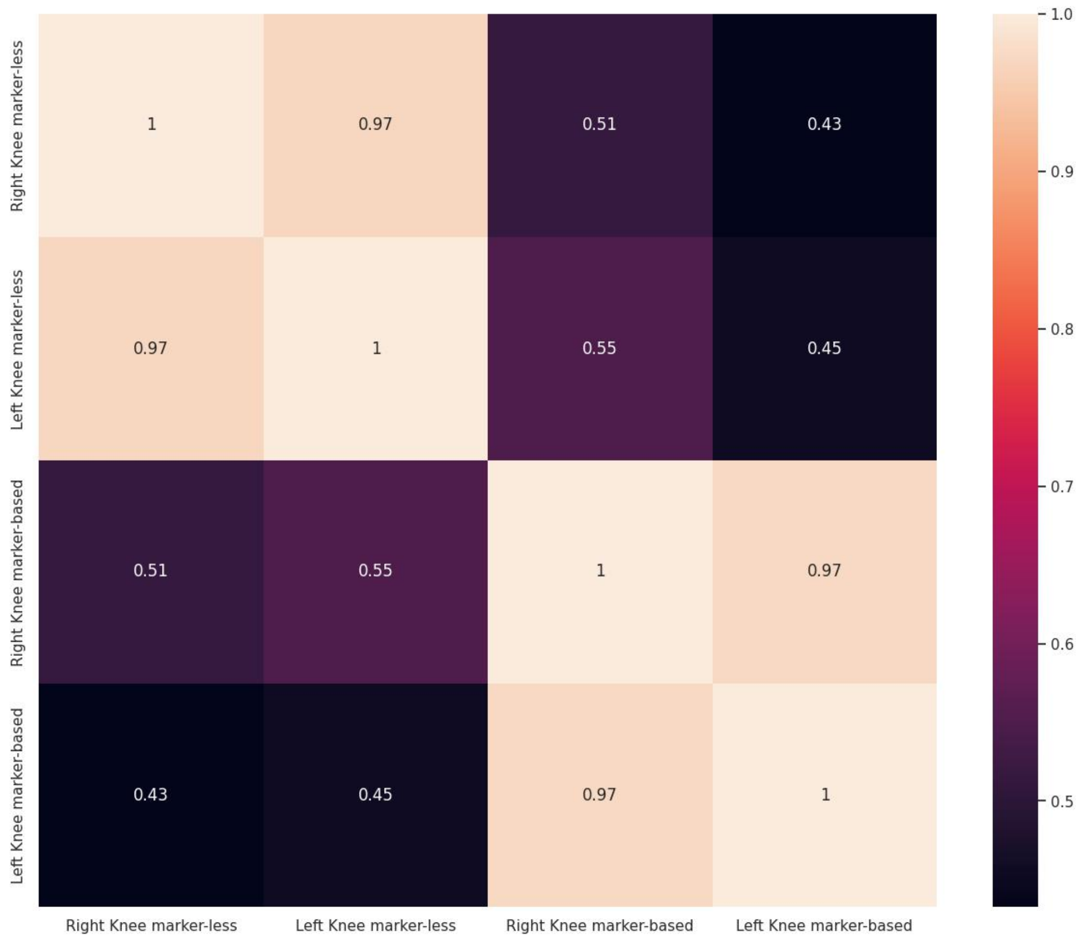

Figure 5.15: Spearman's correlation heatmap between marker-less angular displacement and marker-bases angular displacement for female participants in squat exercise.

5.3 Interpretation of Results

Clinical instruments such as inclinometer, inertial based sensing system, goniometer, and measuring tape used for measuring ROM require user expertise for data collection. Even the marker-based method necessitates meticulous camera and skeleton calibration procedures, the resulting data is considered as gold standard. But, motion capture systems are unfeasible in the clinical setting and require a large physical space. Smartphones with embedded (Inertial, accelerometer, and gyroscope) sensors capable of detecting the joint position, measuring joint ROM, active cervical ROM (Guidetti et al.,2017) and active craniocervical ROM (Pourahmadi et al.,2018) have demonstrated robustness (Sedrez et al.,2020). These alternatives are required by the health professionals for the motion assessment. The angle estimates by considering a single reference marker (lower lumbar) to observe the displacement of the cervical, thoracic, and lumbar spinal columns from the two techniques were comparable. This demonstrates that a single RGB camera and post-processing software (application) could be a viable marker-less motion capture technique for clinical applications with age/gender/exercise-specific reference/prediction models developed using gold-standard techniques like marker-based capture based on clinical-level reference model.

