GAIT ANALYSIS & BIOMECHANICAL MODELLING

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STATEMENT OF CANDIDATE

I, Bradley Beck, declare that this report, submitted as part of the requirement for the award of Bachelor of Engineering in the Department of Mechatronic Engineering, Macquarie University, is entirely my own work unless otherwise referenced or acknowledged. This document has not been submitted for qualification or assessment an any academic institution.

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ABSTRACT

To help improve knee replacements or understanding of knee injuries, gait analysis of human locomotion can be performed to identify kinematics and dynamics of the specific joint. Specific trials are performed on the subjects to determine how the knee handles the tasks of walking on flat ground and climbing up or down stairs. A marker set must be used as a non-invasive method to model the internal motions. This project aims to compare multiple different marker sets to find the most accurate and reliable method for computer modelling. The project has shown consistent improvement in the use of a 24 marker set over the standard modified Helen-Hayes 16 marker set. Inter-trial tests of subjects from two age groups was shown to decrease standard deviation between trials, implying a more reliable marker set for tracing the skeleton gait.

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Chapter 1

Introduction

The study of human locomotion is beneficial to many medical fields, from patient rehabilitation to lower limb prosthetic design and implementation. Human gait can be separated into two separate parts: stance phase and swing phase. When analysing gait only one leg will be focused on at a time and the phase will be determined by where that leg is within the gait cycle. The stance phase begins at "heel strike", where ground reaction forces are applied to the leg. This phase lasts until the "toe-off" of the same leg, where afterwards there will be no external forces on the extremity. The stance phase typically lasts approximately 60% of a full gait cycle. At the point where stance phase ends, swing phase begins and will continue while the leg is in the air. This will finish when the heel lands back on the ground and a full gait cycle is completed, repeating from the beginning of the stance phase. A diagram of the full gait cycle can be seen in Figure 1.1. For a full gait cycle to be recorded heel strike to heel strike, the minimum amount of force plates necessary is two.

By using ever-increasing technology to measure human gait, a more accurate result can

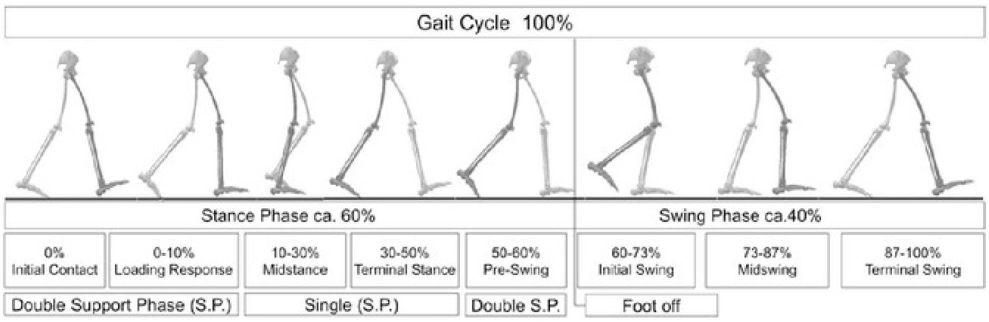

Figure 1.1: *Diagram of a full gait cycle for the right leg [1]*

be collected and used to improve our understanding. However, since walking is controlled by the internal musculoskeletal system it is difficult to accurately monitor during motion. There are multiple methods for gait analysis (GA) to be performed, all of which have their positive and negative aspects. This paper will focus on using a three-dimensional motion capture setup for data collection to create a computer model of the subject. This chapter will give a brief introduction to the technology and equipment used within the project, as well as an overview of current goals and final objectives.

1.1 Motion Capture Gait Analysis

One of the most common methods for gait data collection is to use external reflective markers to represent the underlying bone structures. Each marker is attached to the subject at points manually identified by one of the gait laboratory faculty using double sided wig tape designed for human skin adhesion. To track these markers in the capture zone multiple special intra-red (IR) emitting cameras are set up to view a pre-determined 3D space.
These cameras will only pick up the IR reflections from the markers, making them the predominant display. The display is rendered in the program Vicon Nexus which also shows camera positions. Data processing is required from this stage in the operation which will bring possible errors in data analysis. The primary goal of this project is to compare the motion capture results of subjects to one another as well as themselves using different marker sets for varying results from data collection. The effect of age is also examined as a key point for future studies. The project can be broken into two separate focuses: the data collection stage which occurs in the gait laboratory, and the data processing stage, which occurs after and involves multiple steps through multiple programs to get out a meaningful set of data from each subject trial. The secondary goal was to reduce the amount of time the data processing required, as well as improving the reliability of the output data. This problem was approached by creating multiple scripts and codes, primarily in MatLab 2014b, to help batch process and organise data.

The main issues involved within the data collection stage are linked to the accuracy at which the human skeleton can be measured. The external market set method is a non-invasive technique which cause accuracy errors due to tissue, skin, and fat artefact between the marker and the underlying bone structure making it more difficult to represent the true skeletal structure. Many of the markers are used to estimate joint centres and bone proportions, which becomes less accurate when each marker is not a fixed distance from one another when attached on one segment (or rigid body part). Even small variations from the skin artefact stretching and contracting will result in a joint centre moving and will adversely affect kinematics and dynamics. Joint kinematics are a measurement of the angles that each joint makes within its own relative coordinate system. Although a joint may in practice have only one degree of freedom (such as a hinge joint), motion in the other directions is an important measurement when considering the health of a subject and their movement patterns. Joint dynamics are a measurement of the moments and forces that occur within each joint, however this project is only concerned about the moments involved. The placement of markers is also going to effect measurements and

should take into consideration the overlaying skin when attaching markers.
By researching marker sets and attempting to optimise this aspect of data collection, this project plans to increase the reliability and accuracy of subject data collected at the Macquarie University gait laboratory. A marker set is any arrangement of the reflective markers placed on the subject to record their motion. The most prominent way of determining the value of any changes made will come from the standard deviation between tests due to not being able to get an exact measurement from the tests. Results will be compared to existing literature to give validity to produced results, however inter- and intra-test comparisons will be the main focus of analysis to try to reach a highly repeatable result with little variation between trials.

1.2 Project Overview

The project as a whole can be broken into different goals and milestones ranging from streamlining data processing and analysis to the altering the design of the physical system and its components. The goal for the end of the semester is to identify and implement the most effective data collection operation possible for the Macquarie University gait laboratory while analysing the differences in subjects and collection methods. To achieve this, analysis by looking at the effect of the various marker sets used on the subjects must be completed. Identifying the differences and possible improvements between proposed marker sets can be done by comparing collected data from the gait laboratory as well as comparing to published papers which had a similar focus.

Chapter 2 acts to give background information on the technologies used in gait analysis, as well as the existing field of study in the form of a literature review. By identifying limitations of the motion capture GA and expected results from the specific motions used in experimental trials, a higher degree of confidence can be made about the results collected from the Macquarie University (MQU) gait lab. Papers published in journals about the effects of skin artefact, distance between marker and skeleton, expected kinematics and dynamics for specific motions of healthy patients, alternate marker sets, and effects of other motion aspects are all included and can be considered for their relevance in how to determine the most efficient marker placement for knee-focused GA. This project was initiated to help with knee injuries and surgery so all output data will focus on knee kinematics and dynamics despite having data for other joints available.

Chapter 3 expands on the methods of data collection, the equipment used in the gait lab, how data is processed and analysed to reach conclusions, and how these methods of analysis were performed. Details of the subjects involved in completed testing are explained along with the differences between them and the planned subject demographic for future testing.

Chapter 4 displays the results generated from the full process, along with a breakdown of the values into categories that are desired to be investigated for their effects. Results from inverse kinematics (IK) and inverse dynamics (ID) for all subjects can be compared to literature results, as well as themselves when found with alternate marker sets.

Chapter 5 gives the details of the results shown in Chapter 4 with respect to the project as a whole and the conclusions that can be drawn from them. With further explanation of the results provided, conclusions to the project can be made as to what aspects of human gait do effect the knee kinematics and dynamics, as well as whether specific marker sets can be said to be a statistical improvement over others for data collection in the purpose of knee analysis.

Chapter 6 will summarise the final conclusions of the project and, if not implemented, a recommendation of how to proceed in the future to continue moving towards the goal of a high-repeatability data collection method and analysis. Any future plans and further improvements that could be made to the motion capture system as well as the operations will be mentioned and explained in small detail with reasoning of why they will benefit the project.

Chapter 2

Background Information & Theory

2.1 External Marker Placement

Creating a completely new marker set is not a viable approach to improving the generated results. A standard marker set exists throughout the field and is commonly referred to as the "Helen-Hayes" or "Plug-in Gait" marker set [2]. The non-modified lower limb Helen-Hayes can be seen in Figure 2.1. Since this standard identifies many of the necessary skeletal structure landmarks it is able to produce acceptable results in most subjects. However since different studies will be focusing on different aspects of subject gait, a modified marker set is made to increase effective modelling for that specific project. H. Xu et al. notes that the placement of markers can cause up to 75% of failures in measured kinematic parameters due to slight misplacement errors [3]. Making the markers as close to the underlying structure is the best way to minimise these errors, which mean any clothing is going to cause higher uncertainty.

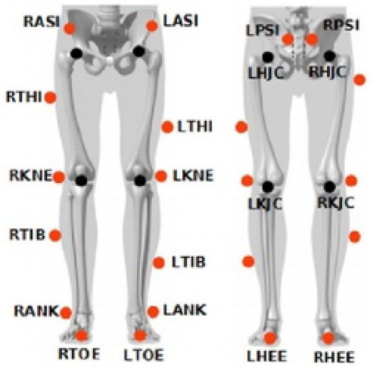

Figure 2.1: *A standard Helen-Hayes marker set diagram for lower limb monitoring. Red circles represent markers while black circles represent the joint centres that will be calculated [4].*

The three kinematics parameters are Flexion/Extension, Adduction/Abduction, and Internal Rotation/External Rotation. Each is a rotation around a different direction of the body's local coordinate system. With respect to the knee, Flexion/Extension is the knee rotating in the Posterior/Anterior direction, respectively. This can be seen as moving along the sagittal plane and gives the highest range of motion for the knee joint. Knee Adduction/Abduction is rotation in the Medial/Lateral direction, moving across the coronal plane. Any angles or motions in this direction may also be labelled as "Varus/Valgus" motion, commonly affiliated with deformities or injuries. Knee Internal/External rotation is the movement along the transverse plane. Due to marker placement limitations, this motion is the most difficult to accurately track with motion capture technology. This error is known as "cross-talk" and most commonly is identified by an increase in measured angles of Adduction/Abduction and Internal/External Rotation [4].

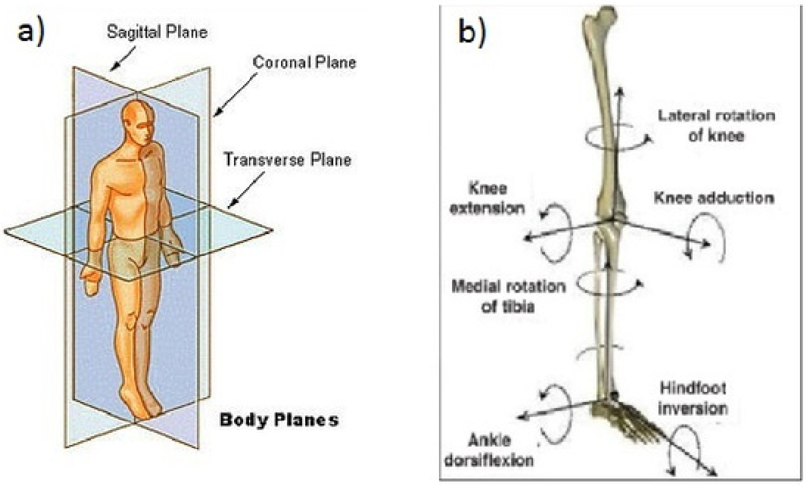

Figure 2.2: *a) A diagram of the anatomical body planes for reference of motion. b) Computer model of a human right knee to show relevant positive directions of rotation [5]*

As well as tracking the skeleton, markers are used to help identify joint centres. Due to the movements while walking, a marker directly on the skin is not always the most effective position. To measure kinematics such as pelvic tilt and knee abduction, a small cluster of markers connected together by rigid material can help show these rotations and calculate joint centres based off them. Clusters on the sacrum were shown to decrease the standard deviation of maximum pelvic tilt between inter-session tests for obese patients and no significant change for other health class subjects [6]. This supports the goal of improving the method for all demographics so clusters should be considered at the knee joint. Knee kinematics are known to vary significantly between subjects [7], with one aspect of this project being to identify the causes of these changes, such as velocity; anthropometric measurements such as height, weight, and leg length; or age.

