Contents

Collection parameters

1. Describe the equipment used to collect the data (e.g. model/manufacturer, number of cameras. (2)

To collect the data, a Northern Digital Inc. OptoTrak active motion capture system was used. The setup consisted of 5 housings, each with 3 cameras, for a total of 15 cameras. 3 of the housings were the older 3020 system and 2 were the newer Certus system. The participant had a total of 17 markers placed in clusters on their right foot, shank, thigh, and back of the pelvic region. Each segment cluster had 4 markers, except for the pelvic region which had 5. Bony landmarks on the right side were then digitized relative to these markers using a probe.

2. What was the sampling rate and what trial durations were collected? (3)

A sampling rate of 64 Hz was used for all trials. The four static trials of standing, squatting, unilateral and supported kneeling ran for about 5 seconds each. The walking trail lasted for about 10 seconds; however, the participant was only in the capture volume for a fraction of that time, reducing the usable data timeframe significantly. A single trial for each pose/action was analyzed in this report.

3. Describe your participant (anthropometric info, sex, etc.) (3)

The participant was a young female (~23 years old), who was 165.8 cm tall. Weight was not collected because it was unnecessary for our purposes.

4. Describe the calibration procedures used to calibrate the motion capture system and the outcome of that calibration. (2)(i.e. how do you know it was a good calibration?)

The cameras began by undergoing a registration process, which informs the system where the cameras are relative to one another in space. To do so, a cube with known marker geometry was waved in the capture volume. For this study, lower limb movement was the primary area of interest, so the cube was waved low to the ground, up to waist height, to ensure the necessary capture volume was calibrated. When doing so, we want to minimize any error. The error represents the average difference between the known marker geometry on the cube and data the capture system collected during calibration, and an error of less than 0.5 mm is considered acceptable. The calibration for this study produced an error of 0.451 mm, indicating that this calibration was a good one.

5. Describe the calibration procedures needed to orient the markers relative to the participant. (3)

To begin, a global coordinate system (GCS) was created for the capture space. To do so, we first defined the origin by digitizing the corner of the force plate boundary with a probe. Next, the X-axis was defined by placing the probe in the direction of gait progression, relative to the origin. The probe was then placed within the +X/-Z plane, which was done by placing the probe laterally in the -Z direction. From the defined origin, X-axis and +X/-Z plane, the system could define and locate the GCS. For this trial, the positive X, Y, and Z axes pointed toward the forward progression of the participant, upward, and to the right of the participant, respectively. The clusters of markers placed on each segment were used to digitize the desired landmarks needed for analysis. During this process, the participant posed with a standing posture in the capture volume with all physical markers visible to the cameras.

Calculate the 3D positions, translational velocities, and accelerations of the ankle, knee and hip joint centres for all tasks.

6. Describe the mathematical procedures used to generate this data, including filtering of the data and any procedures/equations needed to obtain joint centres from collected data. A numbered list of steps is acceptable and encouraged. (8)

1. Crop the beginning and end of the data to get useable frames.
    a. This varies from task to task and is done manually.
    b. Delete rows that have large gaps at the beginning or the end of the data. Do this for the pair of marker data with the largest gaps before and after.
    c. Delete the columns containing the cluster data.
2. Interpolate missing data points using a cubic spline function.
3. Filter the data.
    a. Use a second-order lowpass Butterworth filter with a cut-off frequency of 6Hz for each column of the interpolated data [1]. Use the *butter* and *filtfilt* MATLAB functions.
4. Define the ankle joint centre.
    a. Midpoint of the lateral and medial malleoli [3].

$$A_{JC,x} = \frac{LM_x + MM_x}{2}$$
$$A_{JC,y} = \frac{LM_y + MM_y}{2}$$
$$A_{JC,z} = \frac{LM_z + MM_z}{2}$$
$$\vec{A}_{JC,Global} = [A_{JC,x} \quad A_{JC,y} \quad A_{JC,z}]$$

