Preliminary Study: Bilateral Gait Symmetrical Validation for Different Genders

Naga Kishan Munjulury Venkata
2018
Cover picture: IMU sensors placement during walking gait with the help of Velcro straps.
Naga Kishan, January 2018.
Preface

Firstly, I would like to thank Dr. Sajid Rafique and Prof. Niclas Björssel for giving me this opportunity to complete my master degree with this thesis work.

Special thanks, to my brothers and friends from Africa for their unconditional help and support in participating for the assessment.

Finally, the fantastic four: Family, Friends, and Faculty and for the future:

Family: I will always be your ever loving son, and brother, and without your unconditional help at all the obstacle times, I would have not come this far.

Friends, you were with me at times of encouragement, which meant a ‘help for help’ from ‘hand to hand’.

Faculty: The best faculties of ‘University of Gavle’, who have given me the knowledge of wisdom for my future.

Future: Dare me; I am coming to achieve you.
Abstract

This thesis presents the methods of validating bilateral gait symmetry for both genders. Particularly, the study focuses on the behavior of each participant’s right and left knee joint flexion/extension angles during normal walking at self-selected gait speeds. The participants consist of 10 males (mean age 26.07±6.31 (SD), a range of 20-40 years) and 10 females (mean age 35.46±10.07 (SD), a range of 23-53 years). The tests were conducted considering them as healthy individuals, free of any apparent walking disability.

The experimental results of the study were validated with the benchmark ground truth results obtained from OpenSim Biomechanics software. Anthropometric and spatiotemporal parameters were measured with the help of a linear scale on the floor, a BMI analyzer (Height scale and weighing machine) and a measuring tape. The study presented gender comparisons based on analysis of variances (ANOVA) and revealed positive significant differences (p<0.0053) in relation to differences in age, BMI, and the participant’s step length, height, knee lengths, gait speeds (cm/s) and cadence (steps/minutes). Female participants were identified to have, less right and left steps and stride lengths at greater gait speeds compared to male participants. The results of maximum right and left knee flexion, measured with inertial sensors, found to be in the range of 30.87°±3.91° and 30.80°±3.0° (mean ± (SD)) respectively for male participants. For female participants, the maximum flexion knee angle was found to be 30.74°±3.20° for right knee and 28.45°±3.6° for the left knee. It was found that none of the participants exhibited hyperextension during normal walking. However, as per anatomy of the knee, a normal gait pattern has a maximum knee flexion of up to 60 degrees in the sagittal plane. The shorter knee flexion observed in this study might be due to the fact that the participants were walking on a shorter track of 6m only, whereas, the knee flexion angle increases gradually for a long run. Hence, this research used normalization method of compensation to retrieve the comparable knee angles with respect to the subject’s natural height or stature.

When the variables of lengths (step length, stride length, height…) were normalized with respect to individual’s knee height measure of stature, and phase variables were normalized with respect to each individual’s stride time, there were no specific significant gender differences. The normalized findings suggest that, there were age related significant differences found between the mixed groups of age’s ±26 years, but not due to their individual gait speeds. Hence, it is concluded that normalization based on different genders might not be valid irrespective of their statures. It is pertinent to mention that the present study was done in collaboration with Department of knee surgery at Hässleholm hospital, Sweden. The results of the study are likely to be used as an initial platform for further research to identify abnormalities in the knee joint.
Table of Contents

1 Introduction ............................................................................................................................................. 1
  1.1 Background .................................................................................................................................. 1
  1.2 Motivation .................................................................................................................................... 2
  1.3 Materials and methods .................................................................................................................... 2
  1.4 Outline of this work ........................................................................................................................ 2
2 Theory .................................................................................................................................................. 3
  2.1 Human knee joint anatomy ........................................................................................................ 3
  2.1.1 Biomechanics of internal knee joint and its Range of motion ...................................................... 4
  2.1.2 Common injuries of the Human Knee joint .................................................................................. 5
  2.2 Gait analysis .................................................................................................................................. 6
  2.2.1 Cyclic Nature of Gait in 3-dimension .......................................................................................... 7
  2.2.2 Gait cycle ................................................................................................................................... 7
  2.2.3 Gait and Spatiotemporal parameters ......................................................................................... 9
  2.2.4 Abnormal or Pathological gait patterns ...................................................................................... 10
  2.3 Kinematics of Knee Joint and Anthropometry of Lower- body .......................................................................... 12
  2.4 Gait analysis methods ..................................................................................................................... 15
  2.4.1 Hardware: Inertial sensors ........................................................................................................ 15
  2.5 Software: Application program interface .......................................................................................... 17
  2.5.1 Attitude and Heading Reference System ................................................................................. 17
  2.5.2 Xsens extended kalman filtering ............................................................................................ 18
  2.6 Gait instrumentation pipeline design flow ......................................................................................... 19
  2.7 Statistical analysis and regression ..................................................................................................... 19
  2.8 Literature review ............................................................................................................................. 22
3 Methods ................................................................................................................................................ 26
  3.1 Gait assessment ............................................................................................................................... 26
  3.2 Subjects/ Participants ....................................................................................................................... 27
  3.3 Measured variables for gait analysis .................................................................................................. 27
  3.4 Discrete Knee Angular parameters (K1 to k6) .................................................................................. 28
  3.5 Bilateral gait symmetry comparison with both legs and genders .................................................................. 28
  3.6 Data Acquisition from motion trackers ............................................................................................ 29
4 Results and Discussion .......................................................................................................................... 32
  4.1 Gait parameters and stride characteristics ....................................................................................... 32
  4.2 Age, Gender and BMI effects .......................................................................................................... 33
  4.3 Inverse kinematics and normalization - Knee angle ........................................................................ 36
    4.3.1 Knee swing width ROM ........................................................................................................... 36
    4.3.2 Kinematics of Knee joint of the subjects ............................................................................... 37
  4.4 Discrete Knee Angular parametric values (K1 to k6) ....................................................................... 39
  4.5 Bilateral Gait symmetry .................................................................................................................. 42
  4.6 Additional discussion ....................................................................................................................... 44
5 Conclusion .......................................................................................................................................... 46
  5.1 Future work .................................................................................................................................... 47
6 References .......................................................................................................................................... 48
Appendix A: Matlab Scripts ..................................................................................................................... A1
Appendix B: Hardware and software ....................................................................................................... B1
Appendix C: Stats of the participants..........................................................C1
Appendix D: Excel ToolPak Data analysis tool results..............................................D1
LIST OF ACRONYMS

ROM – Range of motion
ANOVA – Analysis of variances
API – Application program interface
MTw – Wireless motion tracker
XKF3 – Xsens extended Kalman filter
AHRS – Attitude heading reference system
GS – Gait Symmetry
BMI – Body mass index
IMU – Inertial measurement unit
CNS – Central nervous system
PNS – Peripheral nervous system
GRF – Ground reaction force
ACL – Anterior cruciate ligament
PCL – Posterior cruciate ligament
CL – Collateral ligament
cm – centimeters
IRT – Infrared thermography
EMG – Electromyography
GPS – Global positioning system
GSR – Gait symmetry of right knee
GSL – Gait symmetry of left knee
SDI - Strap down integration
LIST OF FIGURES

Figure 1. Knee joint schematic representation
Figure 2. Internal Knee joint motion in tri-axial dimension
Figure 3. Top-down approach of neural activity during any Gait Patterns
Figure 4. Standard anatomical positioning of human body
Figure 5. Example of a Normal Gait cycle of a young boy with gait cycle %
Figure 6. Eight main periods or events of the cyclic nature of human gait
Figure 7. Distance based Gait parameters
Figure 8. Few illustrations of the pathological walking patterns
Figure 9. Anthropometric measurements of the lower body for Gait parameters
Figure 10. External Knee joint motion with reference frames of the left leg
Figure 11. Extreme Hyper-extension ROM illustrations
Figure 12. Anatomical differences between gender's pelvis gap that affect walking gait
Figure 13. (a) Current mode under non-magnetic.
Figure 13. (b) Current mode under magnetic field
Figure 14. Pipeline design flow of measurement system
Figure 15. Null hypothesis representation
Figure 16. Flow chart of the gait assessment procedure
Figure 17. Discrete Knee angular parameters at main key phases of the gait cycle (%)
Figure 18. Sensors 3D alignment / orientation
Figure 19. Placing straps and alignment of motion sensors
Figure 20. FLOW CHART OF THE EXPERIMENTAL PROTOCOL
Figure 21. Swing width range of Knee flexion angle
Figure 22. Knee flexion/extension angle of Female Participants
Figure 23. Knee flexion/extension angle of Male Participants
Figure 24. Bilateral Gait Symmetry validation (GSR/GSL) to identify abnormality
LIST OF TABLES

Table 2.1: Maximum and minimum motions of internal knee joint during a gait
Table 2.2: Gait parameters
Table 2.3: Functional range of motion (ROM) at the knee
Table 2.4: Literature review of the appended references
Table 2.5: Review of various Human motion tracking systems
Table 4.1: Gait parameters of Female subjects (Both right and left knee)
Table 4.2: Gait parameters of Male subjects (Both right and left knee)
Table 4.3: Comparisons: Spatiotemporal and Anthropometric data
Table 4.4: Knee Flexion/Extension Mean Values max and min (Degrees) of male
Table 4.5: Knee Flexion/Extension Mean Values max and min (Degrees) of Female
Table 4.6: Maximum Knee joint ROM between the genders
Table 4.7: Discrete Knee Angular parametric values (K1 to k6) of male
Table 4.8: Discrete Knee Angular parametric values (K1 to k6) of female
Table 4.9: Male Phase Variables
Table 4.10: Female Phase Variables
Table 4.11: Male and female distance variables
Table 4.12: Bilateral Gait Symmetry of 20 participants
Table 4.13: Mean values of the subjects having Asymmetry Bilateral Gait Pattern
Table C1: Male Subjects: Gait and kinematic parameters
Table C2: Female Subjects: Gait and kinematic parameters
1 Introduction

The main purpose of this thesis is to do a ground work on bilateral gait symmetrical validation of different genders. The study involves the validation based on knee joint flexion/extension angle in the sagittal plane. The outcome of this study will help to identify the abnormalities in the human knee joint using gait analysis. Different gender based comparisons on their walking gait patterns are very contemporary in the lower extremity of their body. According to gait studies and anatomy and physiology of the human body [1-11], apart from hip joint, the functionality of the knee joint to the foot is similar for both male and female genders. Therefore, gender classification is relevant and an important task to prove their performance of knee joint motion during gait analysis using human motion tracking systems. The gait analysis certainly at a normal walking speed is most commonly used in today’s era to identify walking styles with the measures of kinematics and kinetics of the lower extremity function which will help diagnose abnormalities that can appear in the future changes of functional status of the individual's (male or female) walking patterns.

1.1 Background

One of the demographics of the world, the population, is ageing with an associated increase in age-related problems which includes osteoarthritis that affects one or more joints of the human body. But more commonly, knees which leads to disability, social isolation and morbidity [1]. Now-a-days, rehabilitation for the patients during pre and post knee surgeries has been very successful.

Gait analysis is the biomechanical study of human walking analyzing the body movements. It helps the patients to get diagnosed with the walking abnormalities and also helps to regain their normal range of motion in their lower extremities. It is a well-balanced psychological remedy to get the patient, his behavior back of moving forward. The conventional methods of identifying knee abnormalities are time consuming and also involve frequent surgeries of knee replacements. The total knee replacement through surgery is not a very useful method as it reduces the range of motion of the knee. Therefore, the main motivation of this study was to investigate alternative methods of identifying knee abnormalities based on biomechanics.

There is a main difference in gender gait asymmetry of walking gait which is, women have an increased non-sagittal movement in the pelvis and hip abduction range of motion. However, it is not known if this difference exists under a variety of locomotion conditions [2].
1.2 Motivation

The study is to validate the anthropometric and spatiotemporal parameters and a practical assessment using wireless inertial measurement units (IMUs) by obtaining the knee range of motion (ROM) for bilateral symmetrical validation. Gender can be compared based on the variance of analysis in relation to the differences in ages, body mass index, and the participant’s step length variables.

1.3 Materials and methods

The main requirements for the proposed work are:

Subjects: 10 male and 10 female healthy participants for the gait assessment.

Gait Analysis: The process is carried out to be in a laboratory condition and the standard distance for the assessment is 6 to 10 meters.

Instrumentation: A linear scale (measurement label), body mass index analyzer (height meter and weighing scale), inertial sensors for motion tracking system of the normal gait and Matlab tool.

Statistical methods: Analysis of variances (ANOVA), student’s t-tests, regression analysis and normalization with a standard.

1.4 Outline of this work

This thesis work comprises of five chapters,

Chapter 1- Introduction to the thesis

Chapter 2- Theory: describes the background study of the whole research.

Chapter 3- Methods: describes the gait assessment, Gait parametric analysis, and procedure of the data acquisition from motion tracking system with a flow chart.

Chapter 4- Results: depicts the quantitative measurements and or analysis, statistical analysis, Kinematics and normalization, also contains the discussion of this thesis,

Chapter 5- Conclusion: provides the overall summary and the future work of this thesis.
2 Theory

This chapter describes the important things in detail which are key points of this research work. The focus is on bilateral gait symmetrical comparative study and analysis of different gender to identify their abnormalities based on their knee joint flexion/extension angle.

2.1 Human knee joint anatomy

In the human body, the knee joint is the most complicated and largest joint than the shoulder, wrist and hip joints. This joint connects the thigh and shank of the leg in the human body [4]. The knee joint connection includes three main articulating bones, which are the femur (thigh bone), patella (knee cap), and tibia (shin bone), in the lower limb of the body. The femur is the strongest and longest bone in the body. The two round excrescences or protuberances at the edge of the femur are called femoral condyles as shown in figure 1[4]. These femoral condyles form a pattern named the patellofemoral groove. The patella which is also called knee cap glides along under the surface of the femur edge between the femoral condyles [4].

The function of the knee cap (patella) is to protect the knee joint by relieving frictions between the smooth elastic tissues (cartilages) and muscles, during the knee bending motions. The shinbone which is so-called Tibia helps to stabilize the knee. Two crescent-shaped menisci are attached above the tibia as shown in figure 1[4]. The fibula which is the bone next to the tibia also supports the joint stability of the knee. However, it is not involved along with the knee joint capsule.

\[ \text{Figure 1: Knee Joint Schematic Representation} \]  

The knee joint consists of three functional compartments which is the form of a kind of the juncture of bones are [4]:

- a. The patellofemoral articulation (junction) locates between the knee cap (patella) and the thigh bone (femur),
- b. Lateral femorotibial articulation between the femur and the tibia,
- c. Medial femorotibial articulation between the femur and the tibia.
The type of joints inside the knee are the patellofemoral articulation which is a synovial gliding joint and the other two femoro-tibial articulations between the femur and the tibia are synovial hinge joints [3]. The gliding of the joint between patella and femur is due to synovial fluid which is secreted by a synovial membrane located in the inner layer of the capsule; this makes the knee joint an intricate synovial joint [3]. A synovial capsule surrounds the articular surface of the joint. This fluid in the knee joint helps as a cushion and lubricates the joint without any kind of friction during the motions.

2.1.1 Biomechanics of internal knee joint and its Range of motion

The range of motion of knee joint is explained [5] as the return of full motion, with bending (flexion) and straightening (extension) of the knee joint as shown in the figure 2. As per the reference [6], the knee joint is a pivotal hinge joint which is the combination of ginglymus and arthrodial which is also a gliding joint [6]. It usually assumed to be 6 degrees of freedom which consist of 3 translations and 3 rotations as shown in the figure 2. However, the internal-external rotation of the knee joint has 3 axes namely, sagittal axis, frontal axis and a transverse axis and their ROM is shown in table 2.1. External knee joint ROM is given in detail in Section 2.3.

![Figure 2: Internal Knee Joint Motion in Tri-Axial Dimension](image)
Table 2.1: Maximum and minimum motion of internal knee joint during a gait [6]:

<table>
<thead>
<tr>
<th>Rotation:</th>
<th>flexion-extension: ≤160 deg of flexion (up to -5 deg flexion – hyperextension)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Varus-valgus: 6-8 deg in extension</td>
</tr>
<tr>
<td></td>
<td>internal-external rotation: 25-30 deg in flexion</td>
</tr>
<tr>
<td>Translation:</td>
<td>anterior-posterior: 5–10 mm</td>
</tr>
<tr>
<td></td>
<td>compression: 2–5 mm</td>
</tr>
<tr>
<td></td>
<td>Medio-lateral: 1-2 mm</td>
</tr>
</tbody>
</table>

The behavior of the knee joint is complex resulting in the individual behavior and interaction between the three different factors as follows [6]:

a. Static-stability which are due to geometry and anatomy of the joint surfaces.

b. Active-stability which are due to muscle contractions.

c. Passive-stability which are due to ligaments, menisci and retinacula.

### 2.1.2 Common injuries of the Human Knee joint

There are many kinds of knee injuries which cause instability and can also loose the sense that the knee is giving way [9]. The most common injuries [9] are as follows:

a. Fractures: Commonly, broken bone around the knee is the patella.

b. Dislocation: Caused by an abnormality in the structure of a person's knee.

c. Anterior Cruciate Ligament (ACL) Injuries:
   Related to injuries during sports activities where knee twist by changing direction rapidly inside or jump and land incorrectly which can tear the ACL.

b. Posterior Cruciate Ligament Injuries:
   Related to injuries occur in sports-related contact and motor vehicle crashes, where a blow to the front of the knee when the knee is bent [9].

d. Collateral Ligament Injuries:
   Related to injuries during sports related contact or falling down from a stairs, and caused by a force, this pushes the knee sideways.

e. Meniscal Tears:
   These injuries related to tears in the meniscus which can occur while twisting, pivoting, cutting, or being tackled also can occur as a result of aging or arthritis.

f. Tendon Tears:
   Related to injuries commonly in the middle aged people who are in running /jumping sports, where the thigh muscle quadriceps and patellar tendons can be stretched and torn.
2.2 Gait analysis

Gait analysis is basically a systematic study of human physical behavior such as walking, running, jumping, and squatting. Before going into the main study, it is very important to look inside the functionality of neural activity of cause and effect of a human gait [9]. It is called top-down analysis of gait [10]. The functionality of a gait process starts with a nerve impulse in the central nervous system (CNS) and follows till the ground reaction force [10]. The seven components during this top-down analysis are illustrated in figure 3.