Chapter 6

Conclusions

6.1 Summary of Results

Spinal joint centers are difficult to identify with skin-mounted sensors due to difficulties in identifying bone landmarks, low intervertebral ranges of motion, and difficulty incomparing to radiograph ground truth values. Subject-specific spinal alignment of the markers and comparing them to radiographs have addressed some shortcomings (Schmid et al., 2017; 2021). Motion capture's significant advantage compared to static alignment data is in estimating the contributions of the spine columns from naturalistic kinematics models. Understanding the ROM of each segment is critical for diagnoses of spinal conditions, which requires a reference models from normal or healthy vertebral kinematics, which we have attempted in this study.

While there are studies investigating the whole trunk, only a few have focused on each segment and the intersegmental movement. For example, a local coordinate system was used to extract the relative orientations, say pelvic and thoracic orientations, to generate lumbar spine kinematics (Schinkel-Ivy et al., 2013). A study Zwambag et al. (2018) closest to our approach used a separate reference marker for the thoracic and lumbar spinal columns to compare intersegmental and electromagnetic techniques. In contrast, by estimating angles using a single reference marker and extracting displacement of all points on the spine, we attempt to resolve possible errors due to incorrect segment identification and evaluate the role of multi-segments in a full range flexion, bend, and twist movement to design technique independent model. This method is particularly useful when studying the variance due tothoracic kyphosis and lumbar lordosis curves, where segment identification is challenging. A single reference point/base marker is also optimal for comparing data from a marker-less single RGB camera technique since the skeletal frame extracted from the camera feed represents the spinal column with 27 nodes –from C1 to lumbar/sacrum. If there is imprecision in predicting the location of nodes/spine's S-shaped curvein the estimated 3D human mesh, the error will be higher if three reference frames (for each spinal segment) are considered.

The data from the spine and knee biomechanics from Asian-Indian young adults contributes to studies on skeleton, race and ethnicity (Looker, 2002). The in-depth analysis of physical characteristics and activity helps identify factors contributing to musculoskeletal flexibility. The models are more robust asthe same cohort was analyzed using two techniques. Future research could include a diversified (age, BMI, WHR, physical-activity) population and more trials for each exercise. Other physical parameters such as torso-to-leg-length ratio, spine 'S' curvature, and foot length (short vs. long) may be used to understand the height-spine angular displacement relationship better in spine and knee kinematics. Angular displacement accuracy in marker-less captures can be increased with a customized algorithm for pose estimation models focusing on spine movement.

6.2 Limitations and Implications for Future Work

A few factors limit this study: due to covid restrictions, data from older, clinical, and non-campus residents could not be collected, and only young and healthy subjects participated in this experiment, limiting population-level inferences. Although the angular displacements, estimated by both techniques, were in the predetermined range mentioned in (Vital et al., 2020), the suit worn by the participants introduces small errors. Increasing the number of mocap cameras could have minimized the marker detection error further. The angular displacements determined employing 3D human reconstruction using an RGB camera were comparable to the marker-based system spinal column angles. It is limited to capturing motion in specific exercises as we could not estimate the motion of spine axial rotations (twists). Lastly, we have used a single metric for physical activity, while a breakup into endurance, strength and flexibility training would help identify the effect of each on the spine biomechanics.

Related Publications

- Sharma, H., Karan, S. S., Agrawal, A. K., Vemuri, K. (2023). The role of individual physical body measurements and activity on spine kinematics during flexion, lateral bending and twist tasks in healthy young adults–Comparing marker (less) data. Biomedical Signal Processing and Control, 82, 104517.
- Sharma, H., Karan, S. S., Agrawal, A. K., Vemuri, K. (2022). " Investigating the association of kinematics of the spine and physical characteristics." Accepted at BIOSIGNALS 2022.

Unrelated Publications

- Karan, S. S., Sharma, H., Agrawal, A. K., Vemuri, K. (2023). EEG microstate analysis of tip-pinch and wrist flexion/extension movement. Brain Topography – **Under Review**
- Karan, S. S., Sharma, H., Agrawal, A. K., Vemuri, K. (2022). " Investigation of microstates from EEG signals of tip-pinch and wrist flexion/extension movement" Accepted at SAN2022.

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Important Responses to Reviewers

1 Please state the limitations of the study?

- Due to covid constraints, data from elderly, clinical, and off-campus residents could not be collected; furthermore, only young, healthy people participated in the study, limiting population-level inferences.
- Although the angular displacements measured by both techniques were within the specified range mentioned in (Vital et al.,2020), the participants' suit may have introduced minor inaccuracies.
- Increasing the number of mocap cameras could have further minimized the marker detection error.
- 3D human reconstruction with an RGB camera produced angular displacements comparable to those obtained with a marker-based approach, indicating that the two methods are comparable, but it is limited to capturing motion in specific exercises as we could not estimate the motion of spine axial rotations (twists).
- Lastly, we employed a single metric for physical activity, but dividing it into endurance, strength, and flexibility training might aid in determining the influence of each on spine biomechanics.