2.2 Subject Variability

Since there is such a large difference between humans body shapes, a marker set must be as applicable as possible to as many subjects as possible. With differences such as obesity causing markers to be more difficult to accurately place and be a less accurate representation of the skeleton, there are specific methods of data analysis that can be used to reduce the effect of soft tissue artefact on joint centre calculation [8-10]. Additional markers can be added to a marker set at points which would be more easily identified. The pelvic markers for overweight subjects are difficult to locate due to the buildup of fat. However if a different point can be identified and used alongside the Anterior Superior Iliac Spine markers, pelvic kinematics could become a lot more reliable for a larger population of people. A cluster on the sacrum or markers on the iliac crest could help in these cases. Leg Length Discrepancy (LLD) is a fairly common condition which affects gait calculations [11]. Since this difference in leg length will not make bones harder to identify but will affect the results, adding markers will not help with joint centre adjustment and is harder to compensate for. This paper by R. A. Resende et al. used varying shoes to adjust the height of subjects' legs. This may not give an accurate result that would match subjects of actual LLD. Since subjects with the condition will have walked with it their entire lives while the subjects from this experiment will not have adjusted to the change in leg length, the gait behaviour between both groups are likely to be different and result in non-standard gait patterns. Knee and hip flexion angles were larger in subjects with one long limb which is likely due to the amount of energy required to lift a long leg being exerted in the small leg as well. This paper confirms the effect of leg symmetry and exemplifies the importance of leg marker placement being symmetrical (excluding femur and tibia height of markers) to make angles measure accurately in testing.

A marker set designed specifically for overweight subjects due to the excess subcutaneous adipose tissue [22]. By utilising marker clusters and digitized markers, the marker set reduced peak contact forces and kinematics of the lower extremities, including the knee. No significant change was found when used by non-obese subjects when compared to the Helen-Hayes model. This paper shows that marker sets can be designed to accommodate multiple body types and produce an improved kinematic result that can be applied to all subjects.

2.3 Gait Analysis Data Refinement

When analysing the produced data from each trial, a slight variation is expected due to large amount of factors that affect how humans walk. The layout to the Macquarie University gait lab is limited in space and requires the subject to walk in a straight line, where the end of the capture zone is a door which cannot be opened. Although the subject can turn slightly near the end to avoid waling into these obstacles (as well as a camera tripod), the end of the room is likely to have a psychological effect and make them slow their walking speed or redirect their walking, which will have an effect on the kinematics of the knee. This problem can be fixed by the administration of the MQU simulation hub

but is hindered due to the bureaucratic nature. The walking velocity will cause changes in knee moments [12] and may cause differences in data between trials as the subject adapts to their stopping method. Specific subject traits will differ themselves and their results from other subjects. Body mass of a subject will have a direct effect on the ground reaction forces produced during locomotion and must be considered when processing the dynamics of each subject. The data is normalised by dividing all moments by body mass, producing a much more consistent range of values.
This technique is common in many papers for lower limb dynamics [13] and should ideally be performed before signal filtering. Due to fluctuations in collected data, a signal filter is recommended to remove any noise that is recorded within the force plates or marker capture data. A low-pass filter is generally used to remove experimental noise, however there are many different types. Butterworth filters are commonly used, but the parameters of order and cutoff frequency will be dependent on the experimental equipment and desired output.

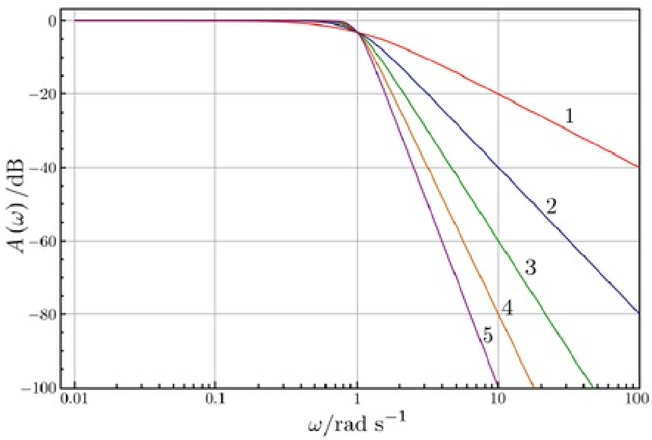

Figure 2.3: *Plot of a low-pass Butterworth filter with a cutoff frequency of $\omega_0 = 1$ and multiple orders to show the effect on signal gain*

As shown above, as the order of the filter increases, the filter will remove noise that is closer to the cutoff frequency and becomes closer to an ideal low-pass filter. Selecting the cutoff frequency will be dependent on the hardware used in collection. For a high-frequency collection, the resulting graph should show a smooth change in values over time and will make any noise or spikes apparent. With this, a lower cutoff frequency can be used to retain the original function's path without filtering unnecessary frequencies.

Chapter 3

Experimental Procedures

3.1 Data Collection

The experiment requires data from multiple human subjects that have agreed to participate in the study. As this thesis is a project to lead up to the study of Total Knee Arthroplasty, ideal subjects are within the age range of 45-75 years. The data collected in the future will primarily be collected for and relevant to that demographic. However this report was focusing more on the setting up of the system for this later clinical use. The subjects used in this report consisted mainly of the undergraduate students involved in the project as well as two older subjects who agreed to help. These subjects were used for ease of scheduling and general practice with the equipment. There were four undergraduate subjects which had an average age of 21 years, while the three older subjects had an average age of 53.3 years. These two groups can be separated into alternate categories for finding any noticeable difference within walking patterns, or more accurately, the resulting measurements. The height range between all subjects ranged from 1.56-1.85 meters with a bodyweight range of 55.0-90.1 kilograms. Out of the 7 subjects, 6 were male while only one was female.

Subjects were instructed to perform everyday motions of walking at a self-selected speed along a flat surface with three KISTLER force plates embedded within the ground. The subjects would walk for around 6 meters before reaching the capture zone and force plates. Once the subjects had a consistent stride they would reach the force plates to continue this motion for another 3 meters. This test was repeated at minimum ten times to be able to get enough data for analysis. Subjects were also instructed to walk up a two-step block with a force plate inserted into a frame to act as the second step. With the step block positioned to have the ground force plates lead up to it, the patient was instructed to walk up the steps beginning with a specific foot. This was repeated ten times and then another ten for the alternate foot. A similar test was repeated for stair descent to gain another twenty subject motion recordings. Each trial captured two physical measurements simultaneously. The cameras recorded the global coordinates of each marker in space with a capture rate of 250Hz. The force plates recorded the ground reaction forces of the subjects as they passed over them during the trials with each one recording at a capture rate of 1kHz. With a total of 50 trials, the 3D capture files must be processed to reduce any errors that occurred during the experiment. All these trials were recorded on the program Vicon Nexus, which creates a computer model of the 3D space captured by the cameras. Due to the nature of the technology, the setup of the gait laboratory, and the movements involved in locomotion, marker drop-out is expected and can be remedied within the program once recording is finished and all markers are appropriately labelled.

A side-goal of this project is to find an optimal camera placement within the limited space available in the Macquarie University gait laboratory that reduces marker dropout. If the doors are opened to increase both walking and camera space, the end of the capture zone can be expanded and given a greater field of view, which would likely decrease marker dropout rate in the top-left corner of the capture zone in Figure 3.1 (left). Cameras were kept at a consistent height during trials, but have changed in between subjects during calibration. Cameras can have alternate heights to one another as this will give different angles to their field of view. Since only lower body analysis is being performed, many cameras are viewing the floor. If cameras could be spread out further by opening the door, this would increase the amount of cameras that could see a specific point in space. This is beneficial to reducing marker dropout as it is required that three cameras be able to see a marker at any given time to appear in Vicon.

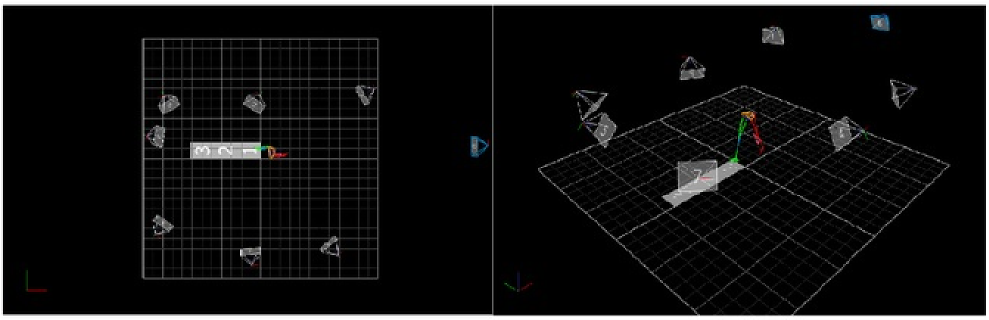

Figure 3.1: *The capture zone viewed from within Vicon Nexus showing camera and force plate positions. The left picture is shown looking along the -Z axis while the right picture is shown from a self-selected perspective.*

During the process of data collection it is important to actively monitor the subject and where their feet land. To get a complete gait cycle recording, the subject must hit all three consecutive force plates, but will not know where these plates are. Each step must be contained completely on the respective force plate or the readings will not be accurate. There is no way of reducing these errors without directing the subject to where to step, which may cause changes in their walking stride and will not represent their every-day walking behaviours. To combat these issues, the minimum ten trials are taken for an excess amount of data. As only approximately six trials are necessary for calculating a respectable average, the four extra are included in case of mistakes being found during data processing.

OpenSim allows for markers to have a weighting applied to each marker to represent how reliable they are. This means specific markers can be set to have a weighting of zero which will essentially remove it from any calculations. By creating a new marker set where all markers were also part of the one used at the gait laboratory, a subset of markers can be used as a new marker set. There are standard marker sets used throughout the community while many people choose to create their own by modifying an existing standard to better suit their needs. The marker set used in experiments was a modified lower-limb Helen Hayes [2] set, where additional markers had been attached to the iliac crest, the front thigh (the quadriceps area), the fibula head, and the front tibula ridge (shin) on both sides of the body. Each marker was at the same height as its counterpart and all additional markers were symmetrical on the sagittal plane.

By using a subset of the 24 marker set and removing the weighting of undesired markers, the same trials can be used twice, with the different marker sets applied. This halves the amount of trials that the subjects had to perform, as well as gives a better comparison of trials since they will be the exact same motion. Any differences between the two in terms of accuracy, reliability, ease-of-use, and consistency cannot be linked to the subject moving differently during the experiment since it is a recording of the exact same motion.

3.2 Data Processing & MatLab Scripts

Vicon Nexus exports two types of files that are used in the further processing steps. A TRC file and a CSV file are exported for each trial (where a trial is one recording of a specific motion) to represent the time-space coordinates of each marker and the force plate readings of ground reaction forces, respectively. These two files run through multiple steps to eventually return the calculated joint angles and joint moments. A flowchart of the generic methodology from file creation to the inverse dynamics of a subject trial through OpenSim can be seen in Figure 3.2

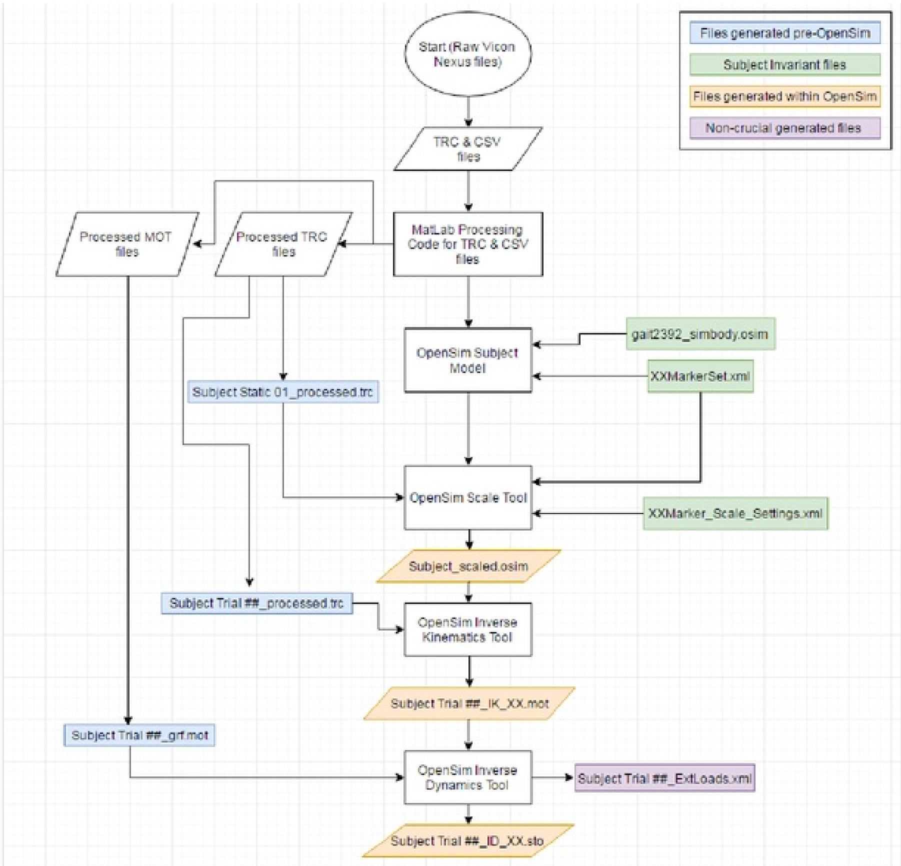

Figure 3.2: *A flowchart of the basic order and file inputs and outputs to reach the kinematics and dynamics of the subject trials*

The format of the files exported from Vicon do not match the requirements OpenSim has, so MatLab script was written to perform transformations and selections on these files to fit OpenSim. The file that records marker position in space with respect to time is the TRC file, which requires each marker to be labelled the same as the OpenSim virtual marker sets (which have also been custom made). The MatLab code relabels the TRC markers, as well as selects a specified time range that contains all markers being visible. This code can be seen in Appendix A.1 and is referenced within the flowchart in Figure 3.2 as the "MatLab Processing Code for TRC files".