![Figure 3: Top-down approach of neural activity during any gait patterns [10]](image)

A brief summary of sequence of events that takes place while walking are as follows [10]:

1. Gait command such as registration and activation in the central nervous system
2. Gait signals transmission to peripheral nervous system (PNS).
3. Develop tension by contraction of muscles.
4. Spawning of forces and moments across and in synovial joints.
5. Anthropometry to regulate the joint forces and moments by the rigid skeletal segments
6. Functional gait recognition by the motion of segments of the geo-bodies.
7. Finally, ground reaction force generation.
2.2.1 Cyclic Nature of Gait in 3-dimension

The human motion or movement is mainly explained in three reference planes namely, sagittal, coronal and transverse plane and are shown in figure 4. The coronal plane is also known as frontal plane. However, sagittal plane is most important which yields useful information about pathologies of human motion tracking.

![Standard anatomical positioning of human body](image1)

**Figure 4: Standard anatomical positioning of human body [10]**

2.2.2 Gait cycle

There are different ways to represent a gait cycle with 8 gait phases as shown in figure 5 [10]. The figure 8 describes a normal walking gait in a cyclic pattern of motion. Basically, there are two phases in a gait cycle, namely, stance phase and swing phase. Stance Phase: During this phase, the foot is on the ground balancing with a double support stance and ends with double support stance. Swing Phase: During this phase, the same foot is no contact with the ground, swings and gets ready for the next strike of the foot.

![Example of a normal gait cycle of a young boy with gait cycle %](image2)

**Figure 5: Example of a normal gait cycle of a young boy with gait cycle % [10]**
These 8 gait phases are denoted as 8 events or periods with 5 events in stance phase and 3 events in swing phase as shown in figure 5 and figure 6. These events are explained as below:

1. **Heel strike**: It initiates the gait cycle. It represents the point at which the Centre of gravity (CG) of the body is at its lowest position. (0%)

2. **Foot-flat**: It is the event when the foot’s plantar surface touches the ground. (0- 10%)

3. **Mid-stance**: It occurs when the contralateral (swinging) foot passes the stance foot and the CG of the body is at its highest position. (10 - 30%)

4. **Heel-off**: It occurs when the heel loses contact with the ground and the triceps surae muscles forces a push-off which plantar flex the ankle. (30 - 50%)

5. **Toe-off**: It terminates, the stance phase as the foot leaves the ground before the swing initiation [8]. (50 - 60%)

6. **Acceleration**: It starts once the foot leaves the ground and the geo-body accelerates the leg forward with the help of hip flexor muscles and hence, called acceleration event. (60 - 70%)

7. **Mid-swing**: It occurs as the foot passes directly beneath the body, similar to mid-stance for but the foot is in the air [8]. (70 - 85%)

8. **Deceleration**: It describes the action of the muscles to stabilize the foot in preparation for the next heel strike as they slow the leg and hence, called deceleration event. (85 - 100%)

---

*Figure 6: Eight main periods or events of the cyclic nature of human gait [10].*
The main considerations of this thesis work of gait parameters are related to the gait cycle and related to each event in the two phases as shown in figure 5. Hence, the stance phase is 60% of the gait cycle and swing phase as 40%.

2.2.3 Gait and Spatiotemporal parameters

The spatiotemporal parameters are also called as time – distance parameters as these exist both in space and time which have a spatial extension and temporal duration of the human gait. Gait parameters include both static and dynamic parameters of the gait analysis and are shown in table 2.2. These parameters are analyzed in this thesis work with a comparative study on bilateral gait symmetry of both legs individually and between genders (Male/ Female).

These parameters can be differentiated, as the measurements will be carried when a subject is steady or in a static position and while moving which are called dynamic parameters. All distance based measurements are called temporal parameters or aspects of human gait and are illustrated in figure 7.

Table 2.2: Gait Parameters

<table>
<thead>
<tr>
<th>Type</th>
<th>Units</th>
<th>Type</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foot/Step size</td>
<td>Centimeters</td>
<td>Gait Speed or Velocity</td>
<td>cm/s</td>
</tr>
<tr>
<td>Step Length</td>
<td>Centimeters</td>
<td>Cadence 1</td>
<td>Steps/minutes</td>
</tr>
<tr>
<td>Stride length</td>
<td>Centimeters</td>
<td>Cadence 2</td>
<td>Stride /minutes</td>
</tr>
<tr>
<td>Body Mass Index</td>
<td>Kilogram/(cm*cm)</td>
<td>Knee Joint angle</td>
<td>Degrees</td>
</tr>
<tr>
<td>Leg Length</td>
<td>Centimeters</td>
<td>Gait Cycle</td>
<td>% (100 samples)</td>
</tr>
<tr>
<td>Thigh Length</td>
<td>Centimeters</td>
<td>Stance phase</td>
<td>% stride</td>
</tr>
<tr>
<td>Shank/ calf length</td>
<td>Centimeters</td>
<td>Swing Phase</td>
<td>% stride</td>
</tr>
<tr>
<td>Stance Height</td>
<td>Centimeters</td>
<td>Discrete Angular parameters</td>
<td>Degrees</td>
</tr>
</tbody>
</table>

Where,

Step Length: It is the distance between the alternative heels after taking a step.

Step Width: It is the mediolateral distance between both the feet.

Stride length: It is the distance travelled by a subject during one full stride (or a cycle) and is measured as the length between the heels from one heel strike to the other heel strike of the same foot as shown in the figure 7.
2.2.4 Abnormal or Pathological gait patterns

Unlike from the example of a normal gait of figure 5, there will be variability in walking gait which occurs due to aging, excess over weight, no proper diet, environmental or climate factors, or even external excess forces on the joint due to blow or hit. The main accomplishment to make the locomotor system of a person to be able to walk normal, the below main aspects are important [11]:

1. Support of the body weight on individual leg without collapsing.
2. Balance maintainability, during single leg stance either statically or during swinging.
3. Swinging leg must advance to a position where it can support the other leg while resting.
4. Sufficient energy or power to the limb movements and to advance the trunk.

The above important aspects are achieved with modest energy consumption in a normal gait. However, pathology of the locomotor system of the walking gait frequently produce gait patterns which are so called pathological or abnormal gait patterns. The specific gait abnormalities leading pathological walking patterns that affect the human knee range of motion are as follows [11]:

1. Lateral trunk bending,
2. Anterior trunk bending,
3. Posterior trunk bending,
4. Increased Lumbar lordosis,
5. Functional leg discrepancy,
6. Vaulting – ankle twist,
7. Abnormal hip rotation,
8. Excessive knee extension,
9. Excessive knee flexion,
10. Inadequate dorsiflexion control (Ankle),
11. Abnormal foot contact,
12. Abnormal walking base, and

The knee joints should have enough strength to hold almost the whole body weight and hence, the above abnormalities are the ways how other masses of other body segments lead to abnormal walking gait [11]. However, the most important diseases and injuries that affect the neuromuscular and musculoskeletal system lead to disorders in gait. Such as [11]

1. Cerebral palsy,
2. Parkinsonism,
3. Muscular dystrophy,
4. Osteoarthritis,
5. Rheumatoid arthritis,
6. Lower limb amputation,
7. Stroke – cerebrovascular accident,
8. Head injury,
9. Spinal cord injury,
10. Myelodysplasia, and
11. Multiple sclerosis.

There is a chance that gait assessment will benefit a subject affected by any one of the above conditions, however, there are greater benefits which are possible in some pathologies compare to others [10].
2.3 Kinematics of Knee Joint and Anthropometry of Lower-body

The major criteria for gait analysis are measuring the parameters of an individual subject’s body segments. The measurements of body segments is called the study of anthropometry [11], such as the total body mass (Weight), leg length, thigh length, height and calf length as shown in the gait parameters table 2.3 for kinematic analysis. However, these can also be used in terms of regression equations to assume the individual masses and moments of inertia of lower body segments of the subject. These are shown in the figure 10 [10].

![Anthropometric measurements of the lower body for gait parameters](image)

The measurements for kinematics of knee joint angles include linear kinematics, which is the position of sensor placements is used to predict the position of landmarks same as the joint centers (segment circles in figure 9). Angular Kinematics is the knee anatomical joint angles are calculated with the help of angular velocities and linear accelerations from the sensors on the segments. As the anthropometry also includes the study of dynamics of joints which further includes centers of gravity, body segment parameters, ground reaction forces and linear and angular kinematics which are all together integrated to yield the resultant knee joint forces and moments.

This work deals with gait analysis as a three-dimensional phenomenon, the concepts and mathematics are pretty complex and time consuming gait assessment and hence, has to be aware of it. However, this analysis involves either usage of a force sensor in the foot to generate a ground reaction force or a fair prediction of body segment circumference which gives us the forces applied at the joint and its respective moments of inertia.
The anatomical joint angles are very important in gait assessment as the ranges of motions are of main interest to clinicians such as hip abduction/adduction angle, knee flexion/extension angle, ankle inversion/eversion angles [10]. These axis of knee ROM along with the 3-dimensional proximal and the distal reference frames are shown in figure 10. The figure 2 shown in Section 2.1.1 was internal knee range of motion and the figure 10 shows the external knee range of motion.

![Figure 10: External Knee Joint Motion with Reference Frames of the Left Leg [10]](image)

The three knee joint ranges of motion are as follows:

- **Flexion and extension**: It takes place about Medio-lateral axis of the left thigh (z2)
- **Internal and external rotation**: It takes place along the longitudinal axis of the left shank/calf (x4);
- **Abduction and adduction**: It takes place about an axis that is perpendicular to both z2 and x4.

These are also shown in table 2.1. However, these three axes will not form a right-handed triad as the axes z2 and x4 are not necessarily at right angles to one another [10].

**Table 2.3: Functional range of motion (ROM) at the knee [6]**

<table>
<thead>
<tr>
<th>Activities</th>
<th>Maximum Knee flexion (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal gait or walking on level surfaces</td>
<td>60°</td>
</tr>
<tr>
<td>Steps or Stair climbing</td>
<td>80°</td>
</tr>
<tr>
<td>Sitting and rising from chairs</td>
<td>90°</td>
</tr>
<tr>
<td>Sitting and rising from a toilet seat</td>
<td>115°</td>
</tr>
<tr>
<td>More advanced function (squatting)</td>
<td>&gt; 115° and almost 140°</td>
</tr>
</tbody>
</table>
The knee extension occurs in sagittal plane as shown in figure 10, and around a medial–lateral axis. It may also be described as the starting position from the end of the knee flexion Range of motion [6]. Generally, knee extension is recorded as the starting position for the flexion (0-degrees).

However, when it exceeds 5 or more degrees as the extension will go beyond the starting position (0 degrees), it is known as hyperextension or so called genu recurvatum [6]. It may be within normal limits in childhood but can be found in the adult age. For example in a gymnast or a sports person the extreme hyperextension ROM can be observed as shown in the figure 11 [7]. It mainly occurs in athletic injuries, when the knee joint is forced to extend, beyond its normal range of motion.

![Standing hyper-extension and Laying hyper-extension](image)

**Figure 11: Extreme hyper-extension ROM illustrations [7]**

Generally, the surgeons or physiotherapists use goniometer to measure the knee joint range of motion during gait analysis or rehabilitation. Goniometer is placed as such to measure degrees of Extension/flexion as the 0° pointing the ankle and the 180° on the hip. Hence, the full extension is 0 degrees of Flexion [6, 7]. The measurements extend with the numbers going high when the foot moves towards to hip which shows the right angle at the knee being 90 degrees and so on [6,7].

The knee joint functionality during walking gait is similar to both male and female. However, there exists gait differences due to diverse pelvic alignment between genders i.e., men vs women and as well as in women of different ages due to hormonal and mechanical changes due to abdominal swelling. Even in female subjects, pelvic asymmetry varies between never-pregnant, pregnant and post-partum (after pregnancy) women. The pelvis gap between male will be 90 degrees, where in female it will be more than 100 degrees as shown in the figure 12.
2.4 Gait analysis methods

Nowadays, there are many technologies and methods that are used to analyze the human gait analysis. The methods are particularly with emphasis in sports and human gait analysis with the help of 3-dimensional linear and angular kinematics and dynamics of the lower body extremity, which include the hip, knee and ankle joints [11]. The most commonly found methods and technologies used in today’s era are as follows [12]:

1. Image processing with time-of-flight, Structured light and infrared thermography (IRT)
   systems.
2. Wearable sensors, such as
   a. Pressure and force sensors
   b. Inertial sensors
   c. Strain-gauge goniometers
   d. Ultrasonic sensors and
   e. Electromyography (EMG)

Gait analysis with motion capture systems which uses image processing technology are very expensive and is more beneficial in a hospital environment as they need to capture the gait patterns in all directions of the respective subject.

2.4.1 Hardware: Inertial sensors

Gait analysis with motion tracking system is less expensive and is more beneficial even in a small laboratory environment. This system works on usage of inertial sensors such as accelerometers, gyroscopes and magnetometers. However, this system requires a good sensor fusion algorithm. The main focus of this work is also inertial sensors which are used to analyze the gait patterns. Inertial sensors are easy wearable on the specific body segments to find the 3-D orientation and position from the data obtained as tri-axial linear accelerations, tri-axial angular velocities and tri-axial magnetometer readings. These sensors combine to form an inertial measurement unit (IMU) [13, 14]. These are source less, hence, are free from range limitations which are commonly seen in kinect based or camera based gait analysis [12].
a. Accelerometers

Accelerometers are devices which measure the acceleration along its sensitive axis.

**Principle:** Accelerometers works based on spring mass system which is a mechanical sensing element which consists of a proof mass connected to a mechanical suspension system relating to a reference axis. Based on Newton’s second Law (force = mass * acceleration), the mass proof can be forced to deflect with the inertial force because of acceleration or gravity. Hence, the acceleration is measured electrically with the help of physical changes in the displacement of the mass along the reference axis [13].

However, there exist 3 types of accelerometers which are capacitive, piezoelectric, and piezo-resistive accelerometers [14]. Out of these three, piezo-resistive and capacitive accelerometers provide dual acceleration components and also have higher stability. These accelerometers are very much suitable for measuring the motion tracking in the human gait analysis [13]. The linear acceleration/velocity of a particular body segment can be determined to perform the gait analysis by placing these accelerometers to the lower limbs such as thighs, shank, feet or legs. It provides a practical and cheaper method to identify human movements by using these accelerometers.

b. Gyroscopes

A gyroscope basically senses the angular velocity which consists of a vibrating element embedded with a sensing element and functions as a Coriolis sensor [13].

**Coriolis Effect principle:** An evident force which manifests itself in the rotating reference axis proportional to its rate of angular rotation. In simple words, the angular rate is obtained by integrating the gyroscopic signal with the linear motion from the Coriolis effort [14, 15].

Although, there are different types of gyroscopes which are microchip-packaged electro-mechanical (MEMS) gyroscopes, solid-state ring lasers, fiber optic gyroscopes, and the very most sensitive quantum type gyroscope [14]. These are used to measure the posture and motion of the human body segment by measuring the angular rate in gait analysis [15]. Furthermore, the angular velocity and angle of a particular body segment such as thigh or shank or ankle can be determined to realize the reorganization at different gait phases during the gait assessment. In gait analysis, to construct the complete inertial sensing system, a gyroscope is usually combined with an accelerometer sensor to find linear acceleration along with angular velocity.

c. Magnetometers

Magnetometer works based on the magneto-resistive effect. It is the device which calculates the strength and the direction of magnetic field in its own locality [12].
Magneto-resistive principle: if a magnetic flux or magnetic field is not applied, the current flows \((i)\) along the InSb (Indium Antimonide) or hall plate and when a magnetic flux is applied, a Lorentz force \((F)\) proportional to the magnetic flux density will deflect the current path. Once the current path is deviated, the current flows through the hall plate for a longer distance, causing an increase in resistance [12]. It is the change in resistivity of a current \((i)\) carrying ferromagnetic material results from a magnetic field, where the resistance change is proportional to the tilt angle with respect to the magnetic field direction [12] as shown in the figure 13. These sensors estimate the change in orientation of a body segment related to its earth’s magnetic North (AN) (along the vertical axis) in human gait analysis [12, 13]. These sensors can provide information which cannot be determined by the accelerometers or integration of gyroscopic angular rates.

![Magnetoresistive Effect](image)

**Figure 13: Magnetoresistive effect. (a) Current mode under non-magnetic. (b) Current mode under magnetic field [15]**

2.5 Software: Application program interface

The sensors explained in 2.4 are fused or combined to form an inertial measurement unit (IMU) [16]. The dialog boxes and the settings in API of the measurement system are shown in Appendix B. The XSENS Awinda network protocol ensures a highly accurate data sampling with time synchronized within 10 microseconds in all the connected motion trackers (MTWs) which is very essential for obtaining accurate joint angles [16]. This includes an intelligent reference system which gives highly accurate kinematic and kinetic data.

2.5.1 Attitude and Heading Reference System

AHRS is mainly provided in the wired motion trackers such as Xsens MTi series trackers [16]. It provides 3D orientation by integrating the gyroscopic angular rates and fusing the data with linear acceleration data and magneto-metric data [16]. During sensor fusion, drift from the angular velocity data integration is compensated for reference vectors which are gravity and earth’s magnetic field vector. This gives a drift-free oriented results, which makes the AHRS a cost effective solution compared to the conventional high-grade Inertial Measurement Units which has only gyroscope integration, depending on the gyroscopes with very high bias stability.
2.5.2 Xsens extended kalman filtering

For specific applications such as human motion, the sensor fusion algorithm needs to be adapted in order to overcome with magnetic disturbances, transient accelerations and vibrations [16]. Xsens API software offers, applying filter setting that can be optimized with respect to user’s needs and can give the best performance [16]. Xsens Kalman Filter computes an MTw (wireless motion tracker) for 3 degrees of freedom orientation for tracking the human motion. It is an algorithm which fuses the sensors data such as 3D inertial data and the 3D magnetometer data which optimally estimate the 3D orientation in accordance to an earth’s fixed coordinate frame (xyz). It has been mainly developed to deal with the transmissions of wireless systems such as irregular updates due to temporal packets losses [20]. Strap down integration (SDI) algorithms provides input to this filter in combination with magnetometer data. SDI is a method which is used to compute the orientation and the velocity increments, by integrating angular velocities measured by with gyroscope and linear acceleration measured with an accelerometer. The steps of sensor fusion using a Kalman filter are data importation, data prediction, measurement and correcting update [16].

a. Principle of XKF3

When a properly calibrated IMU is not surrounded by any ferromagnetic materials, the 3D orientation will be computed using the signals straightforwardly from a magnetometer and an accelerometer much like using a compass needle [16]. However, the accelerometer with magnetometer alone is not sufficient to obtain the orientation as the sensor is moved around or rotated. The use of a tri-axial gyroscope is very essential to track the tri-axial orientation accurately [16]. The combining process of the different sources of information is called sensor fusion. In this work, it is accomplished by XKF3 human motion where it combines linear accelerations, angular velocities, and magnetometer readings to obtain the orientations.