5. Define the knee joint centre.
    a. Midpoint of the lateral and medial femoral condyles [3].

$$K_{JC,x} = \frac{LFC_x + MFC_x}{2}$$

$$K_{JC,y} = \frac{LFC_y + MFC_y}{2}$$

$$K_{JC,z} = \frac{LFC_z + MFC_z}{2}$$

$$\vec{K}_{JC,Global} = [K_{JC,x} \quad K_{JC,y} \quad K_{JC,z}]$$

6. Define the hip joint centre. Adapted from sources [2]-[4].
   a. Using the cited sources' methods, I calculated the local hip joint center [3]. Note that they defined a different LCS axes orientation so I will be adjusting their equations to match my orientation (ISB standard) [2][3]. '

$$H_{JC,x} = -0.19 * (|\overrightarrow{RASIS} - \overrightarrow{LASIS}|)$$
$$H_{JC,y} = -0.30 * (|\overrightarrow{RASIS} - \overrightarrow{LASIS}|)$$
$$H_{JC,z} = 0.36 * (|\overrightarrow{RASIS} - \overrightarrow{LASIS}|)$$
$$\vec{H}_{JC,local} = [HJC_x \quad HJC_y \quad HJC_z]$$

   b. Define the origin for a reference local coordinate system (LCS) for the pelvis. Place the origin at the midpoint between the left and right anterior superior iliac spines [4].

$$O_{p,x} = \frac{LASIS_X + RASIS_X}{2}$$

$$O_{p,y} = \frac{LASIS_y + RASIS_y}{2}$$

$$O_{p,z} = \frac{LASIS_z + RASIS_z}{2}$$

$$\vec{O}_p = (O_{p,x}, O_{p,y}, O_{p,z})$$

   c. Find the midpoint of the left and right posterior superior iliac spines [4].

$$PSIS_{MID,X} = \frac{LPSIS_x + RPSIS_x}{2}$$

$$PSIS_{MID,Y} = \frac{LPSIS_y + RPSIS_y}{2}$$

$$PSIS_{MID,Z} = \frac{LPSIS_z + RPSIS_z}{2}$$

$$\overrightarrow{PSIS}_{MID} = (PSIS_{MID,X}, PSIS_{MID,Y}, PSIS_{MID,Z})$$

d. Define the local z-axis of the pelvis as a line going through the right ASIS from the pelvic origin with the positive direction facing the right. Also, calculate its unit vector.

$$\overrightarrow{z_P} = \overrightarrow{RASIS} - \overrightarrow{O_P}$$

$$(\widehat{k_p}) = \frac{\overrightarrow{z_P}}{|(\overrightarrow{z_P})|}$$

e. Define a temporary vector for the pelvis as a line going through pelvic origin from the mid PSIS with the positive direction facing anteriorly [4].

$$\overrightarrow{v_P} = \overrightarrow{O_P} - \overrightarrow{PSIS}_{MID}$$

f. Take the cross-product of the z and v axes ($\overrightarrow{z_P}$ X $\overrightarrow{x_P}$) to obtain a perpendicular y-axis. Take the cross-product of the y and z axes ($\overrightarrow{y_P}$ X $\overrightarrow{z_P}$) to obtain a perpendicular x axis. Calculate its unit vector. Calculate the unit vectors.

$$\overrightarrow{y_P} = (\overrightarrow{z_P} \times \overrightarrow{v_P})$$

$$(\widehat{J_p}) = \frac{\overrightarrow{y_P}}{|(\vec{y})|}$$

$$\overrightarrow{x_P} = (\overrightarrow{y_P} \times \overrightarrow{z_P})$$

$$(\widehat{\iota_p}) = \frac{\overrightarrow{x_P}}{|(\overrightarrow{x_P})|}$$

g. Define the local to global rotation matrix per ISB recommendations [2]. A ZYX (local to global) matrix is recommended from the cited literature and provides me with the equation for the rotation matrix and Euler angles α, β, and γ. Also define the global unit vectors.