The ground reaction force file that is required in OpenSim must be constructed from the force plate data that is stored within the CSV file. Mathematical operations must be applied to the data to transform all measurements into standard units and desired directions, as well as rearrange the data into the expected order. The file conversion also changes the file type from a Comma Separated Value (CSV) file to a motion (MOT) file, that OpenSim can read. The respective code is found in Appendix A.2 and is referenced in Figure 3.2 as "MatLab Processing Code for CSV files", at the same point in the process as the TRC conversion (although are separate scripts and must be run separately).
Once these processed files have been created and a scaled body has been made within OpenSim, the calculations for IK and ID can be performed in the program called OpenSim. There are multiple steps in the procedure which must be applied to each trial in which the kinematics and dynamics are desired. This was a very time consuming process so another MatLab script was written to increase speed of processing, as well as reduce the amount of places a human error could occur. The code can be found in Appendix A.3 and fulfils the role of the two processes in the flowchart "OpenSim Inverse Kinematics Tool" and "OpenSim Inverse Dynamics Tool". The MatLab code requires manual input of subject scaled model, the marker set used, and type of trial. The type of trial is defined by what motion is being carried out and which leg is the "dominant leg" that determines where the gait cycle is measured from. This means that the code is limited to batch processing only one type of trial per subject at a time, however it is still much faster and more reliable. All the created TRC and MOT files must be placed in a specified folder, where both tools will be performed automatically on all trials within the folder.
Once ten trials of the same type have completed both IK and ID, there will be corresponding MOT and STO files with the kinematics data and dynamics data of all the lower body joints. These files can have the desired values (such as knee flexion moment) selected and re-printed within another file for comparison to other trials of the same session to identify the expected pattern during one gait cycle, find the average and identify any outlier tests. Currently, the way to compare trials to one another is to manually select the time ranges that correspond to one full gait cycle occurring on the force plates, and add the desired measurements into a separate excel spreadsheet.

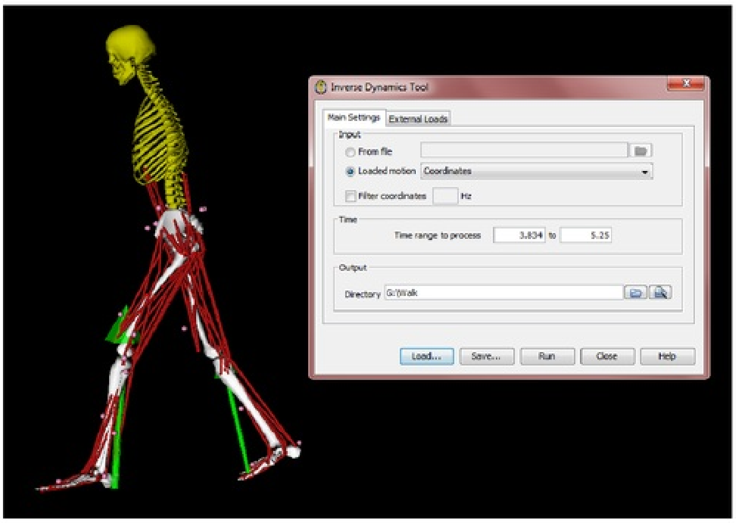

Figure 3.3: *OpenSim model with completed inverse kinematics and incomplete inverse dynamics. AutoOpenSim program runs these steps in batch*

This allows multiple trials to be graphed along the same axes all within phase, as seen in the Results chapter. A MatLab script was created to take the relevant data out of the IK or ID files and export them all in an excel spreadsheet, along with their corresponding time ranges for one full gait cycle from heel strike to heel strike. This code can be found in Appendix A.4 for both Kinematics and Dynamics data selection. Due to the differences in how the data will be plotted, IK and ID results must be treated slightly differently and require different sets of code. The main difference comes when importing the moments from the inverse dynamics, the values are normalised with the subject's body weight, while inverse kinematics data is directly exported and retains the units of degrees. The titles and file names are also different for each script, which help with the automatic plotting which occurs in Excel. Once all data was stored in an XLSX file, plotting the data could be performed. However, this also was a time consuming process, so a macro was created in Microsoft Visual Basic for Applications (VBA) to plot all trials on one set of axes with their respective gait cycles. Another macro was also included in the project for calculating the average values to be included in separate plotting. Due to the varying times per trial, averaging all values became less accurate near the end of the gait cycle where some trials had completed while others had not. This results in many average graphs cutting out at approximately 90% of the gait cycle. All these steps allowed a visual representation of all similar trials compared to one another and identify any outliers, errors, or odd behaviours which helped to reduce future errors.

Chapter 4

Results

Data collected from the seven subjects was all processed up to creating the inverse kinematics files. Due to errors in the gait laboratory, one subject had all walking data having a marker drop out before a full gait cycle could be recorded. Because of this, the walking data for that subject is not usable, decreasing the sample size to six with four young subjects (less than 45 years) and two older subjects (45-75 years). Only walking trials were fully processed, with no OpenSim tools used on any stair ascent or stair descent trials. The results in this paper will focus solely on the walking gait of the subjects. Average values for the two separate demographics can be seen below in Table 4.1.

Subject Group	Young	Old	All
Age (years)	21	56	32.67
Weight (kg)	64.525	86	71.68
Height (m)	1.6515	1.77	1.691
Leg Length (m)	0.84	0.92	0.87
Gait Cycle Time (s)	1.0525	0.9806	1.0286

Table 4.1: *Subject data averages split into age demographics and all subjects considered together*

4.1 Inverse Kinematics

4.1.1 Average Kinematics

The knee kinematics for each subject was averaged over multiple trials (ranging between six to ten, trial count varies between subjects) and plotted against other subject averages. The average knee kinematics of all subjects was then calculated with average standard deviations. Each subject had the standard deviation calculated for each point along the gait cycle. This standard deviation over time was then averaged with all other subjects' standard deviations over time to create the average standard deviation over time. Assuming the data collected is normally distributed, the upper and lower bounds seen in Figure 4.1 give a confidence band of approximately 95%.

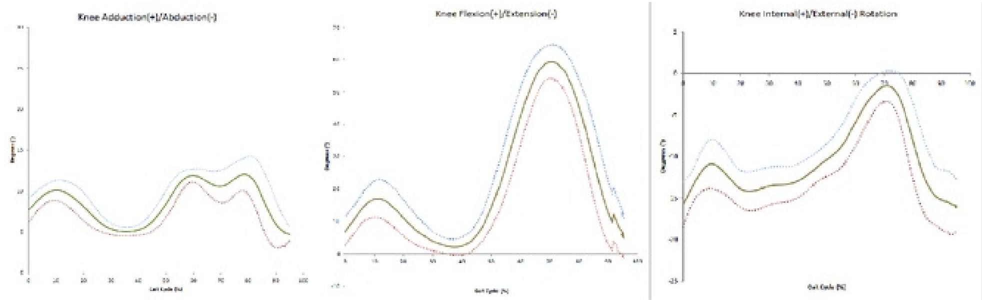

Figure 4.1: *Plots of all knee rotations created from the average of all subjects using a 24 marker set. Confidence band created from ±2 standard deviations*

It is important to note that due to each subject having a different amount of data points for one full gait cycle, the averages do not correspond directly to the average at one point in time. However there is minimal difference between the gait cycle percentages being compared, with an average standard deviation of 3%. The variation between points being compared increases linearly over the gait cycle, causing a higher variation near 100% gait cycle. The end component of knee flexion shows an inconsistent change in degrees near the end of the gait cycle. This is caused by subject trials not having enough data points to be included in the average, causing the weighting of some subjects to increase. This behaviour is also present in the other graphs, but is less noticeable.

By separating the two age demographics and finding their respective averages, a clear result is seen in the differences between the two. An overall increase in knee flexion angle is seen for the younger average. Adduction and Rotation show a dramatic difference between the age groups, showing the older average having much higher recorded angles in both rotational dimensions.

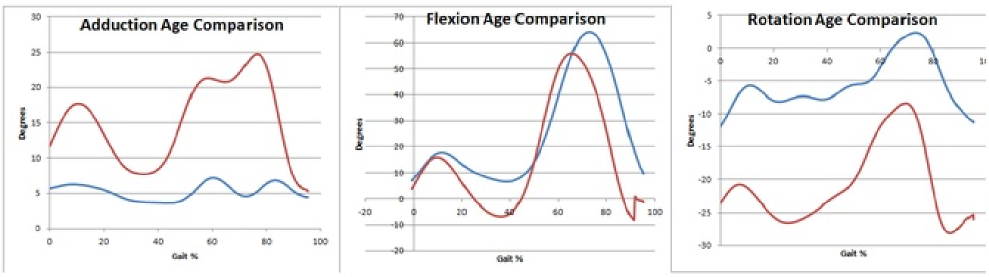

Figure 4.2: *Plots of the average knee angles for both old and young groups. Blue line represents the young group average while red represents the older group average.*

4.1.2 16-24 Marker Set Comparison

A comparison between the 24 and 16 marker sets can be seen better by looking at the reliability between trials. This can be determined by the standard deviation of the standard deviations from each subject. A table of values calculated from the total subject sample is shown in Table 4.2 for the knee kinematics. All units are in degrees and are rounded to 4 decimal places. A lower standard deviation will show less spread between subjects which ideally means the marker set gives a more accurate representation of the musculoskeletal system since a non-accurate representation would be much more susceptible to changes between subjects and their body shape.

Marker Set	16 Marker	24 Marker
Adduction		
StDev Average	0.9415	0.6498
Maximum StDev	1.8204	1.8321
Minimum StDev	0.1004	0.0009
Flexion		
StDev Average	2.6703	3.0065
Maximum StDev	5.7115	5.8498
Minimum StDev	0.3240	0.0112
Internal Rotation		
StDev Average	2.0891	1.3133
Maximum StDev	6.4843	2.3428
Minimum StDev	0.9613	0.8639

Table 4.2: *The effect of different marker sets on the standard deviation of knee kinematics*

The different marker sets have a non-numerical change in their effects on each trial. Due to errors somewhere in the system, trial values have been seen to not use the local coordinates and instead be set to some other point. This results in extreme differences between some trials, but with the same pattern. This can be seen in Figure 4.3

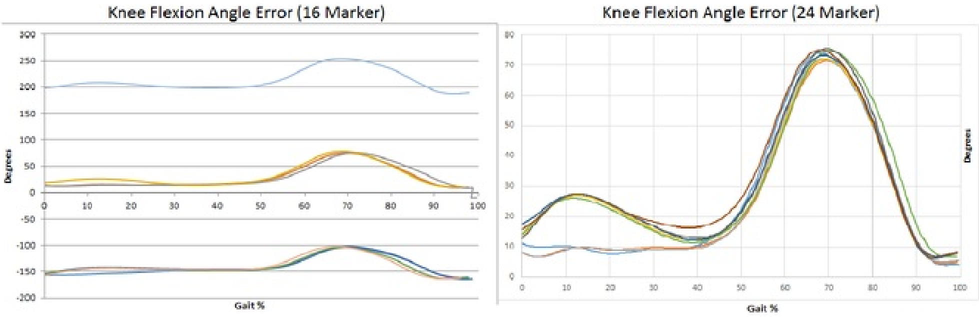

Figure 4.3: *Comparison of errors occurring for one subject between 16 marker set and 24 marker set*

4.1.3 Velocity's Effect on Kinematics

The speed at which subjects walked during the trials was self selected, however this introduces another variable within gait that could have potential changes on the measured kinematics and dynamics. By analysing the time taken to complete one gait cycle and comparing to the graphs of that trial, any statistical significance between the two may become apparent. By finding the trials where the maximum or minimum angles occurred and finding the trial time taken, it can be seen whether the speed of a subject is a factor in knee kinematics. Note subjects 1-2 in Tables 4.3 and 4.4 are from the older group while subjects 3-6 are from the younger group.