By nature, XKF3’s two input sources are complementary to one another. While the gyroscope and accelerometer pre-processed by the SDI algorithm, the gravitational and magnetic parameters gives stabilizing information on a long run which give high-bandwidth and responsive movement signals. SDI captures movements which are short term accurate, high in-resolution and high bandwidth, when inertial sensing signals which are continuously integrated are used. However, during integration an inevitably inherent drift grows over increase in time. These drifts can be stabilized by carefully chosen and applying some precisely formulated assumptions on sensor characteristics and dynamics which will provide the 3D or tri-axial orientation in real time while recording.

b. Initialisation in API

The XKF3 algorithm of human motion computes not only orientation also keeps the track of variables such as properties of local magnetic field or sensor biases in the background [16]. Hence, once the motion trackers are put into measurement mode in API, the orientation output will need time to stabilize.
In order to obtain the optimal stable output, it depends on a number of factors. Such an important factor is to determine the stabilizing time on the bias of the rate gyroscopes with the time to correct for small errors. This bias changes gradually due to different effects, such as exposure to impact or temperature changes. Further, the latest computed gyroscope bias is stored in a non-volatile memory of the sensor unit to reduce the stabilizing time or delay. Hence, this algorithm can converge and reach the optimal robustness faster, if the sensor is started in an anti-magnetic disturbances area. This makes XKF3 better than the basic extended Kalman filter sensor fusion algorithm [16, 17].

### 2.6 Gait instrumentation pipeline design flow

The processing of IMU data is shown as the main pipeline in figure 14. The IMU sensors are used to obtain linear accelerations from the accelerometer, angular velocities from the gyroscope, and readings from magnetometer of the desired activity or motion. The wireless IMU sensors used were sampled at 100 Hz. Xsens API uses a sensor fusion algorithm which is a type of Kalman filter known as XKF-3 to accurately estimate the orientation and position of the IMU sensors as explained in section 2.5.

![Figure 14: Pipeline design flow of measurement system](image)

It estimates kinematics using a combination of orientation and position data from the sensors. API updates using joint uncertainties and feedback updated orientation and position in to the sensor fusion algorithm. Xsens then, outputs this kinematics of estimated model which includes the joint orientation of the model at every time step. In this work, we were specifically looking at knee joint angle in sagittal plane and hence, extracted the Xsens-estimated knee rotation about the X, Y, Z axes. Finally, this 3-dimensional orientation data which is the output as quaternions was translated into knee joint angle using laws of cosines formula and is explained in the Section 3.6.

### 2.7 Statistical analysis and regression

In order to analyse the data in gait analysis, the main concepts to be considered are [18-23]:

1. Does the data acquired is significant and valid to analyse?
2. Do the compared data sets can be correlated with each other?

Therefore, in this work, it is considered to perform two methods on the data from the gait assessment to identify if there are any comparisons between both genders and individual’s data. Statistics is mainly defined as the science of learning or study of or from specific data with its counterpart comparisons [21]. The statistics of the data is to be analysed using simple tests which are the numerical facts as the results of a reference to convince to make a decision such as strong or weakly correlated, positive or negatively significant, etc. Hence, simple methods are chosen to find whether the data has relationship and the data comes under the positively significance with less probability error. These stat comparisons in this work are to be analysed with the help of Microsoft excel data analysis tool which uses t-test or z-test methods. The most common data analysis using excel sheet is ‘Regression’, which includes the tests for finding significance of the data and validate relationship between two sets of data with analysis of variances or ANOVA [20].

As this thesis work is a preliminary study for further research, basic statistical methods were selected in reference to gait analysis of previous studies [19]. To consider the data sets which can be qualified or valid for the data analysis, we must consider two main things [18]:

1. Statistical confidence
2. Statistical significance

The basic distributions such as standard normal distribution with a z-test and a t-distribution using t-tests are mainly considered for the above methods. In comparison to normal distribution, t-distribution is mainly used when the number of samples x are less [21]. This work is considered to have the number of subjects to be 20 (10 male and 10 female) in the gait assessment, t-distribution is very much applicable. T-distribution is also one of the data distributions for data observations for testing the data relationships of contrary data sets such as male versus female or boys vs girls, etc.,. It is also mentioned that t-distribution has less variance compared to the standard normal distribution [18-23]. The first assumptions are the setting the null hypothesis and other hypothesis which comes under hypothesis test under a particular distribution. The tests of significance usually concentrate on $H_0$ which is called the null hypothesis. If a decision has to be made and however there is no case to leave out $H_0$. Simply, there are two hypotheses where, one to be accepted and the other to be rejected. These two hypotheses are represented as $H_0$ and $H_a$ and are shown in figure 16. In the acceptance sampling problem, the decision is made between, $H_0$: the result which meets the standard and $H_a$: the result which does not meet standard.
Statistical inference which draws the conclusions about a process or population based on the sample data. It mainly provides a statement which can be expressed in terms of probability and how much confidence interval can be placed in the conclusions. There are many specific methods for inference however, are only a few general types of statistical inference [18], which are confidence intervals and tests of significance. The excel sheet data analysis tool uses student’s t-tests to find whether the sample data is positively significant. It is a test for significance by finding the statistical inference by knowing the P-values which are so called probability of error values with a standard rate at 5% (P<0.05). In t-tests, such as two sample analysis tools, the test for the equality of the sample population means always rely on each sample of a data set.

There exist three tools that employ in different assumptions, when [20]:

a. population variances which are equal
b. population variances which are not equal, and
c. The two samples represent before and after observations on the same data of subjects.

A t-statistic value is computed for all the three above tools where it depends on the data and the value of t can either be a negative or nonnegative value. To test the hypothesis \( H_0: \) where, \( \mu = \mu_0 \) of sample size \( n \), the one-sample t statistic is computed using the formula: the one-sample t statistic and has the t distribution with \( n - 1 \) degrees of freedom [18].

\[
t = \frac{X - \mu_0}{s/\sqrt{N}}
\]

For the assumptions of underlying equal population means [20],

I. If \( t < 0 \), "P (T <= t) one-tail" can give the probability, a value of the t which would be observed such that is more kind of negative value than t.

II. If \( t >=0 \), "P (T <= t) one-tail" can give the probability, a value of t statistic which would be observed such that it is more positive value than t.

III. The "t Critical one-tail" can give the cut-off value such that the probability of observation, the value of t-Statistic (>=) equal to or greater than the "t Critical one-tail" as Alpha.
IV. "P (T <= t) two-tail" can give the probability, a value of the t that would be observed which is larger in absolute value than t.

V. "P Critical two-tail" can give the cut off value where the probability of the observed t-statistic is larger in absolute value compared to "P Critical two-tail" as Alpha.

**a. Regression Analysis**

Regression analysis or correlation is the method to find linear relationship between two or few more variables [21]. The values of correlation can be non-existent, positive or even negative. Correlation is determined by Pearson’s correlation coefficient (Pearson’s r), where the value ranges between -1 to 1. Here, -1 validates as a perfectly negative correlation and 1 as perfectly positive correlation and 0 represents no correlation between the two sets of variables. The regression analysis excel tool is used to perform linear regression analysis using the least squares method to have a line of best fit using a set of samples or observations. It is used to analyse how can a single dependent variables are affected with the values of single or multi independent variables. For example, we can analyse how a sportsman's performance can be affected with factors such as height, weight, and his/her age. The performance measures to each of these three factors will be based on a set of performance data and use the results to predict a new performance data with the untested sports person. This excel tool uses the worksheet function “LINEST” [20]. A regression line is the linear line which describes how a response variable changes as an explanatory other variable changes. It is often using a regression line to predict the value of a variable for a known and given value of other variable. In contrary, regression unlike correlation requires an explanatory variable and a response variable. An example of a regression line using scatter plot in excel tool is shown in figure in Appendix D along with display of R-squared value. Regression analysis in the excel data analysis tool can also calculates the correlation coefficient or heasoon’s r along with a one-way analysis of variance in finding the test of significance with p-values which are so called probability of error and are shown in Appendix D.

**2.8 Literature review**

This is the review of 3 appended references [24, 25, and 26] with the scope of better relation with the current research.

(1) A Wearable Ultrasonic sensor network for analysis of bilateral gait symmetry

This research had presented how gait patterns can be achieved and proves the differences between the gait asymmetry between both legs [24]. The work was based on using ultrasonic sensor system to estimate 3-dimensional position co-ordinates of the lower body segments [24]. The system used consists of Ultrasonic receivers, a personal computer (PC), radio frequency (RF) transmitter, an Arduino controller and a closed environment with ultrasonic transmitters and RF receivers.
The test was conducted on 5 healthy subjects and the experiment was conducted in a laboratory environment [17]. The system model of this test used state space representations for distance measurements and a unscented Kalman filter algorithm (UKF) was used to estimate the 3-dimensional co-ordinates with non-linear state space model [24]. Data analysis was conducted off-line using Matlab scripting. Gait parameters were calculated such as swing phase and step width. The main point of this work was quantified as bilateral gait symmetry which is the ratio of average swing times of right leg to the left leg.

**Methods used:** Statistical analysis used were Mann-Whitney U test for null-hypothesis and Bland-Altman plots with averages, mean and gait ratios where the limits were set to mean difference ±2 * standard deviation. The setup seems to be much cheaper than the Gait measurement systems that are available now.

**Drawbacks:** Such as low data update rate and interference problem in ultrasonic pulses. Additional motions capture system was used for the validation of achieved results.

(2) **Kinematic and Kinetic analysis during forward and backward walking**

This research work was based on motion capture system to identify the mechanism of forward (FW) and backward walking (BW) patterns through kinematic and kinetic analysis with the main focus on time reversed data in backward walking. The instrumentation for the assessment used was a 3D-VICON motion capture system with 16 retroreflective markers on the subject’s lower limbs. A Woltring filter [25] was used for the sensor fusion purpose. The test was conducted on 31 (26 male, 5 female) healthy subjects with no evidence of previous history of abnormalities. The test runs of each participant were 10 forward walking and 40 backward walking trials on a 10 meter with bare foot on a walkway.

Anthropometric data, stride characteristics and ground reaction forces for kinetic analysis were measured. Significant walking speed reductions during backward walking were noted and compared with the normal gait of forward walking. No significant variations were found in stance phase and stride time of the gait cycle %. Additional to knee joint, this paper [18] has also evaluated on hip and ankle joints along with their dynamic characteristics. The presented results found were the stride length differs significantly and hip angle ranges between 90 to -20 degrees.

**Drawbacks:** However, the main criterion for kinetic analysis is the electromyography or EMG data of lower body muscles and had not used. This work has not compared to analyze for backward walking mechanism.
(3) Three-dimensional knee kinematic analysis during treadmill gait

This paper was based on finding slow and normal gait patterns of 51 subjects (26 Male, 25 Female) using the KneeKG motion tracking system on a treadmill gait [26]. The gait assessment carried out in 3 trails at slow imposed speed (2 km/h) [26] and self-selected walking speeds.

**Methods used:** Various statistical analyses (Mann-Whitney U tests, Paired t-test, signed rank tests and rank correlation coefficients) were used to compare the slow and normal gait kinematics. A questionnaire was used [26] for validation from the participants in the assessment.

Several candidates were excluded from the test where the subject had any kind lower limb injuries. The KneeKG system was used which has 2 main trackers, a tibial and a femoral tracker on one leg and removed and repeated with the other. There is no sensor fusion algorithm mentioned in the research paper. The main important notes from this paper were subjects walking with slow gait had significantly reduced with their knee flexion angle during stance phase and swing phase of the gait cycle (%).

**Drawbacks:** knee forces were not assessed to identify the effect of speed. Long-term run of force plates would detect the kinematic and kinetic alterations effected by slow speed.

**Table 2.4 Literature review of the appended references [24 - 26]**

<table>
<thead>
<tr>
<th>Gait Type</th>
<th>Instrumentation</th>
<th>Sensor fusion algorithm/Filter</th>
<th>Statistical Analysis</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bilateral Gait symmetry</td>
<td>Ultrasonic and RF transmitters and receivers, Arduino controller, Open source (C++)</td>
<td>Kalman filter</td>
<td>Matlab, Mann Whitney U test</td>
<td>Bland-Altman plots, Walking speeds, Root mean square error [RMSE]</td>
</tr>
<tr>
<td>Forward and Backward walking gait</td>
<td>3-D motion capture system (embedded), retro-reflective markers, Force Plates</td>
<td>Woltring filter</td>
<td>ANOVA, Regression model</td>
<td>ANOVA, P-values, Mean standard deviation, values, Matlab Simulated</td>
</tr>
<tr>
<td>Treadmill gait</td>
<td>3-D KneeKG system an infrared motion capture system, Knee3D software suite</td>
<td>Data and support vector machine–based algorithm</td>
<td>KOOS questionnaire, Mann-Whitney U test, Spearman’s rank correlation coefficients</td>
<td>Slow and normal walking plots, Correlation coefficients, Spatiotemporal and demographics</td>
</tr>
</tbody>
</table>
The survey review [27] proves that Gait analysis using inertial system has the best performance in comparison to other types of gait measurement systems. Drifts are the only problems that occur in this kind of systems. However, this thesis work uses the best sensor fusion algorithm with AHRS, which overcomes these drift errors as explained in Section 2.5 [16, 17].

Table 2.5 Review of various Human motion tracking systems [27]

<table>
<thead>
<tr>
<th>Type of Systems</th>
<th>Accuracy</th>
<th>Compactness</th>
<th>Computation</th>
<th>Cost</th>
<th>Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inertial (IMU)</td>
<td>High</td>
<td>High</td>
<td>Efficient</td>
<td>Low</td>
<td>Drifts</td>
</tr>
<tr>
<td>Magnetic</td>
<td>Medium</td>
<td>High</td>
<td>Efficient</td>
<td>Low</td>
<td>Ferromagnetic materials</td>
</tr>
<tr>
<td>Ultrasound</td>
<td>Medium</td>
<td>Low</td>
<td>Efficient</td>
<td>Low</td>
<td>Occlusion</td>
</tr>
<tr>
<td>Glove High</td>
<td>High</td>
<td>High</td>
<td>Efficient</td>
<td>Medium</td>
<td>Partial posture</td>
</tr>
<tr>
<td>Marker High</td>
<td>High</td>
<td>Low</td>
<td>Inefficient</td>
<td>Medium</td>
<td>Occlusion</td>
</tr>
<tr>
<td>Marker-free</td>
<td>High</td>
<td>High</td>
<td>Inefficient</td>
<td>Low</td>
<td>Occlusion</td>
</tr>
<tr>
<td>Combinatorial</td>
<td>High</td>
<td>Low</td>
<td>Inefficient</td>
<td>High</td>
<td>Multidisciplinary</td>
</tr>
<tr>
<td>Robot</td>
<td>High</td>
<td>Low</td>
<td>Inefficient</td>
<td>High</td>
<td>Limited motion</td>
</tr>
</tbody>
</table>
3 Methods

In this chapter, gait assessment method, Kinematics of knee joint (ROM) and the sensor data acquisition and processing are shown along with the statistics of few human participants with respect to their physical measurements. The outcomes of this project are the average of the entire Gait and IMU’s parameters calculated. These results are compared with a ground truth or a standard Knee kinematics as per references [26] and is generated by an example model from Opensim open source bio-mechanical 3D oriented software [26] of a normal subject. Finally, introducing three gait parametric ratios which explains the trade-offs of restrictions of Knee joint range of motion (ROM) which are stability, balanced and flexible strength.

3.1 Gait assessment

The gait assessment during the research is conducted in a laboratory environment, where, the space for the normal gait is fixed (6 meters). The body mass index (BMI) is calculated based on the individual weight per squared height. The mean and standard deviation BMI values are found to be (24.20±4.98) for male and (23.73±2.37) for female subjects. The anthropometry, stride characteristics, and IMU – body alignment of the individual subject are carefully noted and fixed. The 4 test trails are conducted on each individual and collected data at every trail end and the total assessment was carried out for 45 to 60 minutes individually. Overall average of 80±10 gait cycles is considered for both the lower limbs of the subject. This is sufficient to achieve good reliable knee joint flexion/extension angle. The flow chart of the conducted gait assessment is shown in figure 16.

![Flow chart of the gait assessment procedure](image-url)
3.2 **Subjects/ Participants**

Mainly, the results are considered with respect to kinematics of the knee joint angle (flexion/extension) of 10 Male subjects with the age range from 20 to 40 years (26.07±6.31) and 10 female subjects with the age range from 23 to 53 years (35.46±10.07). All the participants involved in the assessment are considered to be perfectly normal while recruiting for the experimental validation. However, selected subjects were interrogated about their history of previous injuries or neurovascular diseases or involvement in some severe physical activities such as yoga or physical fitness training after the whole process and are shown in results. Their data is then compared based on their body mass index, Gender and their respective gait posture and phases while walking. The data is analyzed both qualitatively and quantitatively with the analysis of variances (ANOVA) with mean and standard deviations of every subject’s knee flexion/extension. For verifying the correlation between the data sets of relativity, comparison based on Pearson’s r values [30] and significance values (p<0.05) [30] are used to validate for the weak to strongly correlated (regression analysis) and student’s t-test where, significantly positive value should be under 95% confidence interval (CI).

3.3 **Measured variables for gait analysis**

The gait parameters and the stride characteristic figure are shown in section 2.2.3. Every value or the measurement is the average of at least 4 tests. These parameters are further analyzed for this thesis to be proposed with the bilateral gait symmetry parameters. Gait Cycle time or even cadence are measured with the help of a stop watch, by counting the individual steps taken during a known walking distance. The main formulae [11, 23] are as follows:

1. **Average Gait speed** :
   
   Velocity, \( V = \frac{\text{Distance}}{\text{Total time taken to cover the distance}} \) (cm / s)

2. **Average Gait or step frequency** :

   Frequency, \( F = \frac{\text{Number of steps N}}{\text{Total time taken to cover the distance}} \) (Steps/s)

3. **Average step length** :

   Step Length, \( L = \frac{\text{Velocity}}{\text{Frequency}} \) (cm)

4. **Cadence** :

   Cadence = Frequency \(*\) 60. (Steps/min)

5. **Gait cycle time** :

   Cycle time (s) = \( \frac{(\text{Total time taken to cover the distance} \times 2)}{\text{Number of steps N}} \)
3.4 **Discrete Knee Angular parameters (K1 to k6)**

The Knee angle variables or parameters (Degrees) with a GT - Ground truth or standard knee angle are showed in figure 17 [22].