$$[{}^{L}R_G] = \begin{bmatrix} \cos\alpha\cos\beta & \cos\alpha\sin\beta\sin\gamma - \sin\alpha\cos\gamma & \cos\alpha\sin\beta\cos\gamma + \sin\alpha\sin\gamma \\ \sin\alpha\cos\beta & \sin\alpha\sin\beta\sin\gamma + \cos\alpha\cos\gamma & \sin\alpha\sin\beta\cos\gamma - \cos\alpha\sin\gamma \\ -\sin\beta & \cos\beta\sin\gamma & \cos\beta\cos\gamma \end{bmatrix}$$

$$\beta = -\sin^{-1}(\vec{K} \cdot \vec{\imath})$$

$$\alpha = \sin^{-1}\frac{\vec{J} \cdot \vec{\imath}}{cos\beta}$$

$$\gamma = \sin^{-1}\frac{\vec{K} \cdot \vec{\jmath}}{cos\beta}$$

$$\vec{J} = [1\ 0\ 0]$$

$$\vec{J} = [0\ 1\ 0]$$

$$\vec{K} = [0\ 0\ 1]$$

h. Calculate α, β, and γ between the local pelvis and global coordinate systems [2]. Use the angles to calculate the pelvis to global rotation matrix [2].

$$\beta_P = -\sin^{-1}(\vec{K} \cdot \overrightarrow{\imath_P})$$

$$\alpha_P = \sin^{-1}\frac{\vec{J} \cdot \overrightarrow{\imath_P}}{cos\beta}$$

$$\gamma_P = \sin^{-1}\frac{\vec{K} \cdot \overrightarrow{\jmath_P}}{cos\beta}$$

$$[{}^{P}R_G] = \begin{bmatrix} \cos\alpha\cos\beta & \cos\alpha\sin\beta\sin\gamma - \sin\alpha\cos\gamma & \cos\alpha\sin\beta\cos\gamma + \sin\alpha\sin\gamma \\ \sin\alpha\cos\beta & \sin\alpha\sin\beta\sin\gamma + \cos\alpha\cos\gamma & \sin\alpha\sin\beta\cos\gamma - \cos\alpha\sin\gamma \\ -\sin\beta & \cos\beta\sin\gamma & \cos\beta\cos\gamma \end{bmatrix}$$

i. Use the equation from the literature to convert the local hip joint centre to the global one [3].

$$\vec{H}_{JC,global} = \vec{O}_p + [{}^{P}R_G][H_{JC,local}]^T$$

7. Calculate the time intervals for the trials using the sampling frequency of 64 Hz.

$$\Delta t = \frac{1}{f} = \frac{1}{64} = 0.015625\ s$$

8. Using the time interval determined earlier, calculate the velocity and acceleration of each joint using the 3-point central difference technique.

$$v_{mJC,X,n} = \frac{mJC_{X,n+1} - mJC_{X,n-1}}{2\Delta t}$$
$$v_{mJC,Y,n} = \frac{mJC_{Y,n+1} - mJC_{Y,n-1}}{2\Delta t}$$
$$v_{mJC,Z,n} = \frac{mJC_{Z,n+1} - mJC_{Z,n-1}}{2\Delta t}$$
$$a_{mJC,X,n} = \frac{mJC_{X,n+1} - 2mJC_{X,n} + mJC_{X,n-1}}{\Delta t^2}$$
$$a_{mJC,X,n} = \frac{mJC_{X,n+1} - 2mJC_{X,n} + mJC_{X,n-1}}{\Delta t^2}$$
$$a_{mJC,X,n} = \frac{mJC_{X,n+1} - 2mJC_{X,n} + mJC_{X,n-1}}{\Delta t^2}$$

Where m represents a given joint and n is the frame number.

7. For the static tasks, describe the magnitudes and variation of the time derivative translational values (i.e. velocity, acceleration). (1)

The segment velocities and accelerations fluctuated around zero for all the static tasks. This makes sense since there was almost no displacement occurring, which when derived, will result in almost 0 translational values. The only notable fluctuations were most likely caused by the participant readjusting their pose and even then, they were a few millimeters.

8. For the walking task, produce time-series graphs for each of these quantities (positions, velocities, accelerations) for the ankle joint centre in each direction. (2)