2 How study compared with other similar studies?

- Although studies of individual spinal segments have been reported (Robertson & Roby-Brami, 2011; Evans et al., 2013; Bauer et al., 2015; Anderst et al., 2014; Ignasiak et al., 2017), very few have studied intersegmental movement in the spinal column. Negrini et al(2016)'s meta-analysis of spine biomechanics studies showed that onlyfew which focusedon the whole trunk looked at the inter-intra segmental motion of the cervical, thoracic, and lumbar segments. Through our study, we have explored the inter-intra segmental motion of the spine. The angular displacement of the lumbar spine for flexion, twist and the lateral-bend (Lee & Wong,2002) as determined in our study lies within the reported range (Tafazzol et al.,2014;Lee & Wong,2002;Zwambag et al.,2018;review article: Widmer et al., 2019).
- Prolonged inactivity or a sedentary lifestyle increases body mass and has been associated with non-specific lower back pain in young adults (Andersen et al.,2006; Chen et al.,2009).

In a case of cause & effect, as pain increases, one tends to reduce activity, further aggravating the condition. Even with high physical activity, sitting for long hours can impact Lumbar-pelvic kinematics (Zawadka et al.,2022). To the best of our knowledge, the absence of the studies focusing on the correlation of parameters like WHR, physical activity level with angular displacement, through our study, we have explored the correlation between the kinematics of the entire spine column as a unit with BMI, WHR, and physical activity.

  - Comparative analysis based on the grouping as a function of BMI or WHR as between-subject parameters for males and females yielded mixed results, but no significant difference was observed.
  - For all three exercises, the correlation between angular displacement and physical activity level was statistically significant (flexion, lateral-bend, and for a few conditions in twist). There was a statistically significant correlation between females' physical activity and flexion exercise. The absence of statistical significance in the female cohort for certain exercises could be due to the smaller sample size and the role of higher estrogen levels (Chidi-Ogbolu et al.,2019) in the age group considered and, hence, flexibility may be independent of physical characteristics or activity.

- In contrast to previous studies (Schinkel-Ivy et al., 2013; Zwambag et al., 2018), which extracted angles using multiple reference frames, we evaluated the role of multi-segments in a full range flexion, bend, and twist movement, and designed a technique-independent model by using a single reference frame in the current study which also resolves possible errors due to incorrect segment identification.
  - A single reference point/base marker is also optimal for comparing data from a markerless single RGB camera technique since the skeletal frame extracted from the camera feed represents the spinal column with 27 nodes –from C1 to lumbar/sacrum. If there is imprecision in predicting the location of nodes/spine's S-shaped curvein the estimated 3D human mesh, the error will be higher if three reference frames (for each spinal segment) are considered.

3 What is the future scope of the study?

- In future studies, more trials could be conducted with a broader range of participants (age, body mass index, WHR, and physical activity level).
- The height-spine angular displacement relationship may be clarified with the use of other physical factors such as torso-to-leg length ratio, spine 'S' curvature, and foot length (short vs. long).
- Spine-centric pose estimation models can benefit from a customized method that improves the precision of angular displacement.
- In clinics without access to equipment for restricted movement, the data can be used as a reference.

4 Why the study objective was chosen? What is novelty of the work?

- Spine biomechanics (kinetics & kinematics) is crucial to study as it plays a significant role in human activities from gross motor tasks in daily life to complex movements. Understanding the movements as supported by different trunk segments are essential for clinical diagnosis. Additionally, understanding spine dynamics is crucial for medical conditions affecting motor movements, like hemiplegia caused by a stroke, Parkinson's, lower back pain, spine injury, osteoporosis, age-related musculoskeletal flexibility, ergonomics with continued sitting, and obesity. The lumbar segment has been investigated extensively followed by thoracic, but only limited studies on the whole trunk focused on inter-intra segmental motion of the cervical, thoracic, and lumbar segments. Consequently, we have studied the whole spine with respect to intra- and inter-segment motion while employing marker-based and marker-less motion capture techniques. Utility: In clinics without access to equipment for restricted movement, the data can be used as a reference.
- Prolonged inactivity or a sedentary lifestyle, which results in weight gain and has been associated with the occurrence of non-specific lower back pain in young people due to a loss of muscular power and strength, is a major risk factor (Andersen et al.,2006; Chen et al.,2009). It is a classic instance of cause and effect: when pain increases, individuals tend to slow down, further aggravating the condition. Regardless of high recreational physical activity, sitting for lengthy periods of time might still affect Lumbar-pelvic kinematics (Zawadka et al.,2022). Therefore, more research is required to determine whether or not body mass index, WHR, and physical activity all influence the kinematics of the spine.
- When it comes to biomechanical applications, human motion detection, animations, and even for military use, motion capture systems (Opti Track motion capture systems & Vicon) (Nagymáté et al., 2018) are the gold standard. There are various limitations to using this technique, including its inflexibility, expense, lengthy calibration process, need for dedicated space, and need for specially trained personnel. Analysis of marker-based mechanics can be very complex with correlations between muscle markers and those on spine. Therefore, this work introduces a novel technique/method of measuring spine angles, as incorrect skin marker positioning affects curve measurement and kinematic variability (Severijns et al., 2021).