![Knee Flex/Extension Angles](image)

*Figure 17: Discrete Knee angular parameters at main key phases of the gait cycle (%) [22]*

Where,

- **K1**: Flexion at heel strike
- **K2**: Maximum flexion at loading response
- **K3**: Maximum extension in stance phase
- **K4**: Flexion at toe off
- **K5**: Maximum flexion in swing phase
- **K6**: Point of total sagittal plane excursion

The average gait knee range of motions (angles) with the variables of human knee joint is shown in results in chapter 4. It is observed that the range of Knee joint flexion/extension is 0 to 60 degrees in the sagittal plane. Hence, while doing the comparative study, the ground truths are generated from Opensim biomechanics software (Stanford.edu [19]). The values of discrete knee variables (K1 – K6) are found based on the results from the knee flexion angle obtained from the position and orientation of the motion trackers [27]. These values are then validated by normalizing with the known factors such as stance time (40% of gait cycle) and swing time (60% of gait cycle). The swing time (%) is calculated as the difference between the maximum extensions in stance phase (Heel off) till the point of total sagittal plane excursion (toe off). Similarly, for the stance time (%), it is the measurements of width between K1 flexion at heel strike till the phase K3 the maximum extension in stance phase [22].

3.5 **Bilateral gait symmetry comparison with both legs and genders**

Bilateral gait symmetry validation/ check [24] using the mean swing times of right leg to the left leg for the free walkers is used to find the abnormal subject with swing period from the simulations.
\[ GS = \frac{GSR}{GSL} \]

Where, GS is Gait symmetry Ratio, GSR is the average right knee swing width and GSL is the average left Knee swing width [24].

### 3.6 Data Acquisition from motion trackers

The data is acquired by an application program interface from xsens technology [16], which is integrated with the inertial measurement units. The flow chart of the procedure of acquiring proper and desired data is shown in figure 20.

The theoretical procedure is as follows:

1. Firstly, the sensors are to be fixed to the lower body segments of the human subject as shown in figure 19. Both sensors should be placed, such that they align in the same direction as seen in 3D- orientation as shown in figure 18.

![Figure 18: Sensors 3D alignment/orientation](image1)

![Figure 19: Placing straps and alignment of motion sensors](image2)
2. The Xsens Velcro straps used were very reliable when fixed for the thigh and shank segments as shown in figure 18.

3. Once the sensors are fixed for both the legs, the sensors are to be configured wirelessly connected with the receiver which is fixed with a computer. The system includes the API which integrates the sensors and is used for measurements purpose only.

4. API visualizes all four sensors in 3D orientation when connected and generates the sensor data in tri-axial linear acceleration, tri-axial angular velocity and tri-axial magnetometer readings.

5. Each sensor is represented as 6-degree of freedom as each side of the sensor cube represents a 3-dimensional axis (XYZ).

6. The sensors are fixed on the lateral side of the thigh and shank. The IMU data is processed using extended kalman filter that is included in API and gives output in three different ways such as Euler angles, Quaternions (4D vectors) and rotational matrices.

7. In this assessment, quaternion vectors are used to find the knee joint angles of both right and left legs of each participant.

8. The knee angle is calculated using the laws of cosine formula, [24],

   \[ \text{Angle (Degrees)} = \cos^{-1}\left(\frac{Q_{s1}.Q_{s2}}{|Q_{s1}|*|Q_{s2}|}\right) \]

   Where, Qs1 and Qs2 are the quaternion vectors generated by the Xsens API [16]

9. Once the knee angles are acquired, each subject data is analyzed by statistical procedure using ANOVA which is analysis of variance for p-value to find whether the significant, mean values and its standard deviations and regression model to find the correlation coefficient to check the relation between respective data sets.
START

Sensors ON, Receiver Connected, API synchronized

Wireless configuration Enable ALL Wireless Masters

Sensors

DISABLE ALL Wireless Masters

Synchronized

3D orientation Alignment Check

Perfect

Human tracking Planer gait walk

Collect data Select type of output Export data as txt file

Import into Matlab tool Simulate for Knee flexion/extension angle Test done

Repeat/ Next Trail

Not Synchronized

Reset alignment (API)

Not aligned

FIGURE 20: FLOW CHART OF THE EXPERIMENTAL PROTOCOL
4 Results and Discussion

In this chapter, the knee joint angles during the normal walking gait are measured for different individuals of varying age, weight and gender. The primary purpose of this experimental study is to highlight the abnormalities or deviation from the normal gait pattern during normal walking activity. The data acquisition sensors were attached on both legs at thigh and shank to record the knee flexion/extension angles. The data obtained from the XSens sensors was post-processed in Matlab to depict it in a useful way. The details of data acquisition and processing are presented here along with the pertinent statistical analysis of human participants with respect to their physical measurements.

The data was recorded for several straight walking sessions for each individual, and the average of all the walking sessions was taken, and presented in graphs for each participant. The approach of presenting results after taking the mean of all the walking sessions for each individual reduces the non-uniformities in the data. The measured results are compared with a ground truth or a standard Knee kinematics as per references [29]. The ground truth or bench mark result can also be generated by an example model of Opensim bio-mechanical 3D oriented software [29] of a normal subject and Matlab. Furthermore, the results are compared and analyzed with the already published results as illustrated in chapter 2. The trade-offs of restrictions of Knee ROM while walking gait is proved by normalized gait variables such as bilateral gait symmetry ratios [24].

This chapter mainly focused on the results and their respective explanation. Hence, after every result a simple discussion has been provided.

4.1 Gait parameters and stride characteristics

Gait parameters are the main observations during gait analysis as explained above. Table 4.1 and 4.2 present the physical characteristics and gait parameters of female and male participants of this study. The characteristics, means and anthropometric measures (mean, SD) are also presented.

First milestone: As explained in Section 2.7, the p-values were less than 5% of probability of error and hence have significantly positive values between right and left knees for both genders. This shows that most of the values of the analyzed data are under the t- distribution of data analysis which has less variance compared to normal distribution. However, the correlation coefficient using Pearson’s r and the probability of error (p-value) of the age and BMI of the subjects shows non-significant as the selected subjects were less (10 male, 10 female) and longitivuty range or age differences have more deviation (shown in table 4.1 and 4.2 as *).
Table 4.1 Gait parameters of Female subjects (Both right and left knee)

<table>
<thead>
<tr>
<th>Subject data</th>
<th>Mean</th>
<th>STD dev</th>
<th>p-Value</th>
<th>Pearson’s r</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGE (years)</td>
<td>35.46</td>
<td>10.07</td>
<td>0.66*</td>
<td>0.15*</td>
</tr>
<tr>
<td>Body mass index (Kg/(m*m))</td>
<td>23.73</td>
<td>2.37</td>
<td>0.66*</td>
<td>0.15*</td>
</tr>
<tr>
<td>Step Length (cm)</td>
<td>51.45, 54.3</td>
<td>6.15, 5.68</td>
<td>0.004</td>
<td>0.96</td>
</tr>
<tr>
<td>Stride Length (cm)</td>
<td>107.9, 105.4</td>
<td>9.21, 11.71</td>
<td>0.0002</td>
<td>0.94</td>
</tr>
<tr>
<td>Gait frequency (steps / min)</td>
<td>2.02, 2.14</td>
<td>0.22, 0.24</td>
<td>0.0053</td>
<td>0.81</td>
</tr>
<tr>
<td>Gait Speed (cm/s)</td>
<td>134.3, 139.7</td>
<td>13.13, 14.85</td>
<td>0.0033</td>
<td>0.90</td>
</tr>
<tr>
<td>Cadence (Steps/min)</td>
<td>121.4, 128.4</td>
<td>13.48, 14.63</td>
<td>0.005</td>
<td>0.83</td>
</tr>
</tbody>
</table>

Table 4.2 Gait parameters of the Male subjects (Both right and left knee)

<table>
<thead>
<tr>
<th>Subject data</th>
<th>Mean</th>
<th>STD dev</th>
<th>p-Value</th>
<th>Pearson’s r</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGE (years)</td>
<td>26.07</td>
<td>6.31</td>
<td>0.72*</td>
<td>0.14*</td>
</tr>
<tr>
<td>Body mass index (Kg/(m*m))</td>
<td>24.2</td>
<td>4.99</td>
<td>0.72*</td>
<td>0.14*</td>
</tr>
<tr>
<td>Step Length (cm)</td>
<td>54.1, 55.1</td>
<td>7.8, 7.67</td>
<td>0.0008</td>
<td>0.88</td>
</tr>
<tr>
<td>Stride Length (cm)</td>
<td>109.9, 109.3</td>
<td>15.60, 16.08</td>
<td>0.00004</td>
<td>0.945</td>
</tr>
<tr>
<td>Gait frequency (steps / min)</td>
<td>1.86, 1.88</td>
<td>0.19, 0.18</td>
<td>0.0002</td>
<td>0.917</td>
</tr>
<tr>
<td>Gait Speed (cm/s)</td>
<td>130.7, 131.5</td>
<td>20.26, 18.38</td>
<td>0.0001</td>
<td>0.96</td>
</tr>
<tr>
<td>Cadence (Steps/min)</td>
<td>111.9, 113.3</td>
<td>11.28, 10.63</td>
<td>0.00005</td>
<td>0.94</td>
</tr>
</tbody>
</table>

*If p-Value < 0.05 data is significant and If P-Value > 0.05, Not Significant (N.S). And
R-value should be closer to ±1 to have positive or negatively strong relation between the data.

4.2 Age, Gender and BMI effects

The main effects for gait patterns were observed with respect to aging, body mass index, and genders, respectively. Table 4.3 shows the comparisons of how does age, BMI, and gender affects slow and fast gaits were the best and significant relationships in this thesis work.
Table 4.3: Comparisons: Spatiotemporal and Anthropometric data

<table>
<thead>
<tr>
<th>Normal Versus Abnormal Weight (BMI)</th>
<th>BMI Type</th>
<th>No: Subjects</th>
<th>AGE (years)</th>
<th>Height (cm)</th>
<th>BMI (Kg/m²)</th>
<th>Gait speed (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normal</td>
<td>14</td>
<td>33.10±10.13</td>
<td>166.50±10.69</td>
<td>22.90±1.71</td>
<td>137.39±15.24; 141.02±14.58</td>
</tr>
<tr>
<td></td>
<td>Other type</td>
<td>6</td>
<td>25.32±4.94</td>
<td>169.67±7.0</td>
<td>26.45±6.07</td>
<td>125.88±19.88; 123±15.72</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Male Versus Female (Gender)</th>
<th>Gender</th>
<th>AGE (years)</th>
<th>Height (cm)</th>
<th>Weight (Kg)</th>
<th>R Stride, L Stride time (sec)</th>
<th>R Cadence, L Cadence (steps/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MALE (10)</td>
<td>26.07±6.31</td>
<td>174.7±7.44</td>
<td>74.73±18.15</td>
<td>0.85±0.16; 0.84±0.12</td>
<td>111.89±11.28; 113.34±10.63</td>
</tr>
<tr>
<td></td>
<td>FEMALE(10)</td>
<td>35.46±10.07</td>
<td>160.2±4.98</td>
<td>61.35±7.48</td>
<td>0.81±0.11; 0.76±0.13</td>
<td>121.38±13.48; 128.38±14.61</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Young Versus Adult age (Years)</th>
<th>Age type</th>
<th>No: Subjects</th>
<th>AGE (years)</th>
<th>Height (cm)</th>
<th>R Stride, L Stride time (sec)</th>
<th>R Cadence, L Cadence (steps/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Young &lt; 26</td>
<td>10 (7 M, 3 F)</td>
<td>22.97±1.4</td>
<td>171.00±11.21</td>
<td>0.84±0.17; 0.81±0.13</td>
<td>113.28±13.69; 115.43±11.71</td>
</tr>
<tr>
<td></td>
<td>Adult &gt; 26</td>
<td>10 (3 M, 7 F)</td>
<td>38.55±7.3</td>
<td>163.9±6.59</td>
<td>0.82±0.10; 0.79±0.13</td>
<td>119.98±12.10; 126.29±15.81</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Slow Versus Normal Gait (cm/s)</th>
<th>Young, Male</th>
<th>Male, Female</th>
<th>Knee Length (cm)</th>
<th>R_Gait, L_Gait speeds (cms/sec)</th>
<th>R Cadence, L Cadence (steps/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slow Gait</td>
<td>1, 2</td>
<td>2, 1</td>
<td>47±3</td>
<td>100.48±4.78; 102.86±2.08</td>
<td>95.22±7.54; 98.13±5.83</td>
</tr>
<tr>
<td>Normal Gait</td>
<td>9, 8</td>
<td>8, 9</td>
<td>47.47±4.26</td>
<td>138.13±10.15; 141.39±9.91</td>
<td>120.41±9.68; 124.9±11.68</td>
</tr>
</tbody>
</table>

Where, R stride and L stride are right and left leg stride lengths, respectively, and R cadence and L Cadence are the number of steps carried out during gait analysis of right and left legs, respectively.
The table 4.3 results reveal the answers such as below:

**Normal versus Abnormal BMI Weight**

14 of Normal BMI subjects with a mean age of 33 years and with mean height of 166.5 cm are much faster than the 6 abnormal BMI subjects, who has mean age of 25,32 years of age and height of 169.67 cm. Hence, this proves BMI as one of the notable factors that affect the normal gait that suggests that the subjects with BMI with the range between the values 18.5 to 25 are considered as healthy, in relation with their body weights and statures (natural heights).

**Male Versus Female (Gender)**

Female had an average stride time of 0.815 seconds and standard deviation of 0.12 seconds with an average cadence of 122.5 steps per minutes and deviation of 14.05 steps per minute. Male had an average stride time of 0.825 seconds and standard deviation of 0.15 seconds with an average cadence of 112.62 steps per minutes and deviation of 10.96 steps per minute. The comparison of results with respect to gender difference shows that, the female subjects had less stride time which is the time taken for a stride length of a respective gait pattern of a leg. However, they take more steps to cover the allowed distance. From the above comparisons, the means and standard deviations of both right and left normal gait speeds (cm/s) doesn’t very much in both the genders and has no significant differences.

**Young Versus Adult age (Years)**

In comparison to longevity or aging factor of both genders, both young (22.97±1.4) and elder or older (38.55±7.3) age groups had almost the same speed or stride time of an average stride time of 0.825 seconds for young group and 0.81 seconds for the elder age group. However, young people take very less steps with an average cadence of 114.36 steps per minutes and deviation of 12.7 steps per minute.

**Slow Versus Normal Gait (cm/s)**

Finally, the subjects who had better cadence (steps/min) had the better gait speed despite of the age factor. As per [23], the normal gait speeds range from 118 to 134 cm/s for men and 110 to 129 cm/s for female. This work has considered and analyzed that any value less than 110 cm/s is considered as slow gait pattern and hence found 3 subjects in this category of 20 participants of this study.
4.3 Inverse kinematics and normalization - Knee angle

Kinematics is the study of human motion such as joint angles which are the position and orientations of the particular body segments using acceleration and velocities of that particular body segment motion. The knee range of motion (ROM) of the ground truth was interpreted [25] and generated with the help of Matlab which is shown as the dark (black line) waveform in the figures 21 and 22. The maximum knee flexion angles obtained of subjects ranges between 25 to 38 degrees for both the right and left leg respectively.

4.3.1 Knee swing width ROM

From theory of chapter 2, it has been explained that a normal walking knee flexion ROM to be 60 degrees, however, the knee angle increases exponentially on a long walking distance with the flexibility and balance of the lower extremity. Hence, the research of normalization is used to overcome this deviation [27]. This work obtained the maximum knee angle of 38 degrees for a walk path (short distance) of 6 meters on 4 trail runs to have the mean knee ROM of the participants. It has been observed in this study that the maximum knee angle is acquired when a subject has a steady bigger stride length during walking. The minimum knee ROM occurs during initial swing gait phase as explained in theory section.

However, the obtained results show few abnormal patterns of the left knee swing. The gait symmetry mainly depends on the same width of ROM for both the knees (Right and Left). It can be explained as average swing width. The average swing width is the index range different of the lowest point between the two peaks (P1 and P2) and the index at the other end of the swing which has the same value as the lowest point. This is shown in the figure 21; it is a mean knee angle of 12 gait cycles of a subject generated using Matlab tool [28]. The mean swing widths of right and left knee angles and their results of ratios are shown table 4.12.
4.3.2 Kinematics of Knee joint of the subjects

As explained in chapter 3: methods, the knee flexion angle was calculated and has been observed as shown in figures 22 and 23 of both female and male participants. The illustrations describe both right and left knee angles simultaneously with the help of synchronized data from four xsens motion trackers at the same time. This is more reliable for the bilateral gait symmetrical validation representing with discrete knee angular variables (K1 – K6) with key phases with respect to gait cycle (%). (Appendix A: Matlab script).

**Figure 22: Knee flexion/extension angle of Female Participants**

**Figure 23: Knee flexion/extension angle of Male Participants**
The absolute mean and standard knee ROM measures are not so significantly different between male and females. The observations in the knee angles of both genders has very low flexion angle at stance phase which shows small peak P1 (figure 21) defining no perfect action of flexion ROM during stance phase. However, this has not been considered as abnormality by observations as the maximum angle of a normal gait should have a greater swing range which relates the maximum peak P2 as shown in figure 20. Table 4.4 and 4.5 shows the values of individual’s mean of minimum and maximum knee flexion angles of male and female obtained from the figures 22 and 23. Table 4.6 shows the mean and standard deviation of maximum knee joint range of motion of both male and female participants.

Table 4.4 Knee Flexion/Extension Mean Values max and min (Degrees) of male

<table>
<thead>
<tr>
<th>Subject NO:</th>
<th>Knee Flexion/Extension Mean Values max and min (Deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R_Max</td>
</tr>
<tr>
<td>1</td>
<td>36.78</td>
</tr>
<tr>
<td>2</td>
<td>23.59</td>
</tr>
<tr>
<td>3</td>
<td>36.03</td>
</tr>
<tr>
<td>4</td>
<td>32.12</td>
</tr>
<tr>
<td>5</td>
<td>30.21</td>
</tr>
<tr>
<td>6</td>
<td>27.53</td>
</tr>
<tr>
<td>7</td>
<td>32.47</td>
</tr>
<tr>
<td>8</td>
<td>30.15</td>
</tr>
<tr>
<td>9</td>
<td>28.35</td>
</tr>
<tr>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.5 Knee Flexion/Extension Mean Values max and min (Degrees) of Female

<table>
<thead>
<tr>
<th>Subject NO:</th>
<th>Knee Flexion/Extension Mean Values max and min (Deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R_Max</td>
</tr>
<tr>
<td>1</td>
<td>28.42</td>
</tr>
<tr>
<td>2</td>
<td>28.11</td>
</tr>
<tr>
<td>3</td>
<td>35.63</td>
</tr>
<tr>
<td>4</td>
<td>34.6</td>
</tr>
<tr>
<td>5</td>
<td>32.84</td>
</tr>
<tr>
<td>6</td>
<td>32.38</td>
</tr>
<tr>
<td>7</td>
<td>31.79</td>
</tr>
<tr>
<td>8</td>
<td>27.25</td>
</tr>
<tr>
<td>9</td>
<td>30.04</td>
</tr>
<tr>
<td>10</td>
<td>26.3</td>
</tr>
</tbody>
</table>
Table 4.6: Maximum Knee joint ROM between the genders

<table>
<thead>
<tr>
<th>Knee Flexion angles (degrees)</th>
<th>Male Subjects (mean±std)</th>
<th>Female Subjects (mean±std)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right Knee ROM</td>
<td>30.87±3.91</td>
<td>30.739±3.20</td>
</tr>
<tr>
<td>Left Knee ROM</td>
<td>30.80±3</td>
<td>28.45±3.6</td>
</tr>
</tbody>
</table>

4.4 Discrete Knee Angular parametric values (K1 to k6)

There are more than 124 parameters of gait analysis which can be studied on biomechanics of the lower extremity of a human [22]. This research used the knee angle parameters in order to indicate the reliability of variation of the obtained motion tracking and analysis of knee angle in sagittal plane. The Knee flexion variables (Degrees) are shown in table 4.4 and 4.5 as explained in section 3.3.2 [22].