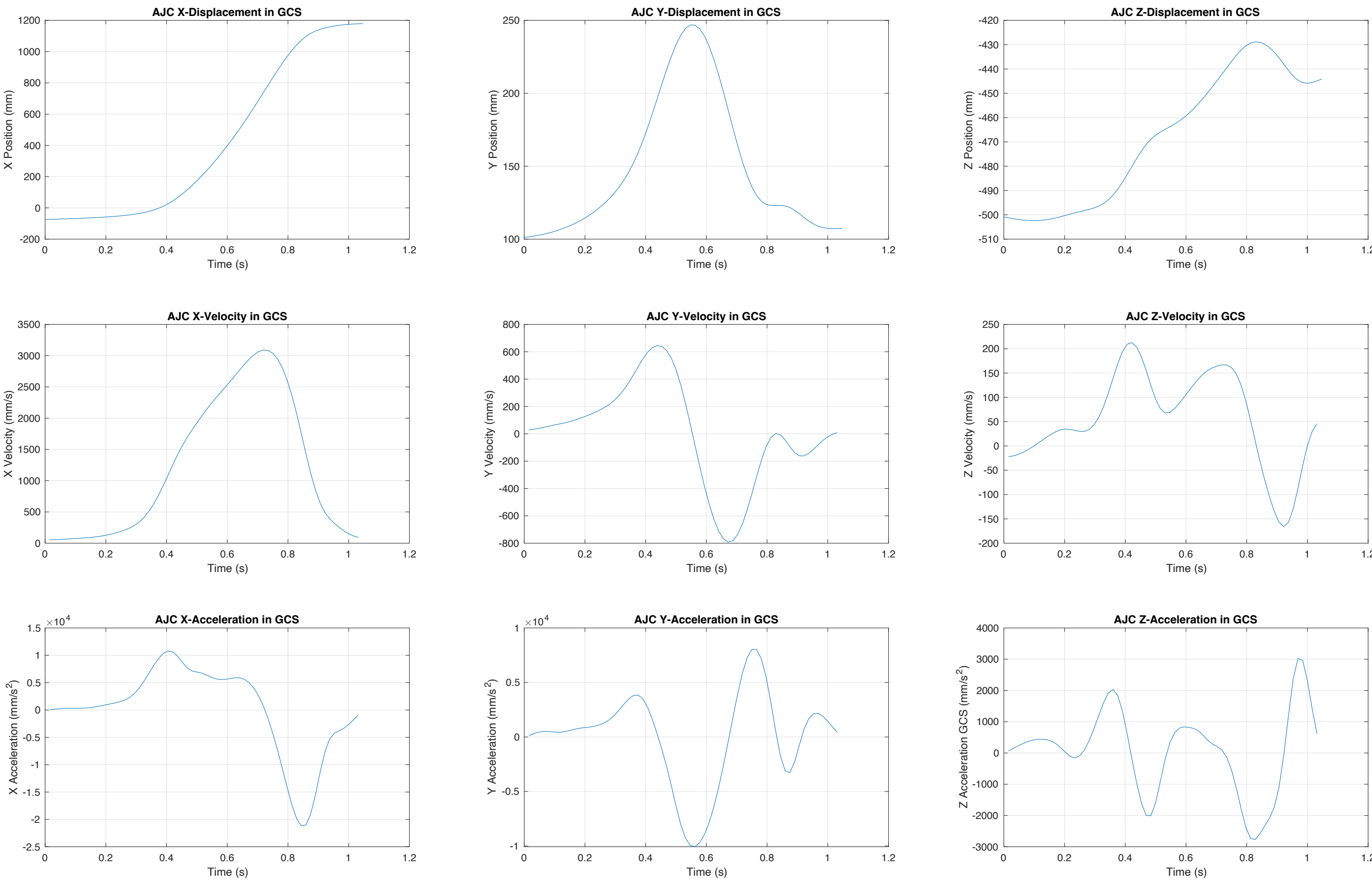

Figure 1: X, Y, Z displacements, velocities, and accelerations of the AJC in the GCS for the gait trial.

9. For the walking task, produce time-series graphs for each of these quantities (positions, velocities, accelerations) for the knee joint centre in each direction. (2)