Subject #	1	2	3	4	5	6
Average Gait Cycle Time (s)	1.0006	0.9607	0.9889	1.0546	1.1468	1.0198
Max Adduction Angle (°)	19.5251	33.6848	-5.0074	0.2914	2.8339	8.9799
Max Adduction Time (s)	1.063	**0.956**	**0.982**	1.092	1.164	**1.013**
Max Flexion Angle (°)	68.3583	71.6320	68.9344	75.2956	65.3226	65.7073
Max Flexion Time (s)	**1**	**0.956**	0.99	**1.018**	1.214	**1.01**
Max Rotation Angle (°)	-9.5540	-2.6296	22.0937	21.8326	2.5022	-2.2461
Max Rotation Time (s)	**0.986**	**0.956**	**0.982**	1.092	**1.121**	1.026

Table 4.3: *Comparison of maximum knee angles to gait cycle time. Trials which took less than average time are displayed in* ***bold***

Subject #	1	2	3	4	5	6
Average Gait Cycle Time (s)	1.0006	0.9607	0.9889	1.0546	1.1468	1.0198
Min Adduction Angle (°)	0.1965	8.8298	-16.3635	-10.5538	-7.6963	-0.6765
Min Adduction Time (s)	**0.986**	**0.922**	**0.984**	1.061	**1.109**	1.036
Min Flexion Angle (°)	-8.8574	1.0014	-0.6379	2.5310	-0.7937	-2.6291
Min Flexion Time (s)	**0.986**	**0.922**	**0.987**	1.076	**1.121**	1.026
Min Rotation Angle (°)	-31.6399	-33.8815	-7.9441	3.8679	-21.1397	-24.8173
Min Rotation Time (s)	**0.985**	**0.956**	0.991	1.076	1.214	1.026

Table 4.4: *Comparison of minimum knee angles to gait cycle time. Trials which took less than average time are displayed in* ***bold***

4.2 Inverse Dynamics

4.2.1 Average Knee Moments

The dynamics of a human walking are much less standardised between subjects due to an increase in factors that make up the ground reaction forces. With the main discrepancy between subjects that has a large effect on ground reaction forces being body weight, all moments were normalised using the subject's body weight. These normalised values were then averaged between subjects to create the graphs shown in Figure 4.2. Each subject started with ten trials, however due to errors throughout the process some become unusable in calculating the average. This means that each subject has an average calculated from between six to ten trials. The final overall average is then calculated from the six subjects.

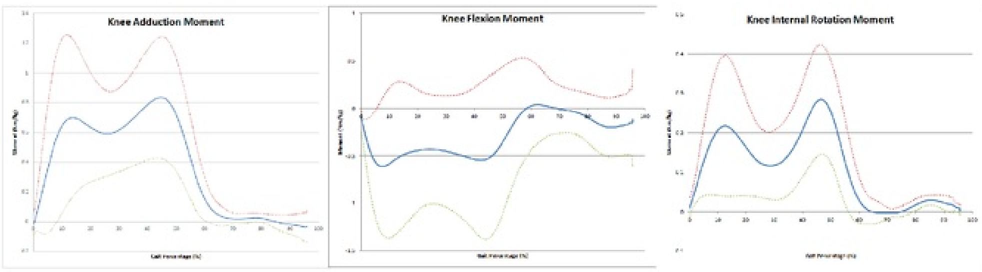

Figure 4.4: *Plots of all knee joint moments created from the average of all subjects using a 24 marker set. Confidence band created from* ± 2 *standard deviations*

The joint moments are dependent on the joint kinematics and the ground reaction forces. A figure for a single subject has been included to show the variation experienced by the ground reaction forces between trials.

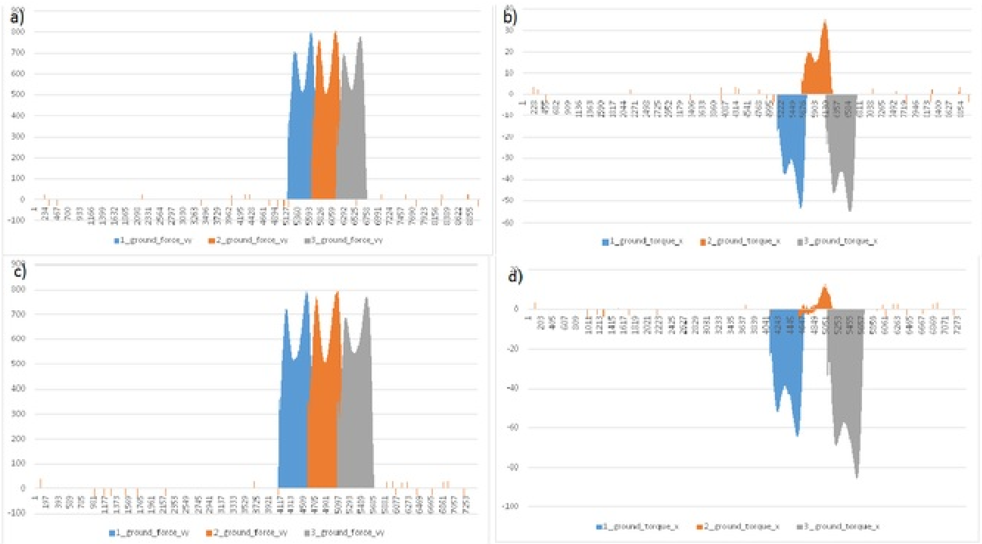

Figure 4.5: *a) and b) show one trial's results for vertical force and moment around the x-axis. c) and d) show an alternate trial results of the same measurements*

4.2.2 16-24 Marker Set Comparison

The differences between marker sets is apparent within the knee moment graphs, but the effect varies drastically between subjects. An average comparison will not show a meaningful trend that outlines the variation for each subject.

Figure 4.3 shows a comparison between two young subjects and their knee adduction moment variation between marker sets. Since there is visually no extreme difference between subject 5's results, a better approach of interpreting the difference is done with numerical data. The standard deviation differences of knee moments between the marker sets are shown below in Table 4.5.

All values in Table 4.5 are in Newton-meters per kilogram from the knee moments normalised with bodyweight, giving the moment in terms of body weight percentage. All subjects were included in the calculations and calculated in the same method as the kinematics values were.

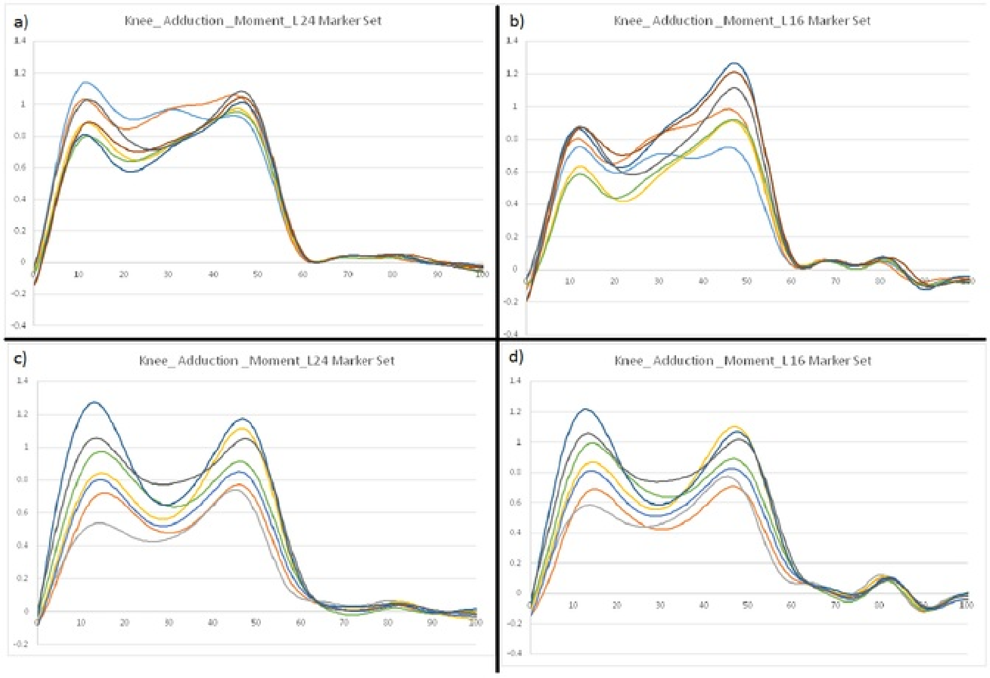

Figure 4.6: *a) All knee adduction moments from Subject 3 using the 24 marker set. b) All knee adduction moments from Subject 3 using the 16 marker set. c) All knee adduction moments from Subject 5 using the 24 marker set. All knee adduction moments from Subject 5 using the 16 marker set.*

Marker Set	16 Marker	24 Marker
Adduction		
StDev Average	0.1311	0.1049
Maximum StDev	0.3063	0.2927
Minimum StDev	0.02505	0.0083
Flexion		
StDev Average	0.2423	0.2551
Maximum StDev	0.5226	0.4264
Minimum StDev	0.01687	0.03918
Internal Rotation		
StDev Average	0.05205	0.03475
Maximum StDev	0.1174	0.08938
Minimum StDev	0.005332	0.00520

Table 4.5: *The effect of different marker sets on the standard deviation of knee dynamics*

Chapter 5

Discussion

The results of the project have shown large variation in the similarities found in published papers. While some events seem to correspond very closely to the literature, other datasets do not seem to have those similarities. The flowchart in Figure 3.2 helps identify any points within the project where errors may be present or affect the following steps. The first computer modelling of a subject at requires user input is the "OpenSim Subjcet Model" creation process. The scaling of the model is performed by matching a virtual marker set with the recorded marker set from Vicon Nexus in the "Subject Static" trial. Joint centres are defined in Vicon, which has shown to produce fairly consistent results.

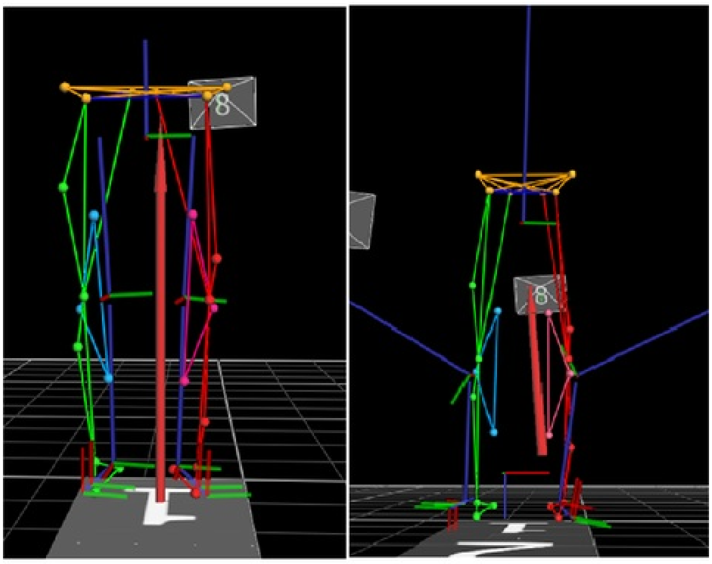

Figure 5.1: *A comparison of a correct static calibration (Left) and an incorrect calibration (Right) as seen in Vicon Nexus*

Figure 5.1 shows multiple coordinate systems at each joint of the lower body. A correct coordinate system should have the z-axis, shown by the dark blue lines, pointing in the direction of the superior bone segment. An incorrect scaling will be inherited by the later stages of the data analysis and will change both IK and ID results. However due to the local coordinates being used in kinematics, the angles are likely to be less affected , while ID results will try matching the force plate coordinates to all joint coordinates and will result in errors.

The step of scaling in OpenSim will match the marker positions from the static calibration TRC exported from Vicon to the virtual marker set created in OpenSim. The differences in placement will be calculated and represented as the root mean square error, which can be used to further improve the accuracy of the subject models. This step was not carried out as it was recommended that the effect is not a major concern when first performing gait analysis using OpenSim.

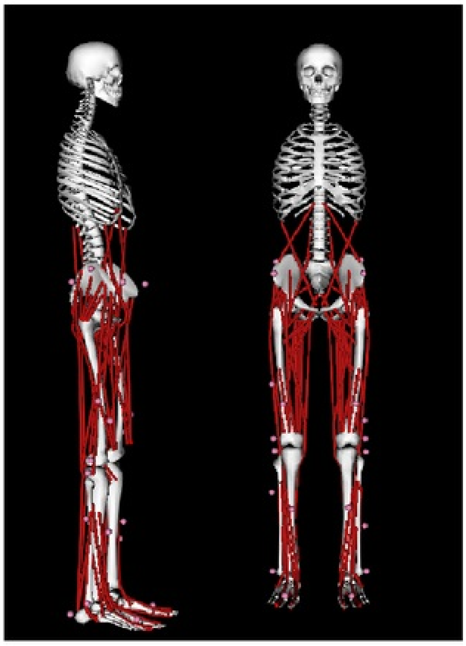

Figure 5.2: *Unscaled OpenSim model with the 24 marker set attached.*

The unscaled skeleton model shows the position of the markers relative to the expected skeletal landmarks. These markers are placed within the program and do not come from experimental procedures. The same markers can also be seen in Figure 5.1, where their position can be seen relative to other markers. To reduce the scaling error, virtual marker placement must be as close to experimental marker placement as possible.