5 Please enumerate limitations of employing "RGB camera" over other standard devices.

- Although angular displacements extracted from 3D human reconstruction with an RGB camera are comparable to those obtained with a marker-based system, the method is still constrained to capturing motion during only a subset of exercises as it was unable to provide an estimate of the motion of the spine's axial rotations (twists).
- The skeleton frame extracted from the RGB camera represents the spinal column with 27 nodes, from C1 to the lumbar/sacrum; hence having a single reference point/base marker

is also preferable when comparing data with a marker-less single RGB camera approach. If there is imprecision in predicting the location of nodes/spine's S-shaped curve in the estimated 3D human mesh, the error will be higher if three reference frames (for each spinal segment) are considered. While imaging methods with RGB camera feed is fine-tuned, the kinematics parameters need to be compared with accurate data – which marker-based camera capture can offer.

6 **The premise of the first part of the study that is based on correlations between spinal motion and certain physical characteristics is not very novel and not intuitively relevant. The thesis fails to justify the reasons for finding these specific associations. The initial chapters are written well describing the various techniques available. But the document needs to have another section to describe about what is known about the variability of spinal motion across age, gender, and other flexibility measures (Beighton score / Schober test). In other words, the student should strengthen the rationale of the study and support it with literature. As the study is completed with healthy subjects, the relevance of knowing spinal motions across over- weight/ normal weight or active/sedentary individuals is not very clear.**

Thanks for the feedback, ma'am,

- In accordance with the guidelines outlined in section 4.1.2, the data collection for this study was conducted during the first and second waves of the Covid-19 pandemic. Consequently, we faced limitations in gathering a more diverse population, including individuals from various age groups and those with spinal disorders, and achieving a balanced gender ratio among participants. We were able to collect the data only from young and healthy participants. However, we agree that we should also include these parameters in our literature study and that we already included them in section 2.3, 2nd paragraph: "Another study on the effect of age on thoracic segments ...", and this limitation is already mentioned in section 6.2: "A few factors limit this study: due to covid restrictions, data from older, clinical, and non-campus residents could not be collected, and only young and healthy subjects participated in this experiment, limiting population-level inferences.".
- Furthermore, to the question, "The thesis fails to justify the reasons for finding these specific associations", has already been addressed in section 1.1 First paragraph of why we chose these specific parameters to study with the spine angles, and we do agree that the study the spine angles with physical parameters are not novel, but according to the literature, all these parameters have not been studied as a unit.

7 **What is the reason for choosing these specific parameters - BMI, WHR and physical activity? In my clinical practice, the ability to move the spine is far more dependent on age, gender and history of participation in sports that include flexibility exercises. The study by McClure1 (1997) and Esola2 (1996) have rightfully correlated the ability to move the spine on hamstring flexibility. Kindly justify the use of these parameters.**

- We base the study on previous findings (for example: Body mass index and waist circumference in early adulthood are associated with thoracolumbar spine shape at age 60-64: The Medical Research Council National Survey of Health and Development Pavlova AV, Muthuri SG, Cooper R, Saunders FR, Gregory JS, et al. (2018) Body mass index and waist circumference in early adulthood are associated with thoracolumbar spine shape at age 60-64: The Medical Research Council National Survey of Health and Development. PLOS ONE 13(6): e0197570. https://doi.org/10.1371/journal.pone.0197570), on spine shape, and the work of (Taweetanalarp S, Purepong N. Comparison of lumbar spinal angle between normal body mass index and overweight young adults. J Phys Ther Sci. 2015 Jul;27(7):2343-6. doi: 10.1589/jpts.27.2343. Epub 2015 Jul 22. PMID: 26311979; PMCID: PMC4540877) on lumbar angles. While physical activity is the major factor, as also found in our study, the idea was to extend the studies on static spine analysis to kinematics. When the experiment was planned, the scope included gender age, we could not complete it due to covid restrictions for almost 2 years. Hence restricted the study to students who were staying in college and vaccinated. The long periods of no-physical activity did show an increase in BMI in some students, but we did not note the change in the 2 year period.