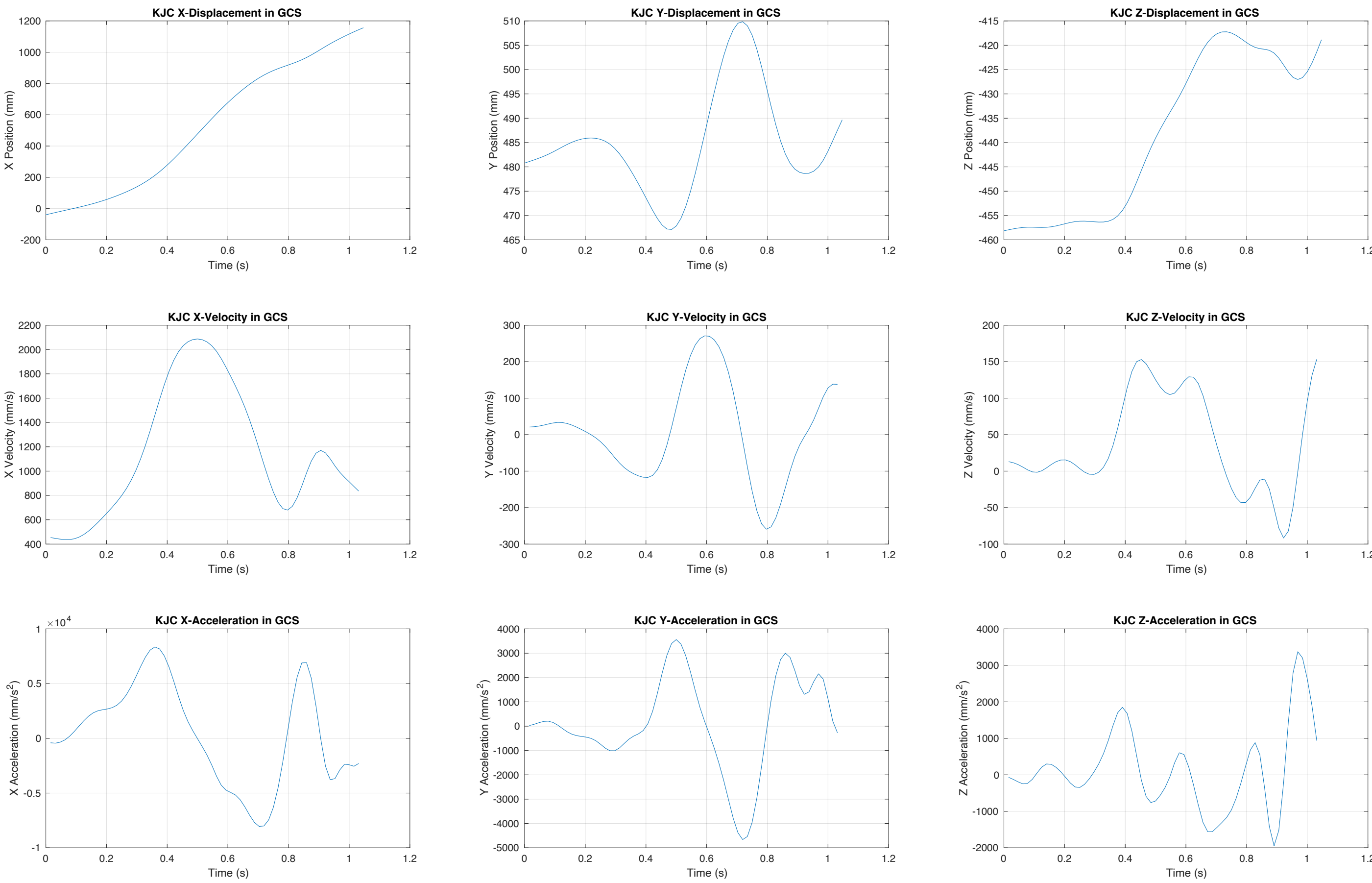

Figure 2: X, Y, Z displacements, velocities, and accelerations of the KJC in the GCS for the gait trial.

10. For the walking task, produce time-series graphs for each of these quantities (positions, velocities, accelerations) for the hip joint centre in each direction. (2)