5.1 Kinematics

The results for the knee kinematics in Figure 4.1 are quite similar to the pattern seen in the literature for healthy patients [4, 14]. Knee flexion is the least susceptible to variation due to the large expected range of motion during gait. These graphs show a very similar pattern with the peak magnitudes also matching up. This gives a strong reason to believe that marker placement for the lower leg was accurate in its mapping of the skeletal system and the resulting motions. With the knowledge that recording begins on the heel strike and that stance phase takes approximately 60% of the full gait cycle, the flexion graph shows exactly what is expected, with peak knee flexion occurring during swing phase.
The remaining rotational dimensions are much more susceptible to variation due to the knee being a hinge joint and only required to move in the one direction. Marker placement has a much higher impact on the varus-valgus angle, and even more so for the internal and external rotation. This issue is know as "cross-talk" and is expected to raise the recorded angles above what their true measurements are [4]. As can be seen in Figure 4.1, if compared to other published papers, the collected varus-valgus angles are shown to be always positive, ranging from +5 to +10°. Although a similar shape is present, along with an expected angle range, the published results sit closer to the x-axis ranging between -5 to +5° , or in some cases, -10°. This issue has been researched and can be reduced by using Principal Component Analysis (PCA), but was not applied during this project. By being aware of the offset caused by marker misplacement, the generated results are satisfactory to claim the process of data analysis is correct in methodology.

Internal rotation is considered the most difficult to accurately trace with external markers, but the basic pattern is again comparable to the literature. This scenario has shown external rotation to be present throughout the entire gait cycle with maximums of approximately 15° at heel strike. There is wide variation in the patterns found in literature, ranging from all positive internal rotations [14] to all constant external rotations, as seen from the experimental data and the clinical gait analysis web page [15].

5.1.1 Effect of Age on Kinematics

Another aspect of the differences in the knee kinematics is the differences between age demographics. Although adduction angles from experimental data was shown to be higher than expected, when separating the averages into age groups it becomes evident that the older group had a much higher adduction angle on average, and pulled the total average up as well. The young group had an average almost exactly matching the literature with much less variation than the other subject set.

This result seems to suggest older people have a higher adduction angle and internal rotation when walking. Although this is possible and could be linked to other aspects of older age such as higher risk of knee damage or cartilage wearing out, there are many other factors that separate the two subject groups. As seen in Table 4.1, the old group was taller, on average, by $\approx 12cm$, as well as a leg length difference of 8cm. All subjects confirmed to not have had any knee injuries or issues in the past so the discrepancy is unlikely to be caused by injury. With such a small sample size in both categories there is no way to draw a conclusive relation between age and adduction/abduction angle or internal/external rotation angle. What can be said with certainty, however, is that the older subject group had a much higher variance of knee motion in the medial-lateral direction. The graph shows a range of motion reaching close to 30 with a range of almost 20°, which seems high. Subject 1 had a range of 17.0° while Subject 2 had a range of 22.3°. Even with the assumption that Subject 2 had an error occur during testing, the range still remains above 15°. More subjects within the 45-75 range are required to see if the age-high adduction range behaviour continues.

5.1.2 Marker Set Differences

With Table 4.2 giving the values for standard deviation between angles measured throughout the gait cycle, the effect of the marker set becomes clear. With higher standard deviation showing in adduction and internal rotation for the 16 marker set, it can be concluded that the 16 marker set does not track the skeletal angles as smoothly or loses information at points which are necessary for OpenSim to calculate the inverse kinematics of the model. Despite the variance of the 24 marker set being less for the more sensitive knee joint rotations, knee flexion was measured to be LESS consistent between trials when using the increased marker set. Therefore there is a trade-off between marker sets in terms of measuring knee joint angles and it must be decided whether or not it is worth it. Just by looking at the values, an increased variance of 1.909* in knee flexion which has a range of approximately 60° is an acceptable trade-off to a decrease in variance in knee adduction and internal rotation by 0.4642 and 2.640, respectively.

*Difference in variance was calculated by $\sigma_{24}^2 - \sigma_{16}^2$, where σ_x is the average standard deviation for "x" marker set.

An effect that is not seen in the results displayed is the decrease in the frequency one specific error occurs during processing. Currently unsure what the cause is, some trials will return incorrect values for the kinematics of ALL joints. The values will follow the expected pattern relative to itself, but the recorded angles will have been shifted drastically but an inconsistent amount. This results in having to similar trials, with one giving readings of 180° above the other. Since the OpenSim component of the project has been automated to perform the same actions for each test, there is no obvious explanation as to why some are affected by this shift in readings. A possible reason is the recorded angles are in a global coordinate reference instead of the knee joint coordinate reference, but trials have been shifted by different values within the same subject.

As seen in Figure 4.3, the 24 marker set retained all trials on the same coordinate system, while the 16 marker set shifted trials both up and down approximately 180°. This example contained the most errors, but other subjects were also affected. It is important to note that these kinematics files act as inputs to the inverse dynamics, so these errors will be cascaded throughout the remaining processes if left ignored. To find the average trials, these errors are removed from the calculation due to a certainty in their inaccuracy when thinking about the physical meaning of knee flexion and general range of motion.

5.1.3 Effect of Velocity on Kinematics

By comparing the time taken to complete the trial that caused a maximum or minimum peak to occur with the average time taken for a trial for each subject, any clear relations between walking faster and higher angle measurements should be seen. With available data, there is not much variation between velocities of each trial. With a very small walkway, having one gait cycle be approximately 1.2 meters, and being limited to walking trials, velocity will remain relatively the same. From Table 4.3, there is no immediate correlation that is applicable to all subjects. Subjects 1 and 2 are the older group participants and they show that 11 out of 12 of the maximum or minimum angle magnitudes were achieved during a trial that was walking slightly faster than average. Young participants show no clear relation between the time taken to complete a gait cycle and the resulting kinematics maximum and minimum values from the knee. Published papers have reported on slower walking speeds producing increased gait variability [16], as well as an increase in velocity causing an increase in peak magnitudes for knee flexion angle [17]. The range of velocities available within this project is not likely enough to give any noticeable difference. In the paper by K. E. Zelik [17], a difference of 1.1 meters per second caused a difference of 10° to knee flexion. With the incredibly close gait times between trials for each subject, the change in velocity is safe to be neglected as a high impact factor on the final results for kinematics. However since velocity will also determine the acceleration at which a subject performs a heel strike, velocity is likely to have a higher impact on the dynamics of human gait. According to J. L. Lelas, the peak parameters from kinematics and kinetics (forces and moments shown from the force plates) were affected by changes in gait speed, with kinetics having a higher predictability [23]. The increase in gait speed was more significant than what occurred in the experimental data which explains why no noticeable change was found within this project. For future testing, if velocity is still desired to be a factor, multiple tests must be performed where the subject is explicitly directed to move at a varying speed. However due to the target demographic for the future, as well as being a study on walking, this is not likely to be a necessary progression in the project.

5.2 Dynamics

The average moment results displayed in Figure 4.4 all follow the same basic shape of a fourth order polynomial during the stance phase and an approximate zero during the swing phase. Since OpenSim performs inverse dynamics using the ground reaction forces and excludes any muscle forces that occur, a zero moment is expected during the swing phase and can be ignored on all of the graphs. When compared to expected plots of knee moments, there is very little similarity found between the project results for knee flexion moments. Knee adduction moments do match the literature in terms of shape, but have peak magnitudes higher than expected. Expected results sit within the confidence band, as well as a large variation between people in general, which mean these results are acceptable and can be used as a future guide for creating the expected standard for the Macquarie University gait lab. Knee Internal/External rotation moments are much harder to make a claim of accuracy. With such variation between published sources, there is no solid 'goal' that the experimental data should resemble. When compared to the T. F. Besier et al. paper, some manipulation would result in experimental data resembling the published knee internal moment paper [14]. By setting external rotation to the positive axis (flipping the plot along the x-axis) a similar pattern emerges. However the paper ranges from 0.04 to -0.08, a much smaller change over time than seen in Figure 4.4.

Differences between genders was considered, but due to having only one female within the sample size there was no separation. It has been shown with a fairly inclusive experiment that there is no statistical difference between female and male knee torques [20]. There was an expected difference between peaks for dominant and non-dominant knee adduction moments for subjects with osteoarthritis [21]. When compared to healthy subjects, although a difference was found between leg moments, there was no full gait cycle recorded for the non-dominant leg.

5.2.1 Ground Reaction Forces

Knee flexion moments are expected to occur in both the flexion and extension directions (anterior and posterior motion) throughout the stance phase [14, 18]. Disregarding magnitude, since even with normalising with respect to body weight a large variation between subjects is expected, there is likely an error at some point during the process. OpenSim inverse dynamics is dependent on two inputs: The inverse kinematics file, which is believed to be correct as seen above; and the ground reaction forces file. A further review of the ground reaction forces file for one specific subject is displayed in results, and shows the ground reaction forces and moments recorded by the Kistler force plates that are applied to the subject's calcaneus within OpenSim. The variation between trials becomes observable, which would cause inconsistencies within the subject trials. The force magnitudes remained consistent within subjects, along with the standard pattern that can be seen in Figure 4.5 a) and c). However a large variation between moments measured is seen with intra-subject testing, as seen in b) and d). Units of the y-axis are Newtons and Newton-meters, respectively, while the x-axis is a measurement of time, shown in milliseconds.

All measurements are taken in the force plate coordinate system where the x-axis is the direction the subject walked during trials and the y-axis is the vertical direction, which gave the most important component of the ground reaction force. With the trial comparison shown below, almost identical forces in all directions were recorded while dramatic changes in moments occurred. The visual representation of forces can be explained into the gait cycle phases. The initial blue peak is the heel strike of the subject on the first force plate while the second is after toe-off from the opposite foot. This places all the subject weight through one leg, just before heel-strike of the next foot onto the second force plate, as seen at first peak of the orange data.

Due to the force plate moments being dependent on the forces along with the centre of pressure, it can be interpolated that the inverse dynamics is much more sensitive to variation in trials. The subject stepping on the force plate in a different position is going to change the moments which will affect the knee moments. One explanation of the difference between b) and d) is that the subject stepped much closer to the centre of the force plate in the seconds trial, which caused a decrease in torque. Other possible limitations could be occurring within the equipment or laboratory setup. Since almost all inconsistencies occur using force plate two, there is a possibility that calibration has not been completed correctly. Due to other projects being performed within the MQU gait lab, complete control over the system is not possible. The sensitivities of each force plate can be changed within the BIOWARE software, which has been changed throughout the project time line. To rule out miscalibration as the cause of error, future tests must be scheduled to perform tests on all underground force plates.

5.2.2 Marker Set Differences

Figure 4.6 showed the resulting difference for two subjects using the 24 and 16 marker set. Only adduction was used as visual examples due to the scepticism of the remaining moments' validity. The effects of the 24 marker set can be seen to decrease standard deviation, which is confirmed in Table 4.5. The same results seen in kinematics are seen here, with an increase in variance for knee flexion/extension moments, but a decrease in adduction/abduction and internal/external rotation moment variation. This tradeoff is likely to be beneficial to the clinical aspect of the trial, as varus-valgus motion is more important to analysing or identifying potential risks in subject gait, such as osteoarthritis [19]. With the current state of the data collected, it is not advisable to draw conclusions on the effectiveness of the self-designed 24 marker set for knee joint moments. However as explained in the marker set effect on kinematics, the 16 set seems to cause a bug to occur throughout the process and generate incorrect data. This data will move into the ID process, making the 24 marker set beneficial in both decreasing the standard deviation of adduction as well as increasing the amount of valid trials that make it through the entire process.

5.2.3 Velocity of Walking

By looking at the graphs and matching the related gait cycle completion time it is seen that there is no obvious relation to the time taken to complete one gait cycle and the maximum peaks of that trial. A wide variety of results were seen, by looking at each subject's fastest and slowest trials and seeing where they sat in reference to the other trials. Some subjects showed an increased adduction moment in their slower trials, while some showed a decrease. Overall there was no statistical significance between the changes in velocity recorded within this experiment due to the minimal changes that existed. K. E. Zelik has shown that the changes in velocity do make a difference, with their graph shown in Figure 5.3. These plots are across one full gait cycle beginning with heel strike. The patterns match other literature [17], but have placed extension along the positive y-axis. To use as a reference, expected graphs would follow the negative of these results.