8 **The details of development of LCS for each segment should be described in further detail. It is very confusing for me to understand how the single reference frame works...I am guessing that all segments are compared to the initial stance position. The numbers are difficult to interpret - For example in Figure 5.3 describing the ROM while bending forwards to reach toes shows that the cervical flexion is 100 degree plus... while in reality, most people keep neck straight, bend slightly or may sometimes extend the neck (as shown in fig 5.2) . Similarly the thoracic spine does not bend so much. What do these numbers mean? And if they cannot be compared with anything done previously, what is the relevance of such evaluations?**

Thanks for providing the feedback,

- The single reference frame there is define to be going into spine's 12th marker's frame and calculating position vector of all the markers which respect to that marker. And at every second the angle has been calculated with respect to initial frame which is when the participant is standing upright (at t=0) as mentioned in the section 4.1.3.1.

- And as seen in the Fig 4.3 (A), the angle from the image is coming in the obtuse angle range which was expected to be around 100-120 degrees.

- As there were no study which has done the analysis like we did, we compared the ROM of lumbar region with the past studies and for the rest of the two section, we showed the ROM analysis to an orthopedic doctors (Dr. Rajendra Kumar Elluri) who suggested that as in this experiment, the participants were not asked to either keep the neck straight or extend.

- The angles estimated for the Thoracic range from 50-110 deg with the median at 70 degrees (as against the normally recorded 75 deg). As the exact position of the marker as a function of the spine column is not possible, there is a scope for error.
- But the use of a single reference to measure the ROM, allows for a quick evaluation of possible issues. Of significance it the temporal or time varying angle plots, which show the flow of a complete flexion.

9 **Was any validity testing done prior to the experimental set up? For example, the use of 12 sensors on cloth over spine versus directly double taped over skin on spine in a sample of subjects may show how much are the errors due to clothing.**

- Yes, it is a valid observation. But for this preliminary dataset, the validation check was not done in terms of comparison with the data captured by directly placing the sensor on the skin. The tight-fitting nature of the suit worn by participants, with the minimal thickness (less than 0.5cm), ensured close proximity of the sensors to the skin. Hence the error which was introduced due to this was predicted to be very small as the angles estimated was within the range as mentioned in the section 6.2: "Although the angular displacements, estimated by both techniques, were in the predetermined range mentioned in (Vital et al., 2020), the suit worn by the participants introduces small errors.".
- We had two issues, one participant's discomfort for any marker directly on the skin and giving data with a shirt or shorts. Hence, we used tight swimming suits.

10 **The figure 4.3 shows the subject performing a full deep squat. But the data presented in Figure 4.23/24 and 5.13 – shows that the maximum hip flexion is about 60-70 degrees. This is surprising knowing that the hip bends to almost >120 degrees for a full squat. Kindly comment and clarify. This was the most intuitive number to me as visually/ by goniometry, it is possible to measure hip ROM. Similar numbers for spine movement are not intuitive as they are difficult to be measured visually. The student may please provide data from previous studies measuring spine movement and compare the results of current study with them. There is ample literature for cervical and lumbar motion analysis.**

Thanks for the feedback,

- Agree that the person in the image is doing the deep squat and the hip flexion should be in the range obtuse angle, but as mentioned in our methodology section of calculating the hip flexion and the theta angle shown in the image, the reference to calculate the hip flexion was the 12th sensor on spine not the hip joint sensor, hence the angle value came in the range 60-70 degrees. The displacement distance of the reference marker to the ground was considered as relevant for our study.
- And as mentioned in the above responses and in our literature, the comparison to lumbar was done in the interpretation section. The use of single-reference frame gave a medium

value (70 deg) which is reported for thoracic in literature. For cervical our method showed a median of 80 degree, while literature reports 80-90 deg for flexion.

11 **Analyzing the axial rotation in global reference frame means that the rotation of the person is a sum total of rotations at the hip, ankle and spine. It should be called full body twist/rotation and not simply spine rotation.**

- Thanks for the feedback, yes, analyzing axial rotation in a global reference frame consider to be the rotation of the person's as the combination of hip, ankle and spine, but the global reference frame in motion capture tracking is with respect to the markers on the spine and hence the same nomenclature was applied. In the next set of experiments, we will be placing markers on the muscles too.