Table 4.7 Discrete Knee Angular parametric values (K1 to k6) of male

<table>
<thead>
<tr>
<th>Sub NO</th>
<th>K1</th>
<th>K2</th>
<th>K3</th>
<th>K4</th>
<th>K5 (Max.p)</th>
<th>K6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Right</td>
<td>Left</td>
<td>Right</td>
<td>Left</td>
<td>Right</td>
<td>Left</td>
</tr>
<tr>
<td>1</td>
<td>4.58</td>
<td>17.67</td>
<td>11.98</td>
<td>25.74</td>
<td>8.10</td>
<td>14.56</td>
</tr>
<tr>
<td>2</td>
<td>7.09</td>
<td>7.50</td>
<td>12.82</td>
<td>13.89</td>
<td>9.24</td>
<td>6.89</td>
</tr>
<tr>
<td>3</td>
<td>4.15</td>
<td>3.42</td>
<td>15.78</td>
<td>10.45</td>
<td>7.39</td>
<td>7.14</td>
</tr>
<tr>
<td>4</td>
<td>5.82</td>
<td>3.09</td>
<td>13.84</td>
<td>10.76</td>
<td>10.75</td>
<td>2.36</td>
</tr>
<tr>
<td>5</td>
<td>4.00</td>
<td>6.50</td>
<td>9.64</td>
<td>6.50</td>
<td>7.02</td>
<td>3.44</td>
</tr>
<tr>
<td>6</td>
<td>3.75</td>
<td>8.88</td>
<td>11.47</td>
<td>16.31</td>
<td>7.63</td>
<td>12.60</td>
</tr>
<tr>
<td>7</td>
<td>7.49</td>
<td>3.58</td>
<td>14.59</td>
<td>13.30</td>
<td>3.64</td>
<td>3.50</td>
</tr>
<tr>
<td>10</td>
<td>4.09</td>
<td>3.65</td>
<td>9.98</td>
<td>11.22</td>
<td>6.98</td>
<td>6.81</td>
</tr>
<tr>
<td>M</td>
<td>5.8</td>
<td>7.3</td>
<td>12.4</td>
<td>13.7</td>
<td>7.0</td>
<td>7.5</td>
</tr>
<tr>
<td>SD</td>
<td>2.6</td>
<td>4.6</td>
<td>2.7</td>
<td>5.1</td>
<td>2.2</td>
<td>4.0</td>
</tr>
<tr>
<td>GT</td>
<td>3</td>
<td>3</td>
<td>17</td>
<td>17</td>
<td>2.35</td>
<td>2.35</td>
</tr>
</tbody>
</table>
Table 4.8 Discrete Knee Angular parametric values (K1 to k6) of female

<table>
<thead>
<tr>
<th>Sub NO</th>
<th>K1</th>
<th></th>
<th>K2</th>
<th></th>
<th>K3</th>
<th></th>
<th>K4</th>
<th></th>
<th>K5 (Max.p)</th>
<th></th>
<th>K6</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Right</td>
<td>Left</td>
<td>Right</td>
<td>Left</td>
<td>Right</td>
<td>Left</td>
<td>Right</td>
<td>Left</td>
<td>Right</td>
<td>Left</td>
<td>Right</td>
<td>Left</td>
</tr>
<tr>
<td>1</td>
<td>4.40</td>
<td>8.5</td>
<td>7.83</td>
<td>9.3</td>
<td>2.83</td>
<td>6.2</td>
<td>25.58</td>
<td>21.2</td>
<td>28.42</td>
<td>23.6</td>
<td>4.02</td>
<td>8.4</td>
</tr>
<tr>
<td>2</td>
<td>6.01</td>
<td>11.4</td>
<td>11.55</td>
<td>22.0</td>
<td>9.23</td>
<td>14.6</td>
<td>25.30</td>
<td>29.8</td>
<td>28.11</td>
<td>33.2</td>
<td>5.85</td>
<td>11.6</td>
</tr>
<tr>
<td>3</td>
<td>11.35</td>
<td>14.6</td>
<td>11.74</td>
<td>24.0</td>
<td>6.94</td>
<td>19.3</td>
<td>32.07</td>
<td>33.3</td>
<td>32.84</td>
<td>29.2</td>
<td>11.18</td>
<td>9.6</td>
</tr>
<tr>
<td>4</td>
<td>5.48</td>
<td>3.7</td>
<td>12.58</td>
<td>9.4</td>
<td>5.14</td>
<td>5.5</td>
<td>31.14</td>
<td>26.4</td>
<td>32.38</td>
<td>25.1</td>
<td>3.38</td>
<td>8.1</td>
</tr>
<tr>
<td>5</td>
<td>11.33</td>
<td>9.3</td>
<td>12.21</td>
<td>9.3</td>
<td>7.47</td>
<td>5.0</td>
<td>29.55</td>
<td>26.2</td>
<td>32.84</td>
<td>29.2</td>
<td>11.18</td>
<td>9.6</td>
</tr>
<tr>
<td>6</td>
<td>4.32</td>
<td>7.7</td>
<td>13.78</td>
<td>7.8</td>
<td>6.70</td>
<td>6.0</td>
<td>29.14</td>
<td>22.6</td>
<td>32.38</td>
<td>25.1</td>
<td>3.38</td>
<td>8.1</td>
</tr>
<tr>
<td>7</td>
<td>7.37</td>
<td>11.1</td>
<td>10.65</td>
<td>13.5</td>
<td>6.88</td>
<td>9.5</td>
<td>28.61</td>
<td>25.3</td>
<td>31.79</td>
<td>28.1</td>
<td>8.20</td>
<td>11.0</td>
</tr>
<tr>
<td>8</td>
<td>3.56</td>
<td>4.0</td>
<td>7.01</td>
<td>5.0</td>
<td>3.41</td>
<td>3.1</td>
<td>24.53</td>
<td>23.4</td>
<td>27.25</td>
<td>26.0</td>
<td>2.95</td>
<td>4.2</td>
</tr>
<tr>
<td>9</td>
<td>6.28</td>
<td>7.2</td>
<td>9.69</td>
<td>11.8</td>
<td>4.87</td>
<td>7.3</td>
<td>27.04</td>
<td>18.7</td>
<td>30.04</td>
<td>20.8</td>
<td>6.50</td>
<td>7.6</td>
</tr>
<tr>
<td>10</td>
<td>6.51</td>
<td>8.8</td>
<td>12.25</td>
<td>10.5</td>
<td>4.97</td>
<td>6.5</td>
<td>23.67</td>
<td>24.5</td>
<td>26.30</td>
<td>27.3</td>
<td>6.00</td>
<td>8.6</td>
</tr>
<tr>
<td>M</td>
<td>6.7</td>
<td>8.6</td>
<td>10.9</td>
<td>12.3</td>
<td>5.8</td>
<td>8.3</td>
<td>27.7</td>
<td>25.1</td>
<td>30.2</td>
<td>26.8</td>
<td>6.3</td>
<td>8.7</td>
</tr>
<tr>
<td>SD</td>
<td>2.7</td>
<td>3.3</td>
<td>2.2</td>
<td>6.1</td>
<td>2.0</td>
<td>5.0</td>
<td>2.9</td>
<td>4.2</td>
<td>2.5</td>
<td>3.4</td>
<td>3.1</td>
<td>2.0</td>
</tr>
<tr>
<td>GT</td>
<td>3</td>
<td>3</td>
<td>17</td>
<td>17</td>
<td>2.35</td>
<td>2.35</td>
<td>$2.43$</td>
<td>$2.43$</td>
<td>$8.25$</td>
<td>$8.25$</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

From above tables 4.7 and 4.8, it is observed that no single subject has the same knee angle ROM and not even gait symmetry between both the knees. It was observed that 3 subjects had more than 10 degrees of knee angles during initial stance (K1) or knee flexing at heel strike and also at knee variable k6 the foot is resting and not tend to have closer range of K1. This shows an indication of asymmetry of both the knee angles with physiological factors like lack of energy conservation or even considered that the subject had more influenced unilateral leg support and more swing with the opposite leg [3, 30]. After generating these plots, the discrete angular knee variables at these 6 key phases from K1 to K6 are obtained.

However, these values can be valid for a short distance walking gait where the knee flexion angle doesn’t increase exponentially. This is because of less strength of the muscles used and the range of motion (ROM) of joints required for an efficient walking. As one knee swings while walking forward (swing phase) and the other leg should give the body, the required stance or support (stance phase). However, both phases of both legs are crucial in a good gait which can influence the opposite leg and the body mass of the upper body. When the subject walks faster, the time of these two phases reduce and, angle required at hip, ankle, and knee joints and strength of controlling muscles to walk will increase exponentially.

Normalization using stride time (%) and Knee length are calculated as below equations [30]:

$$Norm_{Knee\_Phase} = \left[\frac{Phase\_Var}{\text{stride}(\%)}\right] \times 100$$
\[ \text{Norm}_{\text{Knee,Length}} = \left[ \frac{\text{Dis}_\text{Var}}{\text{Knee}_\text{Length}(\%)} \right] \times 100 \]

The tables 4.9 and 4.10 reveal the key phases before and after normalization with their respective means and standard deviation values along with correlation coefficient (Pearson’s $r$) and p-value. Table 4.11 reveals the distance variables comparison before and after normalization. It is validated as the normalization of swing time to compensate the lower knee angles is not significant and very weakly correlated. The values shown are the means and standard deviations (mean±std) respectively.

**Table 4.9 Male Phase Variables**

<table>
<thead>
<tr>
<th>Ground Truth &amp; Values (deg)</th>
<th>Before Normalization (Deg)</th>
<th>After Normalization (Deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Right Knee</td>
<td>Left Knee</td>
</tr>
<tr>
<td>K1 – 3</td>
<td>5.8±2.6</td>
<td>7.3±4.6</td>
</tr>
<tr>
<td>K2 – 17</td>
<td>12.4±2.7</td>
<td>13.7±5.1</td>
</tr>
<tr>
<td>K3 – 2.35</td>
<td>7.0±2.2</td>
<td>7.5±4.0</td>
</tr>
<tr>
<td>K4 – 52.43</td>
<td>27.8±3.5</td>
<td>27.4±3.1</td>
</tr>
<tr>
<td>K5 – 58.25</td>
<td>29,8±3.5</td>
<td>30.8±3</td>
</tr>
<tr>
<td>K6 – 3</td>
<td>5.5±2.9</td>
<td>8.7±4.4</td>
</tr>
<tr>
<td>p-value</td>
<td>0.008</td>
<td>0.008</td>
</tr>
<tr>
<td>Pearson’s $r$</td>
<td>0.78</td>
<td>0.78</td>
</tr>
</tbody>
</table>

**Table 4.10 Female Phase Variables**

<table>
<thead>
<tr>
<th>Ground Truth</th>
<th>Before Normalization (Deg)</th>
<th>After Normalization (Deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values (Deg)</td>
<td>Right Knee</td>
<td>Left Knee</td>
</tr>
<tr>
<td>K1 – 3</td>
<td>6.7±2.7</td>
<td>8.6±3.3</td>
</tr>
<tr>
<td>K2 – 17</td>
<td>10.9±2.2</td>
<td>12.3±6.1</td>
</tr>
<tr>
<td>K3 – 2.35</td>
<td>5.8±2</td>
<td>8.3±5</td>
</tr>
<tr>
<td>K4 – 52.43</td>
<td>27.7±2.9</td>
<td>25.1±4.2</td>
</tr>
<tr>
<td>K5 – 58.25</td>
<td>30.2±2.5</td>
<td>26.8±3.4</td>
</tr>
<tr>
<td>K6 – 3</td>
<td>6.3±3.1</td>
<td>8.7±2</td>
</tr>
<tr>
<td>p-value</td>
<td>0.43</td>
<td>0.43</td>
</tr>
<tr>
<td>Pearson’s $r$</td>
<td>0.28</td>
<td>0.28</td>
</tr>
</tbody>
</table>
Normalization method using stride (%) and knee length (%) had been found almost two decades earlier where the gait assessment was conducted with a video camera (Panasonic AG Model). These normalizations have been used in this research and had retrieved the lost knee angles which would have possible maximum values per subject with respect to his/her phase variables [27].

Table 4.1 Male and Female Distance Variables

<table>
<thead>
<tr>
<th>Subjects</th>
<th>Height (cm)</th>
<th>Knee Length (cm)</th>
<th>Type of leg</th>
<th>Before Norm Step lengths (cm)</th>
<th>P-value</th>
<th>After Norm Step lengths (cm)</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 Male</td>
<td>174.70±7.44</td>
<td>50.30±3.4</td>
<td>Right</td>
<td>54.10±7.8</td>
<td>0.004</td>
<td>107.5±12.23</td>
<td>0.375</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Left</td>
<td>55.10±7.67</td>
<td>0.004</td>
<td>109.5±12.56</td>
<td>0.0728</td>
</tr>
<tr>
<td>10 Female</td>
<td>160.20±4.98</td>
<td>44.5±2.01</td>
<td>Right</td>
<td>51.45±6.15</td>
<td>0.0008</td>
<td>115.44±10.7</td>
<td>0.375</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Left</td>
<td>54.3±5.68</td>
<td>0.0008</td>
<td>121.9±9.76</td>
<td>0.0728</td>
</tr>
</tbody>
</table>

Male statures (Natural height) are more than female statures. The step lengths were better before normalization. Hence, no significant differences due to gender were found for any of the normalized variables. From null hypothesis, if the probability of error p-value is greater than 0.05, then the data is not significantly positive for the comparison as explained in Section 2.7.

4.5 Bilateral Gait symmetry

Finally, bilateral gait symmetry check [24] using the mean swing times of leg to the left leg for the free walkers to find the abnormal subject with swing period from the simulations. It is basically a comparison with both legs of both genders. The research found 3 male and 2 female subjects have been abnormal and their details as shown in table 4.14. Every subject has step length which is equal or more than the shank length (knee joint to the ankle joint), and had stride length equal or more than the leg length (hip joint to the ground). The bilateral gait symmetry of both right and left knee proved from the gait symmetry (GS) ratio which is the average flexion/extension angle of the right knee by the left knee [24]. The result in table 4.15 was based on the observations from the subjects gait parameters and hence had successfully differentiated the normal and abnormal gait of the respective participant. The information of other 15 subjects and comments on their abnormalities is given in Appendix C in the tables C1 and table C2.
Table 4.12: Bilateral Gait Symmetry of 20 participants

<table>
<thead>
<tr>
<th>Subject NO:</th>
<th>Male and Female Swing widths using angle measurements per gait cycle%</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M_RSW</td>
<td>M_LSW</td>
<td>Male GS</td>
<td>F_RSW</td>
<td>F_LSW</td>
</tr>
<tr>
<td>1</td>
<td>49</td>
<td>45</td>
<td>1.36</td>
<td>61</td>
<td>42</td>
</tr>
<tr>
<td>2</td>
<td>56</td>
<td>55</td>
<td>1.02</td>
<td>52</td>
<td>54</td>
</tr>
<tr>
<td>3</td>
<td>54</td>
<td>53</td>
<td>1.02</td>
<td>60</td>
<td>56</td>
</tr>
<tr>
<td>4</td>
<td>43</td>
<td>43</td>
<td>1</td>
<td>48</td>
<td>51</td>
</tr>
<tr>
<td>5</td>
<td>53</td>
<td>59</td>
<td>0.89</td>
<td>49</td>
<td>49</td>
</tr>
<tr>
<td>6</td>
<td>55</td>
<td>52</td>
<td>1.06</td>
<td>51</td>
<td>54</td>
</tr>
<tr>
<td>7</td>
<td>53</td>
<td>54</td>
<td>0.85</td>
<td>64</td>
<td>56</td>
</tr>
<tr>
<td>8</td>
<td>55</td>
<td>53</td>
<td>1.04</td>
<td>48</td>
<td>57</td>
</tr>
<tr>
<td>9</td>
<td>52</td>
<td>56</td>
<td>0.93</td>
<td>48</td>
<td>53</td>
</tr>
<tr>
<td>10</td>
<td>43</td>
<td>47</td>
<td>0.91</td>
<td>50</td>
<td>49</td>
</tr>
<tr>
<td>Mean</td>
<td>51.3</td>
<td>51.7</td>
<td>1.01</td>
<td>53.1</td>
<td>52.1</td>
</tr>
<tr>
<td>Std. Dev</td>
<td>4.79</td>
<td>5.1</td>
<td>0.14</td>
<td>6.14</td>
<td>4.53</td>
</tr>
</tbody>
</table>

Where, GS is gait symmetry, RSW is the right knee swing width and LSW is the left knee swing width.

From the table 4.12, the bold values are abnormal values as per this research criterion of bilateral symmetry of a normal gait and are shown in the figure 24. According to anatomy of human lower limb [2], it explains the symmetrical range of motion between the right and left walking behavior. Hence, this study assumes to have the mean of the ratio to be 1. The allowable probability of error is considered to be under 0.1 (p<0.1) relating to the subjects average.

**Assumptions:** For bilateral symmetry validation

**Symmetry Range:** $1 \pm 0.1$ (mean $\pm$ standard deviation)

**Asymmetry Area:** $1.1 > A < 0.9$
After observing the values in the discrete angular knee variables and compared to the ground truth values, they are not significantly related. Hence, this research work had used a technique for normalizing the knee angles which are mostly dependent on the knee stride time during a full gait cycle (%).