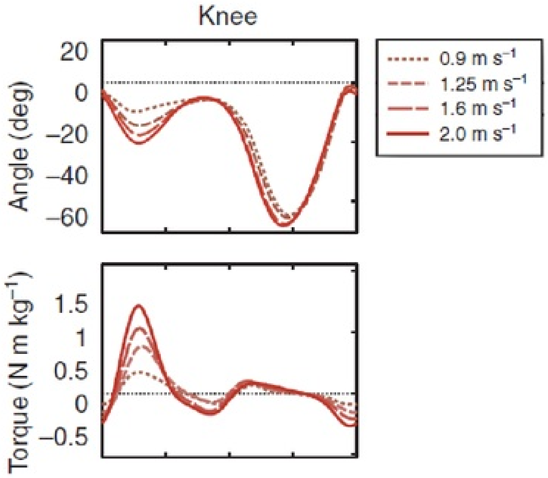

Figure 5.3: *Results from K. E. Zelik et al show the effect of velocity on knee angle and moment in the sagittal plane (Flexion/Extension) calculated from the average of ten subjects [17]*

By keeping velocity constant between subjects, this effect can be ignored as a variable for the changes in kinematics and dynamics. Figure 5.3 shows a change in velocity of 0.35 meters per second produces a small difference of approximately 2° in knee flexion kinematics and a change of 0.3 Newton-Meters per bodyweight in knee flexion dynamics. Assuming each subject had a shared stride length of 1.2m, the same distance between force plate 1 and 3 centre of pressure, average velocity of all subjects was approximately $1.03 \pm 0.066m/s$. By keeping subjects at a self-selected walking pace, as long as they are close to the created standard for the older demographic, velocity can be ignored.

Chapter 6

Conclusions and Future Work

The end result of the project has been successful in implementing a standard method for coolecting, processing, and analysing data by creating multiple scripts to streamline the process. The research question of looking at the effect of the marker sets on the end results was given a conclusive result of one marker set being an improvement over the other. Results showed a decrease in the standard deviation for Adduction and Abduction as well as Internal Rotation and External Rotation when using a modified Helen-Hayes marker set with additional markers placed on key bone extrusions along the lower limbs and waist. Knee kinematics was shown to be affected by cross talk between markers, giving an overestimation of knee angles in the varus-valgus and internal-external rotation directions. Both marker sets were higher than the reference material, so future work to decrease this effect must be implemented. Principal Component Analysis is a statistical approach at reducing these values and can be attempted with existing data to see the changes it has on knee kinematics.

With the result of the 24 marker set returning more reliable data, further improvements can be made on the standard MQU marker set. One experiment has already been attempted with using a full body marker set, following the plugin gait setup. With a total of 44 markers, this marker set was much more difficult to implement and has not yet been analysed for any differences it or the existing 24 set. Once analysed, if there is a noticeable benefit between the two sets, a decision must be made as to whether the increased accuracy and reliability is worth the extra effort that is required in the gait laboratory as well as throughout the post processing events. Due to the project final goal being an analysis of knee motion and is expected to be used to help with post-surgery subjects, the upper body markers are not believed to cause enough benefit to justify using them for lower body analysis.

Other marker sets that were reviewed within the literature review do have potential to be implemented in future testing, with key focus being applied to the knee joint. Small marker clusters have been shown to increase reliability between trials and can be designed for specific purposes. A marker cluster along the tibia or femur would likely have a beneficial impact on the measurements in both kinematics and dynamics.

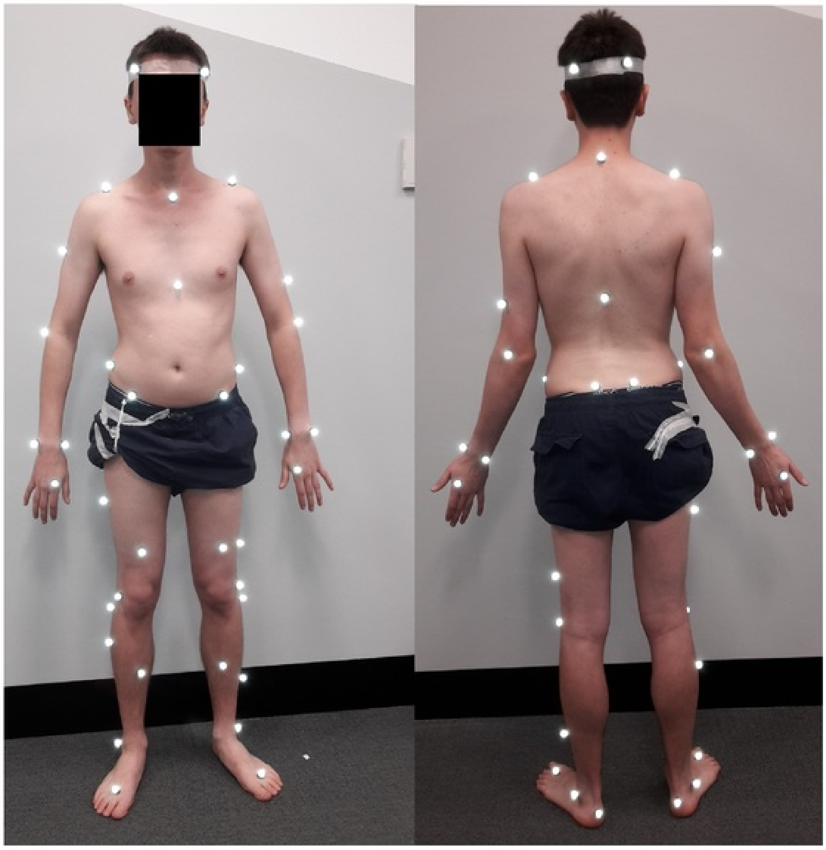

Figure 6.1: *Image of a subject with a full-body plugin gait marker setup*

Each subject also performed multiple step up and step down trials using a force plate step. This data can be processed through the same methods and produce graphs that plot the motion of the subjects during stair ascent and descent. This data can again be compared to literature to confirm whether or not it is acceptable and give further details into the walking behaviours of the subjects. This future work can be begun immediately due to all the files being set up and ready to process. However the most immediate aspect of the project that needs to be reviewed is the results for inverse dynamics. With possibilities of bugs throughout the process, key points should be identified and inspected for possible causes. A possible cause may arise in the automatic OpenSim script written in MatLab, where each trial is run immediately after the previous. A simple running of one trial at a time could rule out any input variables but being set properly or carrying through all trials. Marker weighting was also recommended to be altered within the OpenSim virtual marker set. Currently all markers are set to an equal confidence rating, which may skew results away from the accurate markers. There is no clear method for giving a weighting to a marker, but is generally done with experience and understanding of the underlying bone structure.

The project also showed a definitive difference between age demographics within the knee kinematics for varus-valgus motion. Due to a small sample size and inconsistent dynamics measurements which implied an error exists within the methodology, no confident result can be stated about the knee dynamics at this stage, but is much closer to being available than before. Although there is still a way to go until definitive conclusions can be made, the project overall was a success in confirming the effects of marker sets and age on knee kinematics and, to an extent, dynamics. The creation of multiple MatLab scripts also improved the reliability of the data output by lowering potential human mistakes, making future research in the field much easier and faster to complete.

Chapter 7

Abbreviations

GA	Gait Analysis
IK	Inverse Kinematics
ID	Inverse Dymanics
KAM	Knee Abducton Moment
KFM	Knee Flexion Moment
MQU	Macquarie University
OA	Osteoarthritis
PCA	Principal Component Analysis
RRA	Reduced Residuals Algorithm
TKA	Total Knee Arthroplasty
TKR	Total Knee Replacement

Appendix A

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Appendix B

Programming and Software

B.1 TRC Data Selection

```
% Takes TRC file and selects the framerange where all markers are visible.
% Frame ranges given manually within an .xlsx file with file names

% Code written in MatLab R2014b
% Author: James Naim, Bradley Beck; 2016

function Toplevel = Main_code_Top_level(~, ~, range)
sheetName = 'sheet1';
fprintf('Please select frame range file: \n')
workbookFile=uigetfile('.xlsx');

% If no sheet is specified, read first sheet
if nargin == 1 || isempty(sheetName)
    sheetName = 1;
end

% If no range is specified, read all data
if nargin <= 2 || isempty(range)
    range = '';
end

% Import the data
[~, ~, Toplevel] = xlsread(workbookFile, sheetName, range);
Toplevel(cellfun(@(x) ~isempty(x) && isnumeric(x) && isnan(x), Toplevel)) = {''};

```

```
%Size of array
E=size(Toplevel);
Rowz=E(1,1);

%Search for start and end frames
for i=1:Rowz
    filename=Toplevel(i,1);
    filename1=strcat(filename, '.TRC');
    startframe=Toplevel{i,2};
    endframe=Toplevel{i,3};
    [mainOutput]=Sub_Code(filename1, startframe, endframe);

    [rows,cols]=size(mainOutput);

    exportfile=strcat(filename,'_processed','.TRC');
    fileID=fopen(char(exportfile),'w');
    for j=1:rows
        for k=1:cols
            fprintf(fileID,'%s\t',mainOutput{j,k});

        end
            fprintf(fileID,'\n');

    end

end
```

```
function [mainOutput] = Sub_Code(filename1, StartFrame, EndFrame)
% Initialize variables.

delimiter = '\t';

    startRow = 1;
    endRow = inf;

formatSpec = '%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%[^\n\r]';
% Open the text file.
fileID = fopen(char(filename1),'r');

dataArray = textscan(fileID, formatSpec, endRow(1)-startRow(1)+1, 'Delimiter', delimiter, 'HeaderLines', startRow(1)-1, 'ReturnOnError', false);
% Close the text file.
fclose(fileID);

% Create output variable
mainOutput = [dataArray{1:end-1}];

%size of array
C=size(mainOutput);
Rows=C(1,1);

%create new array with only numerical entries
A=zeros(Rows-5,C(1,2));

%Search for start and end frames
for i=6:Rows
    A(i-5,:)=str2double(mainOutput(i,:));
end
for i=1:Rows-5
    if A(i,1)==StartFrame;
        B=i
    end
    if A(i,1)==EndFrame;
        D=i
    end
end
```

```
%Start and End rows in original array
clear startRow endRow
startRow=B+5;
endRow=D+5;

formatSpec = '%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s
    %s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%
    s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s %[^\n\r]';

% Open the text file.
fileID = fopen(char(filename1),'r');

dataArray = textscan(fileID , formatSpec, endRow(1)-startRow(1)
    +1, 'Delimiter', delimiter , 'HeaderLines', startRow(1)-1, '
    ReturnOnError', false);
% Close the text file.
fclose(fileID);


% Create numerical part of output variable
Numbers = [dataArray{1:end-1}];

%Create Array Header
delimiter = '\t';

    startRow = 1;
    endRow = 5;


formatSpec = '%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s
    %s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%
    s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s%s %[^\n\r]';
% Open the text file.
fileID = fopen(char(filename1),'r');

dataArray = textscan(fileID , formatSpec, endRow(1)-startRow(1)
    +1, 'Delimiter', delimiter , 'HeaderLines', startRow(1)-1, '
    ReturnOnError', false);

% Close the text file.
fclose(fileID);
```

```
%Create header for output variable
Header = [dataArray{1:end-1}];

%Create final variable by combining Header and Numbers
mainOutput=vertcat(Header,Numbers);

%Change Column Headings
A=[cellstr('Frame#'),cellstr('Time'),cellstr('LASI'),cellstr(''),cellstr(''),cellstr('RASI'),cellstr(''),cellstr(''),cellstr('LPSI'),cellstr(''),cellstr(''),cellstr('RPSI'),cellstr(''),cellstr(''),cellstr('LTOR'),cellstr(''),cellstr(''),cellstr('RTOR'),cellstr(''),cellstr(''),cellstr('LTHI'),cellstr(''),cellstr(''),cellstr('LKNE'),cellstr(''),cellstr(''),cellstr('LTIB'),cellstr(''),cellstr(''),cellstr('LANK'),cellstr(''),cellstr(''),cellstr('LHEE'),cellstr(''),cellstr(''),cellstr('LTOE'),cellstr(''),cellstr(''),cellstr('LQUA'),cellstr(''),cellstr(''),cellstr('LFIB'),cellstr(''),cellstr(''),cellstr('LSHI'),cellstr(''),cellstr(''),cellstr('RTHI'),cellstr(''),cellstr(''),cellstr('RKNE'),cellstr(''),cellstr(''),cellstr('RTIB'),cellstr(''),cellstr(''),cellstr('RANK'),cellstr(''),cellstr(''),cellstr('RHEE'),cellstr(''),cellstr(''),cellstr('RTOE'),cellstr(''),cellstr(''),cellstr('RQUA'),cellstr(''),cellstr(''),cellstr('RFIB'),cellstr(''),cellstr(''),cellstr('RSHI'),cellstr(''),cellstr('')];
mainOutput(4,:)=A';

F = (D+1)-B;
G=sprintf('%d',F);
mainOutput(3,3)= cellstr(G);
```