### 4.6 Additional discussion

The present research was useful as it helped in finding abnormalities without undergoing any medical or radioactive tests. It was found that 5 subjects (3 male and 2 female subjects) are likely to have abnormality during walking gait and, hence, possibility of having abnormalities in their knee joints. Their details are shown in table 4.1 with the spatiotemporal data of individual participant and their previous history of any disability. The results shown in this chapter were analyzed statistically with the help of student’s t tests and correlation test (regression analysis), and achieved satisfactorily with the data of 20 participants in the gait assessment. The obtained results from data analysis such as gait anthropometric parameters and the data obtained from motion tracking using Xsens measurement system as knee flexion/extension angle in sagittal plane were successful and positively significant in this preliminary study. All the subjects who had slow or normal gaits with any abnormal pattern due to low physical strength or external factors that affect the subject’s walking are briefed in tabulations in Appendix C.
Table 4.1: Mean values of the subjects having Asymmetry Bilateral Gait Pattern

<table>
<thead>
<tr>
<th>Subject Number</th>
<th>Age, BMI</th>
<th>Avg. Step Length (cm)</th>
<th>Avg. Stride Length (cm)</th>
<th>G Speed (cm/sec)</th>
<th>Gait Freq. (Step/sec)</th>
<th>Cadence (Step/min)</th>
<th>Comments/causes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, Male</td>
<td>39.7 Normal</td>
<td>43.5 cm</td>
<td>86.5</td>
<td>99.76</td>
<td>1.9935</td>
<td>119.71</td>
<td>Back chronic Pain, Recently met accident</td>
</tr>
<tr>
<td>5, Male</td>
<td>30 Over</td>
<td>55 cm</td>
<td>113.5</td>
<td>137.75</td>
<td>2.005</td>
<td>120.44</td>
<td>Previously had left ankle fracture and hence the double support error</td>
</tr>
<tr>
<td>7, Male</td>
<td>21.33 Normal</td>
<td>55 cm</td>
<td>111.5</td>
<td>126.15</td>
<td>1.835</td>
<td>110.2</td>
<td>Double support discomfort and right knee swings less Football Player Sports injury</td>
</tr>
<tr>
<td>1, Female</td>
<td>32.9 Over</td>
<td>46.5</td>
<td>103.5</td>
<td>105.6</td>
<td>1.63</td>
<td>97.8</td>
<td>Fatigue = Low energy Very low cadence Very slow gait</td>
</tr>
<tr>
<td>10, Female</td>
<td>36.25 Normal</td>
<td>64.75</td>
<td>130.5</td>
<td>134.75</td>
<td>2.02</td>
<td>121.2</td>
<td>Very fast gait Bigger step and stride lengths</td>
</tr>
</tbody>
</table>

The bolded values reveal the abnormal differences between the individuals. The observations shows the below:

a. The subject 1 in male and in female subjects has very short step length while walking gait.
b. The subject 5 in male and subject 10 in female has more gait speed and cadence and they can be considered the individuals with fast gait speed.
c. However, the subject 7 in male list has an asymmetry in comparison with his stride lengths with right and left leg.
d. Also, the subject 7 in male and subject 1 in female has very less gait speed and they can be considered the individuals with slow gait speed.
5 Conclusion

This thesis is to present the methods of validating bilateral gait symmetry for both genders. Particularly, the study focuses on the behavior of each participant’s right and left knee joint flexion/extension angles during normal walking at self-selected gait speeds. The participants consist of 10 males (mean age 26.07±6.31 (SD), range of 20-40) and 10 females (mean age 35.46±10.07 (SD), range of 23-53). The tests were conducted considering them as healthy individuals and free of any apparent walking disability and found abnormal gait patterns for a few subjects and had been given in results. The results were analyzed based on walking pattern in sagittal plane.

The basic procedure followed in this thesis work was as follows:

1. Background study of gait analysis and biomechanics of knee joint.
2. Selection of equipment for real time data recording or tracking.
3. Selection of environment and the experimental setup.
4. Recruiting subjects for the gait assessment.
5. Collecting data of each subject’s spatiotemporal and anthropometric measurement details.
7. Data acquisition and processing.
8. Data analysis using signal processing procedures.
9. Validating the data whether the data is statistically significant and correlated.
10. Finally, finding abnormal subjects based on bilateral gait symmetry.

These 10 points were followed strictly to ensure that the gait patterns of the participated subjects are ethically valid enough for a comparison. For ensuring that, we have been following the proper procedure of gait analysis and this research team was in contact with collaboration to Department of knee surgery at Hässleholm hospital, Sweden. Finally, this preliminary study will be a great bench mark for the future research works in bio-medical rehabilitation.
5.1 Future work

This thesis work has immense scope of improvement in many ways; a few of them are as follows:

1. Finding the knee abduction / adduction angles, knee internal/ external rotation angles, along with Hip joint and pelvis tilt angle at the end of the spinal cord for more comparisons of the gender differences.

2. Kinetic analysis using a force sensor and EMG data to analyse the lower limb forces and moments, which can give more information of the ROM of participants.

3. Involvement of exoskeleton with inertial sensors.

4. Shapiro-wilk test for analysing abnormity [19], where, the output is a p-value, which is interpreted and classified into 5 different ranges of intervals such as:
   a. P-value < 0.001 – Very strong evidence
   b. P-value < 0.001 – strong evidence
   c. P-value < 0.001 – moderate evidence
   d. P-value < 0.001 – mild or weak evidence
   e. P-value < 0.001 – No compelling evidence
6 References


[20]. "Use the Analysis ToolPak to perform complex data analysis", [Online]. Available: https://support.office.com/


Appendix A: Matlab Scripts

Script 1:

```matlab
%% Importing and processing data of .txt file
close all
clear all
clc

%% Importing data
data1_R_T=importdata('_MT_~data_Subject1_data1~00B42979.txt'); % Right Thigh
data1_R_S=importdata('_MT_~data_Subject1_data1~00B42995.txt'); % Right Shank
data1_L_T=importdata('_MT_~data_Subject1_data1~00B429AA.txt'); % Left Thigh
data1_L_S=importdata('_MT_~data_Subject1_data1~00B42976.txt'); % Left Shank

%% Quaternion data of the subject test1
D1RT = data1_R_T.data(:,38:41); % Right Thigh
D1RS = data1_R_S.data(:,38:41); % Right Shank
D1LT = data1_L_T.data(:,38:41); % Left Thigh
D1LS = data1_L_S.data(:,38:41); % Left Shank

Length_Q_R_T = length(D1RT); % Number of samples
Length_Q_R_S = length(D1RS); % Number of samples
Length_Q_L_T = length(D1LT); % Number of samples
Length_Q_L_S = length(D1LS); % Number of samples

% Vectors to angle conversion data1 Right
Dotp_D1R = (dot(D1RT',D1RS'));

for i = 1:size(D1RT)
    Mag_DIRT(i) = norm(D1RT(i,:));
end

for i = 1:size(D1RS)
    Mag_DIRS(i) = norm(D1RS(i,:));
end

zR1 = (Dotp_D1R ./ ((Mag_DIRT.*Mag_DIRS)));

Angle_RAD_DIR = (acos(zR1'));
Angle_Deg_DIR = (180/pi).*Angle_RAD_DIR;
xlswrite('Subject1_Knee1R.xlsx',Angle_Deg_DIR);

Angle_Deg_DIR22 = Angle_RAD_DIR.*(180/pi);

figure(1)
subplot(3,1,1);
plot(Angle_RAD_DIR);title('Knee joint angle in Rad pattern 1');
xlabel('Number of samples')
ylabel('dot product by magnitude based angle')

subplot(3,1,2);
plot(Angle_Deg_DIR);title('Knee joint angle in Deg eqn 1');
ylabel('norm based angle')
xlabel('Number of samples')

subplot(3,1,3);
plot(Angle_Deg_DIR22);title('Knee joint angle in Deg eqn 2');
ylabel('norm based angle')
xlabel('Number of samples')
```
% Vectors to angle conversion DATA 1 Left

Dotp_D1L = (dot(D1LT',D1LS'));

%%%Magnitude of Thigh values-----------------
for i = 1:size(D1LT)
    Mag_D1LT(i) = norm(D1LT(i,:));
end

%%%Magnitude of Thigh values-----------------
for i = 1:size(D1LS)
    Mag_D1LS(i) = norm(D1LS(i,:));
end

zL1 = (Dotp_D1L ./ (Mag_D1LT.*Mag_D1LS));

Angle_Rad_D1L = (acos(zL1'));
Angle_Deg_D1L = (180/pi).*Angle_Rad_D1L;

% ThetaInDegrees = atan2d(norm(cross(x.Sheet1,y)),dot(x.Sheet1,y));
xlswrite('Subject1_Knee1L.xlsx',Angle_Deg_D1L);
figure(2)
subplot(2,1,1);
plot(Angle_Rad_D1L);title('Knee joint angle in Rad pattern 2');
xlabel('Number of samples')
ylabel('dot product by magnitude based angle')

subplot(2,1,2);
plot(Angle_Deg_D1L);title('Knee joint angle in Deg pattern 2');
ylabel('norm based angle')
xlabel('Number of samples')

%angle 1 Done 

% similarly for 4 trails 

Script 2: Mean and standard deviation for a subject’s 4 Trails

%% Gait parametric analysis of the knee angle of the subject

close all
clear all
clic

%%%% 1. range of the gait cycle period and active region (number of periods)
%%%% 2. folding each cycle to find the variance -- reshape
%%%% 3. Average of the knee angle at distinct points
%%%% 4. mean and standard deviation

% where R is right knee angle; L is the Left knee angle

data_Knee_R1 = importdata('Subject1_pattern2_Knee1R.xlsx');
data_Knee_L1 = importdata('Subject1_pattern2_Knee1L.xlsx');
data_Knee_R2 = importdata('Subject1_pattern2_Knee2R.xlsx');
data_Knee_L2 = importdata('Subject1_pattern2_Knee2L.xlsx');
data_Knee_R3 = importdata('Subject1_pattern2_Knee3R.xlsx');
data_Knee_L3 = importdata('Subject1_pattern2_Knee3L.xlsx');
data_Knee_R4 = importdata('Subject1_pattern2_Knee4R.xlsx');
data_Knee_L4 = importdata('Subject1_pattern2_Knee4L.xlsx');
% maximum and minimum values of the signal knee angle
Max_R1 = max(data_Knee_R1.Sheet1);
Min_R1 = min(data_Knee_R1.Sheet1);
Max_L1 = max(data_Knee_L1.Sheet1);
Min_L1 = min(data_Knee_L1.Sheet1);
Max_R2 = max(data_Knee_R2.Sheet1);
Min_R2 = min(data_Knee_R2.Sheet1);
Max_L2 = max(data_Knee_L2.Sheet1);
Min_L2 = min(data_Knee_L2.Sheet1);
Max_R3 = max(data_Knee_R3.Sheet1);
Min_R3 = min(data_Knee_R3.Sheet1);
Max_L3 = max(data_Knee_L3.Sheet1);
Min_L3 = min(data_Knee_L3.Sheet1);
Max_R4 = max(data_Knee_R4.Sheet1);
Min_R4 = min(data_Knee_R4.Sheet1);
Max_L4 = max(data_Knee_L4.Sheet1);
Min_L4 = min(data_Knee_L4.Sheet1);

% by looking at the minimum values, found to have no hyper extension

figure(1)
subplot(4,1,1); title('Right Knee joint angles of 4 Tests');
plot(data_Knee_R2.Sheet1)
subplot(4,1,2)
pplot(data_Knee_R3.Sheet1)
subplot(4,1,3)
pplot(data_Knee_R4.Sheet1)
subplot(4,1,4)
pplot(data_Knee_R1.Sheet1)

figure(2)
subplot(4,1,1); title('Left Knee joint angles of 4 Tests');
pplot(data_Knee_L2.Sheet1)
subplot(4,1,2)
pplot(data_Knee_L3.Sheet1)
subplot(4,1,3)
pplot(data_Knee_L4.Sheet1)
subplot(4,1,4)
pplot(data_Knee_L1.Sheet1)

% reshaping code
%%%%% reshaping and averaging the gait periods of the active region

%%%%% Right Leg
N_R2 = 3; %number of active gait cycles in the test
L_R2 = length(Avg_R2);
S_R2 = size(Avg_R2);
S_avg_R2 = L_R2 /N_R2;
res_R2 = reshape(Avg_R2, ((L_R2-0)/N_R2), N_R2); % averaging the gait cycles
figure;plot(res_R2)

% figure;plot(mean(res_R))
figure;plot(mean(res_R2,2))
figure;plot(std(res_R2,[],2))
figure;plot(std(res_R2,[],2)./ mean(res_R2,2))

mean(std(res_R2,[],2))

%%%%%%%% Left Leg 2

Avg_L2 = data_Knee_L2.Sheet1(139:438);
figure;plot(Avg_L2)

N_L2 = 3; %number of gait cycles in the test
L_L2 = length(Avg_L2);
S_L2 = size(Avg_L2);
S_avg_L2 = L_L2 / N_L2;
res_L2 = reshape(Avg_L2(1:(L_L2-0)),((L_L2-0)/N_L2,N_L2));
figure;plot(res_L2)

figure;plot(mean(res_L2,2))
hold on
plot(mean(res_R2,2))
hold off

%################################################################ 2 done

%%%%%%%% Right Leg 3

Avg_R3 = data_Knee_R3.Sheet1(299:589);
figure;plot(Avg_R3)

N_R3 = 3; %number of gait cycles in the test
L_R3 = length(Avg_R3);
S_R3 = size(Avg_R3);
S_avg_R3 = L_R3 / N_R3;
res_R3 = reshape(Avg_R3(1:(L_R3-0)),((L_R3-0)/N_R3,N_R3));
figure;plot(res_R3)

figure;plot(mean(res_R3))
figure;plot(std(res_R3,2))
figure;plot(std(res_R3,[],2))

mean(std(res_R3,[],2))

%%%%%%%% Left Leg

Avg_L3 = data_Knee_L3.Sheet1(299:589);
figure;plot(Avg_L3)
N_L3 = 3; %number of gait cycles in the test
L_L3 = length(Avg_L3);
S_L3 = size(Avg_L3);
% S_avg = size(Avg_L) /N;
S_avg_L3 = L_L3 /N_L3;

res_L3 = reshape(Avg_L3(1:(L_L3-0)),(L_L3-0)/N_L3,N_L3);
figure;plot(res_L3)
% res_L = reshape(Avg_L(1:600),600/N_L,N_L);
figure;plot(mean(res_L3,2))
hold on
plot(mean(res_R3,2))
% hold off

%%%%%%%%%%%%%%%%%%%%%%%%%% Leg Number 3 done ££££££££££££

%%%%%% Right Leg 4 €€€€€€€€€€€€€€€€€€€€€€€€€€€
Avg_R4 = data_Knee_R4.Sheet1(225:521);
figure;plot(Avg_R4)
% size(Avg_R)
% size(Avg_R) /6

N_R4 = 3; %number of gait cycles in the test
L_R4 = length(Avg_R4);
S_R4 = size(Avg_R4);
% S_avg = size(Avg_L) /N;
S_avg_R4 = L_R4 /N_R4;

res_R4 = reshape(Avg_R4(1:(L_R4-0)),((L_R4-0)/N_R4),N_R4);
figure;plot(res_R4)

figure;plot(mean(res_R4))
figure;plot(mean(res_R4,2))
figure;plot(std(res_R4,[],2))
figure;plot(std(res_R4,[],2)./ mean(res_R4,2))

mean(std(res_R4,[],2))

%%%%%% Left Leg 4 €€€€€€€€€€€€€€€€€€€€€€€€€€€
Avg_L4 = data_Knee_L4.Sheet1(225:521);
figure;plot(Avg_L4)

N_L4 = 3; %number of gait cycles in the test
L_L4 = length(Avg_L4);
S_L4 = size(Avg_L4);
% S_avg = size(Avg_L) /N;
S_avg_L4 = L_L4 /N_L4;
res_L4 = reshape(Avg_L4(1:(L_L4-0)),(L_L4-0)/N_L4,N_L4);
figure;plot(res_L4)
% res_L = reshape(Avg_L(1:600),600/N_L,N_L);
figure;plot(mean(res_L4,2))
hold on
plot(mean(res_R4,2))
% hold off
Preliminary Study: Bilateral Gait Symmetrical Validation for Different Genders

```
% Right Leg 1
figure;plot(Avg_R1)
% size(Avg_R)
% size(Avg_R) /6

N_R1 = 3; %number of gait cycles in the test
L_R1 = length(Avg_R1);
S_R1 = size(Avg_R1);
% S_avg = size(Avg_L) /N;
S_avg_R1 = L_R1 /N_R1;
res_R1 = reshape(Avg_R1(1:(L_R1-0)),((L_R1-0)/N_R1),N_R1);
figure;plot(res_R1)
figure;plot(mean(res_R1))
figure;plot(mean(res_R1,2))
figure;plot(std(res_R1,[],2))
figure;plot(std(res_R1,[],2)./ mean(res_R1,2))
std(res_R1,[],2)

%% Left Leg 1
figure;plot(Avg_L1)

N_L1 = 3; %number of gait cycles in the test
L_L1 = length(Avg_L1);
S_L1 = size(Avg_L1);
% S_avg = size(Avg_L) /N;
S_avg_L1 = L_L1 /N_L1;
res_L1 = reshape(Avg_L1(1:(L_L1-0)),(L_L1-0)/N_L1,N_L1);
figure;plot(res_L1)
% res_L = reshape(Avg_L(1:600),600/N_L,N_L);
figure;plot(mean(res_L1,2))
hold on
plot(mean(res_R1,2))
hold off

Leg Number 1 done

%% combine 4 test results to find mean
M_R2 = interpft(mean(res_R2,2),100);
M_R3 = interpft(mean(res_R3,2),100);
M_R4 = interpft(mean(res_R4,2),100);
M_R1 = interpft(mean(res_R1,2),100);
M_L2 = interpft(mean(res_L2,2),100);
M_L3 = interpft(mean(res_L3,2),100);
M_L4 = interpft(mean(res_L4,2),100);
M_L1 = interpft(mean(res_L1,2),100);
```

A6
Mean_R = [M_R2 M_R3 M_R4 M_R1];
figure;plot(mean(Mean_R,2))
figure;plot(std(Mean_R,[],2))

Mean_L = [M_L2 M_L3 M_L4 M_L1];
figure;plot(mean(Mean_L,2))
figure;plot(std(Mean_L,[],2))

figure;plot(mean(Mean_R,2)); title({'Final plot of 4 tests','FontSize',24)}
hold on
plot(mean(Mean_L,2))

%%% Interpolating the plots to get desired %%%%%%%%%%%%%%%%
R_M = mean(Mean_R,2);
R_Mean = interpft(R_M(1:100),100);
L_M = mean(Mean_L,2);
L_Mean = interpft(L_M(1:100),100);

Main_SD1_R = xlswrite('subject1_Knee_Right.xlsx',R_Mean)
Main_SD1_L = xlswrite('subject1_Knee_Left.xlsx',L_Mean)

% comparing with ground truth %%%%%%%%%%%%%%%%%%%%
%1. Finding the variance between the GT and the subject data
data_GT_RK = importdata('GT_R.xlsx'); % Right ground truth
GT_RK = interpft(data_GT_RK.GT_RK(1:96),100);
data_GT_LK = importdata('GT_L.xlsx'); % Left ground truth
GT_LK = interpft(data_GT_LK.GT_LK(1:96),100);

figure;plot(R_Mean); title({'Final plot of 4 tests with GT','FontSize',24})
hold on
plot(L_Mean)
hold on
plot(GT_RK)
hold on
plot(GT_LK)

Similarly, the data of 19 more subjects’ data has been analysed and compared as below script:

Script 3: Male Subjects data with swing width comparison script

close all
clear all
clc
%% Male subjects data comparison and is also same for female subjects data
%Right Knee angles with ground truth
S0R = importdata('GT_R.xlsx');
S1R = importdata('subject1_Knee_Right.xlsx');
S2R = importdata('subject2_Knee_Right.xlsx');
S3R = importdata('subject3_Knee_Right.xlsx');
S4R = importdata('subject4_Knee_Right.xlsx');
S5R = importdata('subject5_Knee_Right.xlsx');
S6R = importdata('subject6_Knee_Right.xlsx');
S7R = importdata('subject7_Knee_Right.xlsx');
Naga Munjulury
Preliminary Study: Bilateral Gait Symmetrical Validation for Different Genders

S8R = importdata('subject8_Knee_Right.xlsx');
S9R = importdata('subject9_Knee_Right.xlsx');
S10R = importdata('subject10_Knee_Right.xlsx');
figure;
hold on; set(gca,'FontSize',16); set(gca,'FontName','Times');
set(gcf,'Color',[1,1,1]);
m = [h, '-o', '-+', '-d', '-^', '-v', '>','<', 'p', 'h'];
plot(S1R.Sheet1,[m(1)]); %title('Knee joint angle Mahmoud');
title('Right Knee joint angles with GT');
plot(S2R.Sheet1,[m(2)]); %title('Knee joint angle Hussein');
plot(S3R.Sheet1,[m(3)]); %title('Knee joint angle Franco');
plot(S4R.Sheet1,[m(4)]); %title('Knee joint angle Nara');
plot(S5R.Sheet1,[m(5)]); %title('Knee joint angle Hadi');
plot(S6R.Sheet1,[m(6)]); %title('Knee joint angle Mahmoud');
plot(S7R.Sheet1,[m(7)]); %title('Knee joint angle Hussein');
plot(S8R.Sheet1,[m(8)]); %title('Knee joint angle Franco');
plot(S9R.Sheet1,[m(9)]); %title('Knee joint angle Nara');
plot(S10R.Sheet1,[m(10)]); %title('Knee joint angle Hadi');
plot(S0R.Sheet1/2,'k', 'LineWidth',2); %title('Knee joint angle GT Right');
grid on
ylabel('Right Knee angles (degrees)')
xlabel('Number of samples')
hold off

%Right Knee angles with ground truth
S0L = importdata('GT_L.xlsx');
S1L = importdata('subject1_Knee_Left.xlsx');
S2L = importdata('subject2_Knee_Left.xlsx');
S3L = importdata('subject3_Knee_Left.xlsx');
S4L = importdata('subject4_Knee_Left.xlsx');
S5L = importdata('subject5_Knee_Left.xlsx');
S6L = importdata('subject6_Knee_Left.xlsx');
S7L = importdata('subject7_Knee_Left.xlsx');
S8L = importdata('subject8_Knee_Left.xlsx');
S9L = importdata('subject9_Knee_Left.xlsx');
S10L = importdata('subject10_Knee_Left.xlsx');
figure;
title('Left Knee joint angles with GT');
plot(S1L.Sheet1); %title('Knee joint angle Mahmoud');
hold on
plot(S2L.Sheet1); %title('Knee joint angle Hussein');
hold on
plot(S3L.Sheet1); %title('Knee joint angle Franco');
hold on
plot(S4L.Sheet1); %title('Knee joint angle Nara');
hold on
plot(S5L.Sheet1); %title('Knee joint angle Hadi');
hold on
plot(S6L.Sheet1); %title('Knee joint angle Mahmoud');
hold on
plot(S7L.Sheet1); %title('Knee joint angle Hussein');
hold on
plot(S8L.Sheet1); %title('Knee joint angle Franco');
hold on
plot(S9L.Sheet1); %title('Knee joint angle Nara');
hold on
plot(S10L.Sheet1); %title('Knee joint angle Hadi');
hold on
plot(S0L.Sheet1); %title('Knee joint angle GT Right');
ylabel('Left Knee angles')
xlabel('Number of samples')
hold off

% data set for RMSE

Male_R = [S1R.Sheet1,S2R.Sheet1,S3R.Sheet1,S4R.Sheet1,S5R.Sheet1,S6R.Sheet1,S7R.Sheet1,S8R.Sheet1,S9R.Sheet1,S10R.Sheet1];
Male_L = [S1L.Sheet1,S2L.Sheet1,S3L.Sheet1,S4L.Sheet1,S5L.Sheet1,S6L.Sheet1,S7L.Sheet1,S8L.Sheet1,S9L.Sheet1,S10L.Sheet1];

% Interpolation of ground truths
GT_RM = interpft(S0R.Sheet1(1:96),100);
% GT_L = interpft(S0L.Sheet1(1:96),100)/2;
GT_LM = GT_RM(end:-1:1,:);

xlswrite('GT_R_truth.xlsx', interpft(S0R.Sheet1(1:96),100));
xlswrite('GT_L_truth.xlsx', GT_RM(end:-1:1,:));

GT_RMM = importdata('GT_R_truth.xlsx');
GT_LMM = importdata('GT_L_truth.xlsx');

GT_R = interpft(GT_RMM.Sheet1(1:96),100);
% GT_L = interpft(S0L.Sheet1(1:96),100)/2;
GT_L = GT_R(end:-1:1,:);

% Right Leg Subject 1
S_R1 = interpft(S1R.Sheet1(1:100),100);
Max_R_S1 = max(S_R1);
Min_R_S1 = min(S_R1);
[cr1,lagr1] = xcorr(GT_R, S_R1);
[salr1, idxr1] = max(cr1);
delayr1 = lagr1(idxr1);
S1_Newr1 = circshift(S_R1, delayr1);

% Left Leg Subject 1
S_L1 = interpft(S1L.Sheet1(1:100),100);
Max_L_S1 = max(S_L1);
Min_L_S1 = min(S_L1);
[cl1,lagl1] = xcorr(GT_L, S_L1);
[sall1, idxl1] = max(cl1);
delayl1 = lagl1(idxl1);
S1_Newl1 = circshift(S_L1, delayl1);

% Phase KNEE GAIT PARAMETERS of SUBJECT NUMBER 1
% Right knee Variables - k1, k2, k3, k4, k5 and k6
k1R1 = S1_Newr1(1,:); kR1idex = 1; % flexion at heel strike
[k2R1,kR12idex] = max(S1_Newr1(1:50)); % maximum flexion at loading response
[k5R1,kR15idex] = max(S1_Newr1(50:100,:)); % maximum extension in stance
k3R1,kR13idex] = min(S1_Newr1(40:60,:)); % flexion at toe off
Naga Munjulury

Preliminary Study: Bilateral Gait Symmetrical Validation for Different Genders

\[
k_{4R1} = k_{5R1} - 0.1 \cdot k_{5R1}; \quad \text{% maximum flexion in swing phase}
\]

\[
k_{6R1} = S_{1 \text{ Newr1}}(100,:); \quad k_{R16idex} = 100; \quad \text{% total sagittal plane excursion}
\]

\[
\text{Avg\_Swing\_Gait\_R1} = k_{R16idex} - k_{R13idex};
\]

\[
S_{1 \text{ NewL1}} = S_{1 \text{ NewL1}}(end:-1:1,:);
\]

\[
k_{1L1} = S_{1 \text{ NewL1}}(1,:); \quad k_{L11idex} = 1; \quad \text{% flexion at heel strike}
\]

\[
[k_{2L1},k_{L12idex}] = \max(S_{1 \text{ NewL1}}(1:50)); \quad \text{% maximum flexion at loading response}
\]

\[
[k_{5L1},k_{L15idex}] = \max(S_{1 \text{ NewL1}}(50:100,:)); \quad \text{% maximum extension in stance phase}
\]

\[
[k_{3L1},k_{L13idex}] = \min(S_{1 \text{ NewL1}}(40:60,:)); \quad \text{% flexion at toe off}
\]

\[
k_{4L1} = k_{5L1} - 0.1 \cdot k_{5L1}; \quad \text{% maximum flexion in swing phase}
\]

\[
k_{6L1} = S_{1 \text{ NewL1}}(100,:); \quad k_{L16idex} = 100; \quad \text{% total sagittal plane excursion}
\]

\[
\text{Avg\_Swing\_Gait\_L1} = k_{L16idex} - k_{L13idex};
\]

\[
\text{------------- Subject 1 done ---------------------------}
\]

\[
\text{Similarly, for all other 9 subjects}
\]

\[
\text{------------- Subject No 10 done ---------------------------}
\]

\[
S_{GT\_R} = (GT\_R);
\]

\[
S_{GT\_L} = (GT\_L);
\]

\[
\text{------------- KNEE GAIT PARAMETERS SUBJECT NUMBER GT} \text{---------------------------}
\]

\[
k_{1GTR} = S_{\text{GT\_R}}(1,:); \quad k_{GTR1idex} = 1; \quad \text{% flexion at heel strike}
\]

\[
[k_{2GTR},k_{GTR2idex}] = \max(S_{\text{GT\_R}}(1:50)); \quad \text{% maximum flexion at loading response}
\]

\[
[k_{5GTR},k_{GTR5idex}] = \max(S_{\text{GT\_R}}); \quad \text{% maximum extension in stance phase}
\]

\[
[k_{3GTR},k_{GTR3idex}] = \min(S_{\text{GT\_R}}); \quad \text{% flexion at toe off}
\]

\[
k_{4GTR} = k_{5GTR} - 0.1 \cdot k_{5GTR}; \quad \text{% maximum flexion in swing phase}
\]

\[
k_{6GTR} = S_{\text{GT\_R}}(100,:); \quad k_{GTR6idex} = 100; \quad \text{% total sagittal plane excursion}
\]

\[
\text{Avg\_Swing\_Gait\_GTR} = k_{GTR6idex} - k_{GTR3idex};
\]

\[
S_{1 \text{ NewGTL}} = S_{\text{GT\_L}}(end:-1:1,:);
\]

\[
k_{1GTL} = S_{1 \text{ NewGTL}}(1,:); \quad k_{GTL1idex} = 1; \quad \text{% flexion at heel strike}
\]

\[
[k_{2GTL},k_{GTL2idex}] = \max(S_{1 \text{ NewGTL}}); \quad \text{% maximum flexion at loading response}
\]

\[
[k_{5GTL},k_{GTL5idex}] = \max(S_{1 \text{ NewGTL}}(60:100,:)); \quad \text{% maximum extension in stance phase}
\]

\[
[k_{3GTL},k_{GTL3idex}] = \min(S_{1 \text{ NewGTL}}); \quad \text{% flexion at toe off}
\]

\[
k_{4GTL} = k_{5GTL} - 0.1 \cdot k_{5GTL}; \quad \text{% maximum flexion in swing phase}
\]

\[
% [k_{4GTL},k_{GTL4idex}] = k_{GTL6};
\]

\[
k_{6GTL} = S_{1 \text{ NewGTL}}(100,:); \quad k_{GTL6idex} = 100; \quad \text{% total sagittal plane excursion}
\]

\[
\text{Avg\_Swing\_Gait\_GTL} = k_{GTL6idex} - k_{GTL3idex};
\]

\[
\text{------------- Subject No GT done ---------------------------}\]

\[
k_{1R1idex} = 1; \quad k_{1R2idex} = 1; \quad k_{1R3idex} = 1; \quad k_{1R4idex} = 1; \quad k_{1R5idex} = 1;
\]

\[
k_{1R6idex} = 1; \quad k_{1R7idex} = 1; \quad k_{1R8idex} = 1; \quad k_{1R9idex} = 1; \quad k_{1R10idex} = 1;
\]

\[
\text{ALL\_KR3\_index} = \{k_{1R13idex}, k_{2R13idex}, k_{3R13idex}, k_{4R13idex}, k_{5R13idex}, k_{6R13idex}, k_{7R13idex}, k_{8R13idex}, k_{9R13idex}, k_{10R13idex}, k_{GTR3idex}\};
\]

\[
\text{ALL\_KL3\_index} = \{k_{1L13idex}, k_{2L13idex}, k_{3L13idex}, k_{4L13idex}, k_{5L13idex}, k_{6L13idex}, k_{7L13idex}, k_{8L13idex}, k_{9L13idex}, k_{10L13idex}, k_{GTL3idex}\}';
\]

A10
ALL_KR2_index =
[kR12idex, kR22idex, kR32idex, kR42idex, kR52idex, kR62idex, kR72idex, kR82idex, kR92idex, kR102idex, kGTR2idex ];

ALL_KL2_index =
[kL12idex, kL22idex, kL32idex, kL42idex, kL52idex, kL62idex, kL72idex, kL82idex, kL92idex, kL102idex, kGTL2idex ];

ALL_KR5_index =
[kR15idex, kR25idex, kR35idex, kR45idex, kR55idex, kR65idex, kR75idex, kR85idex, kR95idex, kR105idex, kGTR5idex ];

ALL_KL5_index =
[kL15idex, kL25idex, kL35idex, kL45idex, kL55idex, kL65idex, kL75idex, kL85idex, kL95idex, kL105idex, kGTL5idex ];

ALL_KR6_index =
[kR16idex, kR26idex, kR36idex, kR46idex, kR56idex, kR66idex, kR76idex, kR86idex, kR96idex, kR106idex, kGTR6idex ];

ALL_KL6_index =
[kL16idex, kL26idex, kL36idex, kL46idex, kL56idex, kL66idex, kL76idex, kL86idex, kL96idex, kL106idex, kGTL6idex ];

ALL_R_INDEXs = [ALL_KR2_index, ALL_KR3_index, ALL_KR5_index, ALL_KR6_index];

ALL_L_INDEXs = [ALL_KL2_index, ALL_KL3_index, ALL_KL5_index, ALL_KL6_index];

ALL_GTR_INDEXs = [kGTR1idex, kGTR2idex, kGTR3idex, kGTR5idex, kGTR6idex];

ALL_GTL_INDEXs = [kGTL1idex, kGTL2idex, kGTL3idex, kGTL5idex, kGTL6idex];

%%%%%%%%%% K1 to K6 KNEE GAIT PHASE PARAMETERS %%%%%%%

%%% ALL Maximum ROM and Minimum range of motion

k1_R = [k1R1, k1R2, k1R3, k1R4, k1R5, k1R6, k1R7, k1R8, k1R9, k1R10, k1GTR];
k2_R = [k2R1, k2R2, k2R3, k2R4, k2R5, k2R6, k2R7, k2R8, k2R9, k2R10, k2GTR];
k3_R = [k3R1, k3R2, k3R3, k3R4, k3R5, k3R6, k3R7, k3R8, k3R9, k3R10, k3GTR];
k4_R = [k4R1, k4R2, k4R3, k4R4, k4R5, k4R6, k4R7, k4R8, k4R9, k4R10, k4GTR];
k5_R = [k5R1, k5R2, k5R3, k5R4, k5R5, k5R6, k5R7, k5R8, k5R9, k5R10, k5GTR];
k6_R = [k6R1, k6R2, k6R3, k6R4, k6R5, k6R6, k6R7, k6R8, k6R9, k6R10, k6GTR];

k1_L = [k1L1, k1L2, k1L3, k1L4, k1L5, k1L6, k1L7, k1L8, k1L9, k1L10, k1GTL];
k2_L = [k2L1, k2L2, k2L3, k2L4, k2L5, k2L6, k2L7, k2L8, k2L9, k2L10, k2GTL];
k3_L = [k3L1, k3L2, k3L3, k3L4, k3L5, k3L6, k3L7, k3L8, k3L9, k3L10, k3GTL];
k4_L = [k4L1, k4L2, k4L3, k4L4, k4L5, k4L6, k4L7, k4L8, k4L9, k4L10, k4GTL];
k5_L = [k5L1, k5L2, k5L3, k5L4, k5L5, k5L6, k5L7, k5L8, k5L9, k5L10, k5GTL];
k6_L = [k6L1, k6L2, k6L3, k6L4, k6L5, k6L6, k6L7, k6L8, k6L9, k6L10, k6GTL];

xlswrite('Right KNEE variables.xlsx', [k1_R k2_R k3_R k4_R k5_R k6_R]);
xlswrite('Left KNEE variables.xlsx',[k1_L k2_L k3_L k4_L k5_L k6_L]);

%%% Bilateral Gait Symmetry of the knee joint angle variables
K_var_R = xlsread('Right KNEE variables.xlsx');
K_var_L = xlsread('Left KNEE variables.xlsx');
GS_K_var = K_var_R./K_var_L;
figure;
plot(GS_K_var,'--','LineWidth',2);
title({'Bilateral Gait Symmetry - more than 1 - abnormal'},'FontSize', 24);
grid on
xlabel({'Number of Participants'},'FontSize', 24);
ylabel({'Knee variables - abnormality'},'FontSize', 24);
hold off
legend({'k1','k2','k3','k4','k5','k6'},'FontSize', 24);

figure;set(gca,'FontSize',24); set(gca,'FontName','Times');
subplot(2,1,1)
title({'Right and Left KNEE GAIT PHASES GTs'},'FontSize', 24);
plot(k1_R,'--','LineWidth',2)
hold on
grid on
plot(k2_R,'--','LineWidth',2)
plot(k3_R,'--','LineWidth',2)
plot(k4_R,'--','LineWidth',2)
plot(k5_R,'--','LineWidth',2)
plot(k6_R,'--','LineWidth',2)
grid on
xlabel({'Number of Participants'},'FontSize', 24);
ylabel({'Right Range of k s'},'FontSize', 24);
hold off
legend({'k1','k2','k3','k4','k5','k6'},'FontSize', 24);

subplot(2,1,2)
legend({'Maximum Flexion Left', 'Minumum Flexion Left'},'FontSize', 24);

Knee_Var_R = [k1_R k2_R k3_R k4_R k5_R k6_R];
Knee_Var_L = [k1_L k2_L k3_L k4_L k5_L k6_L];
%% % right and left knee joints combined %%%%%%%%%%%%%%%%%%