B.2 CSV to MOT File Converter

```
% Code will add all files of type .csv to a structure and run through each
% one, creating a .mot file with (rearranged data for OpenSim use)
%
% Code written in MatLab R2014b
% Author: Bradley Beck, 2016
trialsForConv = dir(fullfile(cd, '*.csv'));

% Gives the filecount for how many runthroughs is going to occur
Rows=size(trialsForConv,1);

% Matrix to scale forces (negative of initial)
F = -1*eye(3);
% Matrix to scale positions (meters --> millimeters)
P = [1 0 0; 0 1 0; 0 0 -1]/1000;
% Matrix to rescale and redirect Moments to Torques
T = [-1 0 0; 0 -1 0; 0 0 -1]/1000;

% 0.001 is data collection frequency from the forceplate. If the force
% plates are changed, this value must also be changed to match
V = blkdiag(0.001,F,P,F,P,F,P,T,T,T);

% Runs through each requested file and runs the subfunction to generate the
% .mot file
for i=1:Rows

    filename = trialsForConv(i).name;
    CSV_ConverterV2(filename, V);

end

fprintf('\nYour files have been processed. Thank you, come again!\n \n')
```

```
function CSV_ConverterV2(filename1, convertrix)

%Determines name of produced .mot file
outtemp = filename1(1:end-4);
OutputFile = strcat(outtemp,'_grf.mot');

% Selects data from input file and rearranges it into correct column order
% (excludes time column)
delimiterIn = ',';
headerlinesIn = 5;
A = importdata(filename1,delimiterIn,headerlinesIn);
B = A.data;
B = B(:, [3 5 4 9 11 10 20 22 21 26 28 27 37 39 38 43 45 44 6 8 7 23 25 24 40 42 41]);

% Creates time column to be attached to force data
% Conversion between frames and time
fin = size(B,1);
time = zeros(fin,1);
for i = 1:fin
    time(i) = 4*(A.data(1,1) - 1) + i-1;
end

%Produces a matrix with correct values in correct columns for .mot
MOD = [time B]*convertrix;

rowCount = num2str(fin);
nRow = strcat('nRows=',rowCount);
Header =[cellstr(outtemp), cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr('')
cellstr(nRow), cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr('')
cellstr('nColumns=28'), cellstr(''),cellstr(''),cellstr(''),
```

```
    cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),
    cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),
    cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),
    cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),
    cellstr(''),cellstr(''),cellstr(''),cellstr('')
 cellstr('inDegrees=yes'), cellstr(''),cellstr(''),cellstr(''),
    cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),
    cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),
    cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),
    cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),
    cellstr(''),cellstr(''),cellstr(''),cellstr('')
 cellstr('endheader'), cellstr(''),cellstr(''),cellstr(''),
    cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),
    cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),
    cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),
    cellstr(''),cellstr(''),cellstr(''),cellstr(''),cellstr(''),
    cellstr(''),cellstr(''),cellstr(''),cellstr('')
 cellstr('time'),cellstr('1_ground_force_vx'),cellstr('1
    _ground_force_vy'),cellstr('1_ground_force_vz'),cellstr('1
    _ground_force_px'),cellstr('1_ground_force_py'),cellstr('1
    _ground_force_pz'),cellstr('2_ground_force_vx'),cellstr('2
    _ground_force_vy'),cellstr('2_ground_force_vz'),cellstr('2
    _ground_force_px'),cellstr('2_ground_force_py'),cellstr('2
    _ground_force_pz'),cellstr('3_ground_force_vx'),cellstr('3
    _ground_force_vy'),cellstr('3_ground_force_vz'),cellstr('3
    _ground_force_px'),cellstr('3_ground_force_py'),cellstr('3
    _ground_force_pz'),cellstr('1_ground_torque_x'),cellstr('1
    _ground_torque_y'),cellstr('1_ground_torque_z'),cellstr('2
    _ground_torque_x'),cellstr('2_ground_torque_y'),cellstr('2
    _ground_torque_z'),cellstr('3_ground_torque_x'),cellstr('3
    _ground_torque_y'),cellstr('3_ground_torque_z')];

HeadRow = size(Header,1);
%Convert MOD matrix to a cell and vertcat together with header
Numbers = num2cell(MOD);

finalFile = vertcat(Header,Numbers);

fileID=fopen(OutputFile, 'w');
R = size(MOD,1);
%Writes in all title rows
for i = 1:HeadRow
    for j=1:28
```

```
        fprintf(fileID,'%s\t',finalFile{i,j});
    end
  fprintf(fileID,'\n');
end
%Writes in all numeric data
for i=HeadRow+1:R+HeadRow
    for j=1:28
        fprintf(fileID,'%g\t',finalFile{i,j});

    end
  fprintf(fileID,'\n');

end

fprintf('ding ')
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%Using just a matrix allows easy file creation, but cannot include titles.
%%May be useful
%%dlmwrite('C:\Users\biomechanalysis\Desktop\Bradley Files\MATLAB\other.trc', MOD, 'delimiter', '\t');
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

B.3 Automated OpenSim

```
%-----------------------------------------------------------------------------%
% Executable MatLab code to run through Inverse Kinematics and Inverse
% Dynamics. Created to lower the amount of directoreis required to be set
% for a full runthrough of both.
%
% Code written in MatLab R2014b
% Author: Bradley Beck, 2016
%-----------------------------------------------------------------------------%

% Pull in the modeling classes straight from the OpenSim distribution
import org.opensim.modeling.*

% move to directory where this subject's files are kept
subjectDir = uigetdir('testData', 'Select the folder that contains all other relevant folders');
cd(subjectDir)

prompt = '\nWould you like to use default directories or set your own? \nType "1" for default or any other key to set your own: \n';
default = input(prompt);
%-----------------------ALL REQUIRED DIRECTORIES-----------------------%
%        subjectDir;                                                    %
%        input_data_folder;                                             %
%        IK_data_folder;                                                %
%        ID_data_folder;                                                %
%        XML_folder;                                                    %
%        Setup_folder;
```

```
%
%         genericSetupForIK;
                                                    %
%         genericSetupForID;
                                                    %
%         genericSetupForExtLoad;
                                                %
%
    ---------------------------------------------------------------------
if default == 1
% Current default directories set off the SubDir, easily changed
    here
   input_data_folder = ([subjectDir '\DataFiles']);
   IK_data_folder = ([subjectDir '\IKFiles']);
   ID_data_folder = ([subjectDir '\IDFiles']);
   XML_folder = ([subjectDir '\XMLFiles']);

   fprintf('Default Directories have been set.\n')
else
    fprintf('Get ready!\n')


% Go to the folder in the subject's folder where .trc files are
    input_data_folder = uigetdir(subjectDir, 'Select the folder
       that contains the motion.trc & grf.mot files.');

% specify where IK results will be printed.
    IK_data_folder = uigetdir(subjectDir, 'Select the folder
       where the IK Results will be printed or accessed.');

% specify where ID results will be printed.
    ID_data_folder = uigetdir(subjectDir, 'Select the folder
       where the Inverse Dynamics files will be printed in .sto
       format.');

% Go to the folder in the subject's folder where .xml files are
   saved.
    XML_folder = uigetdir(subjectDir, 'Select the folder that
       will store the XML files generated throughout the process
       ');

end
```

```

%%
% specify generic XML files to build off and run for all tools (no default)
[genericSetupForIK,Setup_folder,FilterIndex] = uigetfile('*.xml','Pick a generic XML file for Inverse Kinematics.');
cd(Setup_folder)
genericSetupForID = uigetfile('*.xml','Pick a generic XML file for Inverse Dynamics.');
genericSetupForExtLoad = uigetfile('*.xml','Pick a generic XML file for appropriate External Loads.');
[modelFile,modelFilePath,~] = uigetfile('*.osim','Pick the the model file to be used.');

% Load the model and initialize
model = Model([modelFilePath modelFile]);
model.initSystem();

%MarkerCount = input('How many markers are used in this trial?');
MarkerCount = model.getNumMarkers();
MarkerCountString = num2str(MarkerCount);


%% ------------------------------ %% Inverse Kinematics Section %% ------------------------------ %%
% An edited version of setupAndRunIKBatchExample.m (Author: Edith Arnold) %


ikTool = InverseKinematicsTool([Setup_folder genericSetupForIK]);

% Tell Tool to use the loaded model
ikTool.setModel(model);

trialsForIK = dir(fullfile(input_data_folder, '*.trc'));

nTrials = size(trialsForIK);

% Loop through the trials
for trial= 1:nTrials;

```

```
    % Get the name of the file for this trial
    markerFile = trialsForIK(trial).name;

    % Create name of trial from .trc file name
    name = regexprep(markerFile,'.trc','');
    fullpath = ([input_data_folder '\' markerFile]);

    % Get trc data to determine time range
    markerData = MarkerData(fullpath);

    % Get initial and intial time
    initial_time = markerData.getStartFrameTime();
    final_time = markerData.getLastFrameTime();

    % Setup the ikTool for this trial
    ikTool.setName(name);
    ikTool.setMarkerDataFileName(fullpath);
    ikTool.setStartTime(initial_time);
    ikTool.setEndTime(final_time);


  % Depending on generic .XML file used may need to add _## to end of name
  % To identify what marker set was used in the trial
    outName = name(1:end-14);
    ikTool.setOutputMotionFileName([IK_data_folder '\' outName '_IK_' MarkerCountString '.mot']);

    % Save the settings in a setup file
    outfile = ['Setup_IK_' MarkerCountString '_' outName '.xml'];
    ikTool.print([XML_folder '\' outfile]);

    fprintf(['Performing IK on cycle # ' num2str(trial) '\n']);
    % Run IK
    ikTool.run();
end

fprintf('Inverse Kinematics has completed, moving onto Inverse Dynamics: \n')

%% ------------------------ %% Inverse Dynamics Section %% ------------------------ %%
```

```
% An edited version of setupAndRunAnalyzeBatchExample.m (Author: Edith Arnold) %

idTool = InverseDynamicsTool([Setup_folder genericSetupForID]);

% Tell Tool to use the loaded model
idTool.setModel(model);

% Load generic External Load file
ext_loads = ExternalLoads(model, [Setup_folder genericSetupForExtLoad]);
% --------------------------------------------------------------------------%

% A string to be used later
cutItOut = (['_IK_' MarkerCountString '.mot']);

trialsForID = dir(fullfile(IK_data_folder, '*.mot'));

nTrials = size(trialsForID,1);

% Loop through the trials
for trial= 1:nTrials;

    % Get the name of the file for this trial
    motionFile = trialsForID(trial).name;

% Create name of trial from .mot file name (removes "_##_IK.mot")
    trialName = regexprep(motionFile,cutItOut,'');
    %trialName = motionFile(1:end-10);
    fullpath = ([IK_data_folder '\' motionFile]);

    % Get mot data to determine time range
    motionData = Storage(fullpath);

    % Get initial and intial time
    initial_time = motionData.getFirstTime();
    final_time = motionData.getLastTime();

% Setting up the external forces xml of ID
    ext_loads.setExternalLoadsModelKinematicsFileName(fullpath)
    ext_loads.setDataFileName([input_data_folder '\' trialName '
```

```
        _grf.mot'])
    ExtLoadName = ([trialName '_ExtLoads_' MarkerCountString '.xml']);
    ExtLoadFullPath = [XML_folder '\' ExtLoadName];
% Save the settings in a setup file
    ext_loads.print(ExtLoadFullPath);


    % Setup the idTool for this trial
    idTool.setName(trialName);
%Directory of where files will be saved and naming of .sto folder
    idTool.setResultsDir(ID_data_folder);

    %idTool.setOutputGenForceFileName([results_folder '\' trialName '_ID.sto'])
    idTool.setOutputGenForceFileName([trialName '_ID_' MarkerCountString '.sto']);
%Input of the IK file
    idTool.setCoordinatesFileName(fullpath)
    idTool.setModelFileName([modelFilePath modelFile]);

%Input of the time range
    idTool.setStartTime(initial_time);
    idTool.setEndTime(final_time);
% so confused as to whether use file name or full directory
    idTool.setExternalLoadsFileName(ExtLoadFullPath);

% ------------------------------------------------------------------------
    % Save the settings in a setup file
    outfileID = ['Setup_ID_' MarkerCountString '_' trialName '.xml'];
    idTool.print([XML_folder '\' outfileID]);

% Create a new object of InverseDynamicsTool since the idTool doesn't seem
% to update properly. Can load in generated XML directly for working run
    idRunner = InverseDynamicsTool([XML_folder '\' outfileID]);

    fprintf(['Performing ID on cycle # ' num2str(trial) '\n']);
```

```
    % Run ID
    idRunner.run();
    % idTool.run();
end

fprintf('Inverse Dynamics has completed. Selecting specific data
    to analyse can be done with "Data Selector" code.\nHave a
    nice day! \n')

%%
cd(subjectDir)
```

B.4 Data Selection

```
% Code written in MatLab R2014b
% Author: Bradley Beck, 2016
function DataSelectorIKV2(~, ~, range)
sheetName = 'sheet1';
workbookFile=uigetfile('.xlsx');

% If no sheet is specified, read first sheet
if nargin == 1 || isempty(sheetName)
    sheetName = 1;
end

% If no range is specified, read all data
if nargin <= 2 || isempty(range)
    range = '';
end

% Import the data
[~, ~, FileInformation] = xlsread(workbookFile, sheetName, range);
FileInformation(cellfun(@(x) ~isempty(x) && isnumeric(x) && isnan(x),FileInformation)) = {''};