%% ALL Maximum ROM and Minimum range of motion
Max_GTR = max(GT_R.*1.5);
Min_GTR = min(GT_R.*1.5);
Max_GTG = max(GT_L.*1.5);
Min_GTG = min(GT_L.*1.5);

Maxx_R = [Max_R_S1, Max_R_S2, Max_R_S3, Max_R_S4, Max_R_S5, Max_R_S6,
Max_R_S7, Max_R_S8, Max_R_S9, Max_R_S10, Max_GTR];
Minn_R = [Min_R_S1, Min_R_S2, Min_R_S3, Min_R_S4, Min_R_S5, Min_R_S6,
Min_R_S7, Min_R_S8, Min_R_S9, Min_R_S10, Min_GTR];
Maxx_L = [Max_L_S1, Max_L_S2, Max_L_S3, Max_L_S4, Max_L_S5, Max_L_S6,
Max_L_S7, Max_L_S8, Max_L_S9, Max_L_S10, Max_GTG];
Minn_L = [Min_L_S1, Min_L_S2, Min_L_S3, Min_L_S4, Min_L_S5, Min_L_S6,
Min_L_S7, Min_L_S8, Min_L_S9, Min_L_S10, Min_GTG];

figure;set(gca,'FontSize',24); set(gca,'FontName','Times');
set(gcf,'Color',[1,1,1]);mk = ['--*','--o','--*','--*.'];

subplot(2,1,1)
plot(Maxx_R,'--*', 'LineWidth',2)
title({'Right and Left Max and Min flex/ext angles with GTs(black)'}, 'FontSize', 24);
hold on
plot(Minn_R,'--*', 'LineWidth',2)
grid on
xlabel({'Number of Participants'}, 'FontSize', 24)
ylabel({'Right Range of motion'}, 'FontSize', 24)
hold off
legend({'Maximum Flexion Right', 'Minimum Flexion Right'}, 'FontSize', 24);

subplot(2,1,2)
% title({'Left Max and Min flex/ext angles with GTs(black)'}, 'FontSize', 24);
plot(Maxx_L,'--*', 'LineWidth',2)
hold on
plot(Minn_L,'--*', 'LineWidth',2)
grid on
xlabel({'Number of Participants'}, 'FontSize', 24)
ylabel({'Left Range of motion'}, 'FontSize', 24)
hold off
legend({'Maximum Flexion Left', 'Minimum Flexion Left'}, 'FontSize', 24);

%%%% Check for bilateral gait symmetry
% Right swing width
Swing_Width_List_R = [Avg_Swing_Gait_R1, Avg_Swing_Gait_R2,
Avg_Swing_Gait_R3, Avg_Swing_Gait_R4, Avg_Swing_Gait_R5, Avg_Swing_Gait_R6,
Avg_Swing_Gait_R7, Avg_Swing_Gait_R8, Avg_Swing_Gait_R9, Avg_Swing_Gait_R10,
Avg_Swing_Gait_GTR];

% Left swing width
Swing_Width_List_L = [Avg_Swing_Gait_L1, Avg_Swing_Gait_L2,
Avg_Swing_Gait_L3, Avg_Swing_Gait_L4, Avg_Swing_Gait_L5, Avg_Swing_Gait_L6,
Avg_Swing_Gait_L7, Avg_Swing_Gait_L8, Avg_Swing_Gait_L9, Avg_Swing_Gait_L10,
Avg_Swing_Gait_GTG];

figure;
% Preliminary Study: Bilateral Gait Symmetrical Validation for Different Genders

Naga Munjulury

plot(Swing_Width_List_R, '--', 'LineWidth', 2)
hold on
plot(Swing_Width_List_L, '--', 'LineWidth', 2)
grid on
xlabel({'Number of Participants'}, 'FontSize', 24)
ylabel({'Average swing width'}, 'FontSize', 24)
hold off
legend({'Swing width Right Knee', 'Swing width Left Knee'}, 'FontSize', 24);

% swing variation by GS = Left_avg / Right_avg
GS1 = Avg_Swing_Gait_R1/ Avg_Swing_Gait_L1;
GS2 = Avg_Swing_Gait_R2/ Avg_Swing_Gait_L2;
GS3 = Avg_Swing_Gait_R3/ Avg_Swing_Gait_L3;
GS4 = Avg_Swing_Gait_R4/ Avg_Swing_Gait_L4;
GS5 = Avg_Swing_Gait_R5/ Avg_Swing_Gait_L5;
GS6 = Avg_Swing_Gait_R6/ Avg_Swing_Gait_L6;
GS7 = Avg_Swing_Gait_R7/ Avg_Swing_Gait_L7;
GS8 = Avg_Swing_Gait_R8/ Avg_Swing_Gait_L8;
GS9 = Avg_Swing_Gait_R9/ Avg_Swing_Gait_L9;
GS10 = Avg_Swing_Gait_R10/ Avg_Swing_Gait_L10;
GSGT = Avg_Swing_Gait_GTR/ Avg_Swing_Gait_GTL;

Total_GS = [GS1, GS2, GS3, GS4, GS5, GS6, GS7, GS8, GS9, GS10, GSGT];

figure;
plot(Total_GS, '--', 'LineWidth', 2)
grid on
xlabel({'Number of Participants'}, 'FontSize', 24)
ylabel({'ALL Swing width - check abnormal'}, 'FontSize', 24)
hold off
legend({'Average Swing width - more than 1 - abnormal'}, 'FontSize', 24);
xlswrite('TOTAL_GS_M.xlsx', Total_GS);

%% right and left knee joints combined

figure;
subplot(2,1,1)
hold on; set(gca, 'FontSize', 16); set(gca, 'FontName', 'Times');
set(gcf, 'Color', [1,1,1]);
m = ['h', 'o', 'x', '^-', '^', '<', 'p', 'h'];
plot(S1_Newr1, [m(1)], 'LineWidth', 3);
plot(S2_Newr2, [m(2)], 'LineWidth', 3);
plot(S3_Newr3, [m(3)], 'LineWidth', 3);
plot(S4_Newr4, [m(4)], 'LineWidth', 3);
plot(S5_Newr5, [m(5)], 'LineWidth', 3);
plot(S6_Newr6, [m(6)], 'LineWidth', 3);
plot(S7_Newr7, [m(7)], 'LineWidth', 3);
plot(S8_Newr8, [m(8)], 'LineWidth', 3);
plot(S9_Newr9, [m(9)], 'LineWidth', 3);
plot(S10_Newr10, [m(10)], 'LineWidth', 3);
plot(GT_R, 'k', 'LineWidth', 4);
plot3(S0R.Sheet1)
grid on

ylabel({'Right Knee angles'}, 'FontSize', 24)
hold off
subplot(2,1,2)
hold on;hold on; set(gca,'FontSize',16); set(gca,'FontName','Times');
set(gcf,'Color',[1,1,1]);
plot(S1_Newl1,[m(1)],'LineWidth',3);%title('Knee joint angle ');
title('Left Knee joint angles Before normalization');
plot(S2_Newl2,[m(2)],'LineWidth',3);%title('Knee joint angle ');
plot(S3_Newl3,[m(3)],'LineWidth',3);%title('Knee joint angle ');
plot(S4_Newl4,[m(4)],'LineWidth',3);%title('Knee joint angle ');
plot(S5_Newl5,[m(5)],'LineWidth',3);%title('Knee joint angle ');
plot(S6_Newl6,[m(6)],'LineWidth',3);%title('Knee joint angle ');
plot(S7_Newl7,[m(7)],'LineWidth',3);%title('Knee joint angle ');
plot(S8_Newl8,[m(8)],'LineWidth',3);%title('Knee joint angle ');
plot(S9_Newl9,[m(9)],'LineWidth',3);%title('Knee joint angle ');
plot(S10_Newl10,[m(10)],'LineWidth',3);%title('Knee joint angle ');
%plot(GT_L,'k','LineWidth',4);%title('Knee joint angle GT ');
plot(GT_L.*1.5,'k','LineWidth',4);%title('Knee joint angle GT ');
% plot3(S0R.Sheet1)
grid on
xlabel({{'Gait Cycle %'}},'FontSize', 24)
ylabel({'Left Knee angles'}(),'FontSize', 24)
hold off

legend('Normal Weight', 'Over Weight', 'Normal Weight', 'Obese Class 1', 'Over Weight', 'Normal Weight', 'Normal Weight', 'Extremely Under Weight', 'Normal Weight', 'Ground Truth');

%%%% Normalization

Male_R_N1 = S1_Newr1(:,1)./0.49;(;,1) - to access all its elements on the first column
Male_R_N2 = S2_Newr2(:,1)./0.56;
Male_R_N3 = S3_Newr3(:,1)./0.54;
Male_R_N4 = S4_Newr4(:,1)./0.43;
Male_R_N5 = S5_Newr5(:,1)./0.53;
Male_R_N6 = S6_Newr6(:,1)./0.55;
Male_R_N7 = S7_Newr7(:,1)./0.53;
Male_R_N8 = S8_Newr8(:,1)./0.55;
Male_R_N9 = S9_Newr9(:,1)./0.52;
Male_R_N10 = S10_Newr10(:,1)./0.43;

Male_L_N1 = S1_Newl1(:,1)./0.45;
Male_L_N2 = S2_Newl2(:,1)./0.55;
Male_L_N3 = S3_Newl3(:,1)./0.53;
Male_L_N4 = S4_Newl4(:,1)./0.43;
Male_L_N5 = S5_Newl5(:,1)./0.59;
Male_L_N6 = S6_Newl6(:,1)./0.52;
Male_L_N7 = S7_Newl7(:,1)./0.54;
Male_L_N8 = S8_Newl8(:,1)./0.53;
Male_L_N9 = S9_Newl9(:,1)./0.56;
Male_L_N10 = S10_Newl10(:,1)./0.47;

figure;
subplot(2,1,1)
hold on;hold on; set(gca,'FontSize',16); set(gca,'FontName','Times');
set(gcf,'Color',[1,1,1]);
title('Right Knee joint angles After normalization');
plot(Male_R_N1);%
Similar comparison script for female Subjects data too.
Appendix B: Hardware and software

Figures of the application program interface output acquisition from xsens motion trackers []

1. Xsens Hardware

Motion Trackers

Wireless receiver dongle and body straps:
2. Xsens software

MT Manager – application program interface

Software Installation- Automatic COM Port Scanning
Wireless connection with Awinda USB dongle

MT settings: dialog box

Wireless Network setup in MT Manager: dialog box
Output: ASCII Exporter
MT setting for the motion tracker: filter settings
## Appendix C: Stats of the participants

Table C1: Male Subjects Gait and kinematic parameters

<table>
<thead>
<tr>
<th>Subject no:</th>
<th>AGE</th>
<th>BMI Type</th>
<th>Cadence (steps/min) Right,Left</th>
<th>Knee Flex/Ext Mean Values max and min (Degrees)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>39.7</td>
<td>N</td>
<td>95.5, 100.2</td>
<td>R_Max: 36.78, R_Min: 3.42, L_Max: 37.82, L_Min: 14.56</td>
<td>Recent Accident</td>
</tr>
<tr>
<td>3</td>
<td>22.58</td>
<td>N</td>
<td>123.6, 133.8</td>
<td>R_Max: 36.03, R_Min: 4.15, L_Max: 30.60, L_Min: 1.53</td>
<td>Excess Left leg stride but less angle</td>
</tr>
<tr>
<td>4</td>
<td>23</td>
<td>O1</td>
<td>136.2, 126.6</td>
<td>R_Max: 32.12, R_Min: 5.82, L_Max: 25.32, L_Min: 2.10</td>
<td>Over weight Obese class1</td>
</tr>
<tr>
<td>5</td>
<td>30</td>
<td>O</td>
<td>121.9, 135.34</td>
<td>R_Max: 30.21, R_Min: 3.94, L_Max: 30.38, L_Min: 3.44</td>
<td>Left ankle fracture and total ankle replacement</td>
</tr>
<tr>
<td>6</td>
<td>24.33</td>
<td>N</td>
<td>119.7, 121.8</td>
<td>R_Max: 27.53, R_Min: 3.20, L_Max: 29.60, L_Min: 8.83</td>
<td>More slow gait, basketball player</td>
</tr>
<tr>
<td>7</td>
<td>21.33</td>
<td>N</td>
<td>107.4, 128.4</td>
<td>R_Max: 32.47, R_Min: 3.64, L_Max: 32.26, L_Min: 3.37</td>
<td>Excess Left leg stride</td>
</tr>
<tr>
<td>8</td>
<td>23.75</td>
<td>N</td>
<td>132.35, 141.26</td>
<td>R_Max: 30.15, R_Min: 4.27, L_Max: 28.16, L_Min: 9.45</td>
<td>Right Handed and little stiffness while swinging with left leg</td>
</tr>
<tr>
<td>9</td>
<td>21.75</td>
<td>EUW</td>
<td>141.09, 154.47</td>
<td>R_Max: 31.5, R_Min: 4.66, L_Max: 30.20, L_Min: 4.23</td>
<td>Fatigue, and left side hip chronic pain previously</td>
</tr>
<tr>
<td>10</td>
<td>33.46</td>
<td>N</td>
<td>116.4, 126</td>
<td>R_Max: 28.35, R_Min: 2.86, L_Max: 32.65, L_Min: 2.36</td>
<td>Left knee patella crack sound</td>
</tr>
</tbody>
</table>

Where,
- EXW – Extremely Underweight,
- N – Normal Weight,
- O – Over Weight and O1 – Over weight obese class 1

Note: Comments shows the information of subject’s disabilities that were collected after the gait assessment.
<table>
<thead>
<tr>
<th>Subject no:</th>
<th>AGE</th>
<th>BMI</th>
<th>Cadence (steps/min)</th>
<th>R.Min</th>
<th>R.Max</th>
<th>L.Min</th>
<th>L.Max</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>32.9</td>
<td>O</td>
<td>95.5, 100.2</td>
<td>2.83</td>
<td>28.42</td>
<td>6.20</td>
<td>23.59</td>
<td>No Injury</td>
</tr>
<tr>
<td>2</td>
<td>23.6</td>
<td>O</td>
<td>119.7, 119.7</td>
<td>5.84</td>
<td>28.11</td>
<td>11.22</td>
<td>33.16</td>
<td>Left Knee Physiotherapy</td>
</tr>
<tr>
<td>3</td>
<td>37.8</td>
<td>N</td>
<td>123.6, 133.8</td>
<td>6.93</td>
<td>35.63</td>
<td>14.59</td>
<td>37.02</td>
<td>Left Patella crack snd</td>
</tr>
<tr>
<td>4</td>
<td>23.6</td>
<td>N</td>
<td>136.2, 126.6</td>
<td>3.96</td>
<td>34.6</td>
<td>1.98</td>
<td>29.37</td>
<td>New Immigrant</td>
</tr>
<tr>
<td>5</td>
<td>49.4</td>
<td>N</td>
<td>121.9, 135.34</td>
<td>7.47</td>
<td>32.84</td>
<td>5</td>
<td>29.15</td>
<td>Excess Left leg stride but less angle</td>
</tr>
<tr>
<td>6</td>
<td>38.3</td>
<td>N</td>
<td>119.7, 121.8</td>
<td>3.38</td>
<td>32.38</td>
<td>6.02</td>
<td>25.10</td>
<td>Hip prob, ballet dancer</td>
</tr>
<tr>
<td>7</td>
<td>25.2</td>
<td>N</td>
<td>107.4, 128.4</td>
<td>6.58</td>
<td>31.79</td>
<td>9.51</td>
<td>28.08</td>
<td>Left Knee stiffness</td>
</tr>
<tr>
<td>8</td>
<td>34.6</td>
<td>N</td>
<td>132.35, 141.26</td>
<td>1.15</td>
<td>27.25</td>
<td>3.10</td>
<td>26.04</td>
<td>Right back calf muscle raptured</td>
</tr>
<tr>
<td>9</td>
<td>53</td>
<td>N</td>
<td>141.09, 154.47</td>
<td>4.87</td>
<td>30.04</td>
<td>5.57</td>
<td>20.75</td>
<td>Left pat stiffness</td>
</tr>
<tr>
<td>10</td>
<td>36.3</td>
<td>N</td>
<td>116.4, 126</td>
<td>4.97</td>
<td>26.3</td>
<td>6.5</td>
<td>27.27</td>
<td>Ballet Dancer abduct flex</td>
</tr>
</tbody>
</table>

Where,
- \( R_{\text{min}} \) – Minimum right knee ROM ; \( R_{\text{max}} \) – Maximum right knee ROM
- \( L_{\text{min}} \) – Minimum right knee ROM ; \( L_{\text{max}} \) – Maximum right knee ROM

Note: Comments shows the information of subject’s disabilities that were collected after the gait assessment.
Appendix D: Excel ToolPak Data analysis tool results

Data selection for regression analysis: dialog box

Example: Regression analysis results of relation between right and left gait speeds of an individual

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
<th>K</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject NO.</td>
<td>Age (yrs)</td>
<td>Height (cm)</td>
<td>Weight (kg)</td>
<td>BMI</td>
<td>Sex</td>
<td>Shoe size</td>
<td>Gait Speed (cm/s)</td>
<td>Gait Speed (cm/s)</td>
<td>Tread Height (cm)</td>
<td>Stride Length (cm)</td>
<td>Stride Length (cm)</td>
</tr>
<tr>
<td>1</td>
<td>20</td>
<td>180</td>
<td>70</td>
<td>25</td>
<td>Male</td>
<td>12</td>
<td>0.73</td>
<td>0.177</td>
<td>4.131</td>
<td>0.003291794</td>
<td>0.322389873</td>
</tr>
<tr>
<td>2</td>
<td>21</td>
<td>175</td>
<td>65</td>
<td>22</td>
<td>Female</td>
<td>10</td>
<td>0.70</td>
<td>0.147</td>
<td>3.960</td>
<td>0.002964828</td>
<td>0.322389873</td>
</tr>
<tr>
<td>3</td>
<td>22</td>
<td>182</td>
<td>80</td>
<td>27</td>
<td>Male</td>
<td>11</td>
<td>0.73</td>
<td>0.136</td>
<td>4.030</td>
<td>0.003291794</td>
<td>0.322389873</td>
</tr>
</tbody>
</table>

Regression Statistics

- Multiple R: 0.825
- R Square: 0.681
- Adjusted R Square: 0.641
- Standard Error: 7.865
- Observations: 10

ANOVA

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>Significance F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>1</td>
<td>1055</td>
<td>1055</td>
<td>17.06503446</td>
<td>0.003291794 p &lt; 0.005</td>
</tr>
<tr>
<td>Residual</td>
<td>9</td>
<td>494.9</td>
<td>61.66</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Regression: 0.825, R = 0.825. The data is strongly positively correlated or positive relationship.

Significantly positive relationship between right and left gait speeds.
Regression using scatter plot (Line of Best fit)