% Finds the trial which takes the longest amount of time(& data inputs)
nTrials = size(FileInformation);
fileCount = nTrials(1,1);
max = 0;
for i=1:fileCount
    [DataStart, DataEnd] = properPoints(FileInformation{i,2}, FileInformation{i,3});
    cur = DataEnd - DataStart;
    if(cur>max)
        max=cur;
    end
end

% Initialises a cell foundation of appropriate size to build data into
MaxRowCount = int16(max/0.004)+1;
HeaderCount = 3;
dataCell = cell(MaxRowCount + HeaderCount, 3*(fileCount + 1));
```

```

% Selects which Inverse Dynamics result will be included (limited to one)
% fprintf('What kind of knee data you looking for, fam? \n \n Flexion: 11 \n Rotation: 12 \n Adduction: 13 \n \n')
% wanted = input('Let me know here: ');
for wanted = 11:13

% Variable "flipper" used to make flexion, adducion, and internal rotation
% on the positive y-axis of the final graphs
if wanted == 11
    flipper = -1;
else
    flipper = 1;
end

% Selects time period specified for one full gait cycle
for i=1:fileCount
    filename=FileInformation{i,1};
    filename1=strcat(filename, '.mot');
    StartTime=FileInformation{i,2};
    EndTime=FileInformation{i,3};
    fprintf(['\n Currently checking :' filename])
    [DataStart, DataEnd] = properPoints(StartTime, EndTime);
    [timeOutput, outRight, outLeft] = FileReaderV2(filename1, StartTime, EndTime, DataStart, DataEnd, wanted);

% Writes headings into the data cell
    for j=0:2
        dataCell{HeaderCount,i + j*(fileCount+1)} = filename;
    end

% Reads how many data entries are within one gait cycle of the current file
    mainRows = size(timeOutput,1);

% Writes time and IK data into the data cell
    for j=HeaderCount+1:mainRows+HeaderCount
        dataCell{j,i} = (timeOutput(j-HeaderCount,1));
        dataCell{j,i+(fileCount+1)} = flipper*str2double(outRight(j-HeaderCount,1));
        dataCell{j,i+2*(fileCount+1)} = flipper*str2double(
```

```
            outLeft(j−HeaderCount,1));
%
%
    %
%
    %
%
    end
end


% Defines output file name from subject name and ID data output
  %%% NOTE: ONLY WORKS IF ID FILE HAS SUBJECT NAME SEPARATED BY
      SPACE %%%
g = regexp(FileInformation{1,1}, ' ', 'split');
motion = ' Other ';
if (wanted == 11)
    motion = ' Flexion ';
else if (wanted == 12)
        motion = ' Rotation ';
else if (wanted == 13)
            motion = ' Adduction ';
     end
     end
end
subName = g{1};
dataCell{HeaderCount−1,1} = 'Gait Cycle Percentage (%)';
dataCell{HeaderCount−1,(fileCount+1) + 1} = (['Knee_' motion '
    _Angle_R']);
dataCell{HeaderCount−1,2*(fileCount+1) + 1} = (['Knee_' motion '
    _Angle_L']);
dataCell{HeaderCount−2,1} = 'Number of Files:' ;
dataCell{HeaderCount−2,2} = fileCount;
dataCell{HeaderCount−2,3} = 'Number of data points:' ;
dataCell{HeaderCount−2,4} = MaxRowCount;
exportfile = ([subName motion 'Kinematics.xlsx']);
```

```
% Writes all data from matrix into an excel spreadsheet
xlswrite(exportfile,dataCell)
fprintf('\n ONE DOWN! \n');
end
 end
```

```matlab
% Code written in MatLab R2014b
% Author: Bradley Beck, 2016
function [FileInformation, dataCell] = DataSelectorIDV4(~, ~, range)
sheetName = 'sheet1';
workbookFile=uigetfile('.xlsx');

% If no sheet is specified, read first sheet
if nargin == 1 || isempty(sheetName)
    sheetName = 1;
end

% If no range is specified, read all data
if nargin <= 2 || isempty(range)
    range = '';
end

% Import the data
[~, ~, FileInformation] = xlsread(workbookFile, sheetName, range);
FileInformation(cellfun(@(x) ~isempty(x) && isnumeric(x) && isnan(x),FileInformation)) = {''};


% Read patient weight (can be put in A4 in filedata sheet OR manually input
if (size(FileInformation,2) < 4)
    subjectWeight = input('Please input user weight: \n');
else
    subjectWeight = FileInformation{1,4};
end


% Finds the trial which takes the longest amount of time(& data inputs)
nTrials = size(FileInformation);
fileCount = nTrials(1,1);
max = 0;
for i=1:fileCount
    [DataStart, DataEnd] = properPoints(FileInformation{i,2}, FileInformation{i,3});
    cur = DataEnd - DataStart;
    if(cur>max)
```

```
            max=cur;
        end
end

% Initialises a cell foundation of appropriate size to build data into
MaxRowCount = int16(max/0.004)+1;
HeaderCount = 3;
dataCell = cell(MaxRowCount + HeaderCount, 3*(fileCount + 1));

% Selects which Inverse Dynamics result will be included (limited to one)
% fprintf('What kind of knee data you looking for, fam? \n \n Flexion: 11 \n Rotation: 12 \n Adduction: 13 \n \n')
% wanted = input('Let me know here: ');

% Replaced choosing one file and now produces all three knee information
for wanted = 11:13


% Selects time period specified for one full gait cycle
for i=1:fileCount
    filename=FileInformation{i,1};
    filename1=strcat(filename, '.sto');
    StartTime=FileInformation{i,2};
    EndTime=FileInformation{i,3};
    fprintf(['\n Currently checking :' filename])
    [DataStart, DataEnd] = properPoints(StartTime, EndTime);
    [timeOutput, outRight, outLeft] = FileReaderV2(filename1, StartTime, EndTime, DataStart, DataEnd, wanted);

% Writes headings into the data cell
    for j=0:2
        dataCell{HeaderCount, i + j*(fileCount+1)} = filename;
    end

% Reads how many data entries are within one gait cycle of the current file
    mainRows = size(timeOutput,1);

% Writes time and ID data into the data cell
% Moment data is divided by subject weight to normalise data
```

```
        for j=HeaderCount+1:mainRows+HeaderCount
            dataCell{j,i} = (timeOutput(j-HeaderCount,1));
            dataCell{j,i+(fileCount+1)} = str2double(outRight(j-HeaderCount,1))/subjectWeight;
            dataCell{j,i+2*(fileCount+1)} = str2double(outLeft(j-HeaderCount,1))/subjectWeight;
%         ----------------------------------------------------------------------------------
%                                                                                    %
%                                                                                    %
%         ----------------------------------------------------------------------------------
        end
end


% Defines output file name from subject name and ID data output
  %%% NOTE: ONLY WORKS IF ID FILE HAS SUBJECT NAME SEPARATED BY SPACE %%%
g = regexp(FileInformation{1,1}, ' ', 'split');
motion = ' Other ';
if (wanted == 11)
    motion = ' Flexion ';
else if (wanted == 12)
        motion = ' Rotation ';
else if (wanted == 13)
            motion = ' Adduction ';
     end
     end
end
subName = g{1};
dataCell{HeaderCount-1,1} = 'Gait Cycle Percentage (%)';
dataCell{HeaderCount-1,(fileCount+1) + 1} = (['Knee_' motion '_Moment_R']);
dataCell{HeaderCount-1,2*(fileCount+1) + 1} = (['Knee_' motion '_Moment_L']);
dataCell{HeaderCount-2,1} = 'Number of Files:' ;
```

```
dataCell{HeaderCount-2,2} = fileCount;
dataCell{HeaderCount-2,3} = 'Number of data points:' ;
dataCell{HeaderCount-2,4} = MaxRowCount;
exportfile = ([subName motion 'Dynamics.xlsx']);

% Writes all data from matrix into an excel spreadsheet
xlswrite(exportfile,dataCell)
fprintf('\n ONE DOWN! \n');
end
 end
```

```
Sub PlotNFiles()
'This is the macro to create the appropriate graphs in Excel
'
' Keyboard Shortcut: Ctrl+Shift+R
'
Dim numCols As Integer, numRows As Integer
numCols = Cells(1, 2).Value
numRows = Cells(1, 4).Value
Dim xAxis As String, yAxis As String, subject As String
xAxis = "Gait Cycle Percentage (%)"
yAxis = "Knee Moment per Bodymass (N*m/kg)"
subject = Left(Cells(3, 1).Value, InStr(Cells(3, 1).Value, " "))

Dim i As Integer
ActiveSheet.Shapes.AddChart2(240, xlXYScatterLinesNoMarkers).Select
For i = 1 To numCols
ActiveChart.SeriesCollection.NewSeries
ActiveChart.SeriesCollection(i).Name = Cells(3, i)
ActiveChart.SeriesCollection(i).XValues = Range(Cells(4, i), Cells(4 + numRows - 1, i))
ActiveChart.SeriesCollection(i).Values = Range(Cells(4, (numCols + 1) + i), Cells(4 +
numRows - 1, (numCols + 1) + i))
Next i
Dim graphVal As String
graphVal = Cells(2, (numCols + 1) + 1).Value
ActiveChart.ChartTitle.Text = subject & graphVal & " vs Gait Cycle (%)"
ActiveChart.HasLegend = True
ActiveChart.Legend.Position = xlLegendPositionBottom

ActiveSheet.Shapes.AddChart2(240, xlXYScatterLinesNoMarkers).Select
For i = 1 To numCols
ActiveChart.SeriesCollection.NewSeries
ActiveChart.SeriesCollection(i).Name = Cells(3, i)
ActiveChart.SeriesCollection(i).XValues = Range(Cells(4, i), Cells(4 + numRows - 1, i))
ActiveChart.SeriesCollection(i).Values = Range(Cells(4, 2 * (numCols + 1) + i), Cells(4
+ numRows - 1, 2 * (numCols + 1) + i))
Next i
graphVal = Cells(2, 2 * (numCols + 1) + 1).Value
ActiveChart.ChartTitle.Text = subject & graphVal & " vs Gait Cycle (%)"
ActiveChart.HasLegend = True
ActiveChart.Legend.Position = xlLegendPositionBottom

End Sub
```

```
Sub DataStatistics()
'This macro will calculate and print the average to all the columns of relevant data
' Keyboard Shortcut: Ctrl+Shift+S
'
Dim numCols As Integer, numRows As Integer

numCols = Cells(1, 2).Value
numRows = Cells(1, 4).Value


' Prints Average
Dim i As Integer, j As Integer
For j = 4 To numRows + 3
For i = 0 To 2
Cells(j, (i + 1) * (numCols + 1)).Value = WorksheetFunction.Average(Range(Cells(j, 1
+ i * (numCols + 1)), Cells(j, numCols + i * (numCols + 1))))
Cells(j, (i + 1) * (numCols + 1)).Interior.ColorIndex = 37
Next i
Next j

End Sub
```

B.5 Data Filtering

```
% Takes the .xlsx file created from "DataSelector.m" and applied
    a
% Butterworth Filter (design parameters specified by Dr. Lauren
    Kirk) to
% the knee moment values.
% Code written in MatLab R2014b
% Author: Bradley Beck, 2016
%Take in .sto file
%fprintf('Please select the file for processing \n')
fprintf('Please select the file for processing and wait until
    your number is called.\n')
InputFile = uigetfile('.xlsx');
filename = InputFile(1:end-5);
delimiterIn = ' ';
headerlinesIn = 3;
A = importdata(InputFile,delimiterIn,headerlinesIn);
% B=A.data([4,size(A.data,1)],:);
```

```
B = A.data;
B(1:headerlinesIn, :) = [];
outputCell = cell(size(B,1), size(B,2)+1);
dataCount = ((size(B,2)-2)/3);

[b,a] = butter(4,0.048);

for trial = 1:dataCount
    rawRight = B(:,(dataCount+1) + trial);
    rawLeft = B(:,2*(dataCount+1) + trial);
    rawRight(isnan(rawRight(:,1)),:) = [];
    rawLeft(isnan(rawLeft(:,1)),:) = [];
% butter(order, (desired cutoff frequency)/(0.5*sampling rate))
% currently 6Hz cutoff with 250Hz sampling rate
    dataOutRight = filtfilt(b,a,rawRight);
    dataOutLeft = filtfilt(b,a,rawLeft);
    for row=1:size(dataOutRight,1)
% Take gait percentage straight with no filtering
        outputCell{row,trial} = B(row,trial);
        outputCell{row,(dataCount+1) + trial} = dataOutRight(row,1);
        outputCell{row,2*(dataCount+1) + trial} = dataOutLeft(row,1);
    end
end

Head = A.textdata;
for i=1:3
    Head{headerlinesIn, i*(dataCount+1)} = 'Average';
end

All = [Head; outputCell];
All{1,2} = A.data(1,2);
All{1,4} = A.data(1,4);
% Writes all data from matrix into an excel spreadsheet
exportfile = ([filename '_filtered.xlsx']);
xlswrite(exportfile, All)
fprintf('Data has been filtered. NEXT!\n')
```