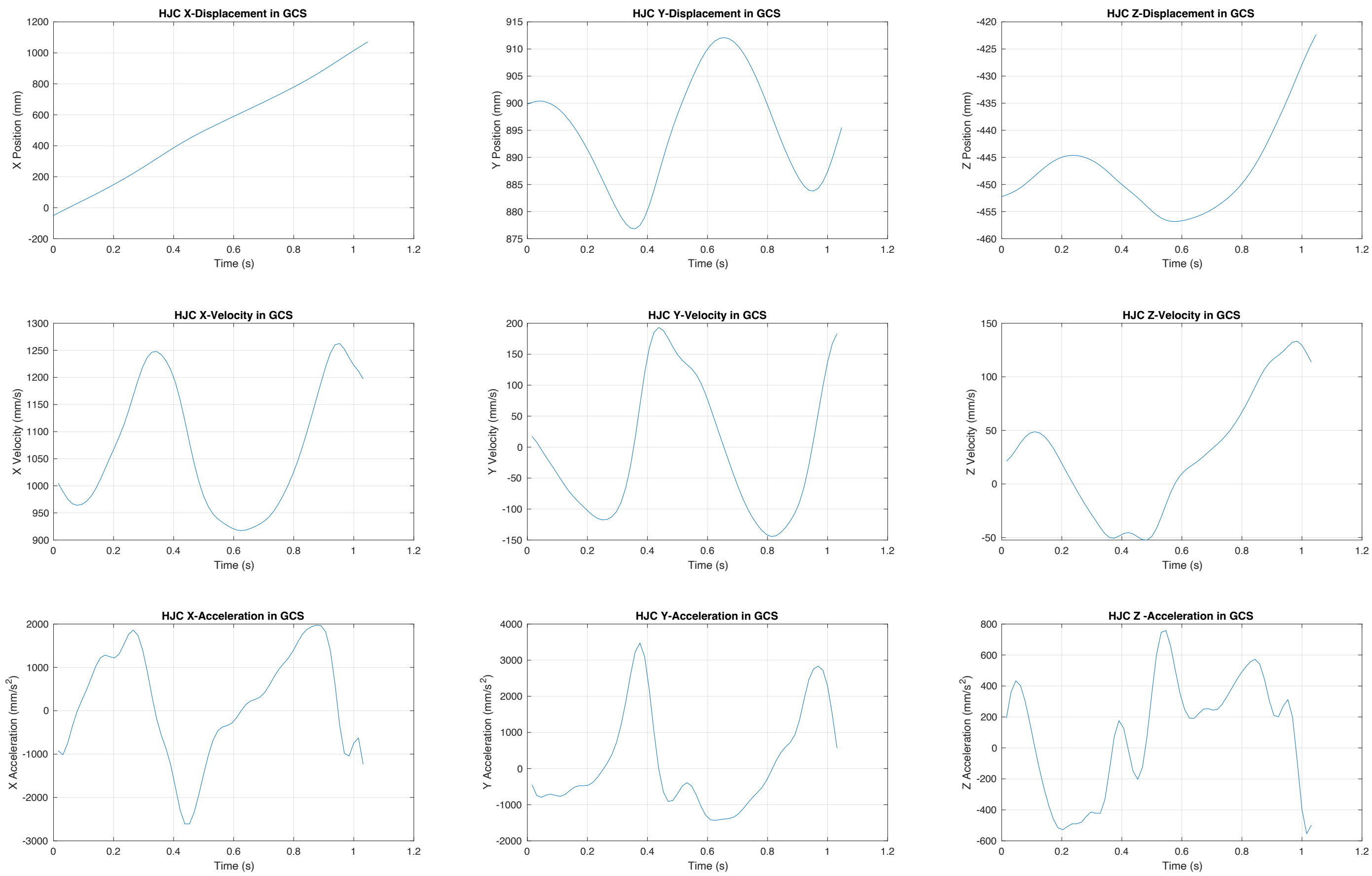

Figure 3: X, Y, Z displacements, velocities, and accelerations of the HJC in the GCS for the gait trial.

11. Comment on the tendencies of these data (from questions 8-10) for each task and movement direction. Describe why these tendencies are or are not what you expected? (4)

Regarding the X-position, the results for all three joint centres are expected, considering that the X-axis represents the direction of progression. They all have a generally linear forward movement along the X-axis, which represents the forward progression that occurs during gait. The HJC had the most linear rate of forward progression while the KJC and AJC both had periods of fluctuation between increased and decreased rates of forward progression, with the AJC having the most drastic change in progression rate. This is reflected in the X-velocity and X-acceleration of the joints as well. The HJC had the smallest change of X-velocity compared to the KJC and AJC, where the AJC had the largest difference from minimum to maximum. The accelerations showed a similar trend. When considering the gait cycle, the data reflects expected behaviour since the KJC and AJC will see a proportionately large change of position during the swing phase, while the HJC is fixed to the torso and will have a more gradual response for all values.

Regarding the Y-position, the results for all three joint centres are expected, considering that the Y-axis represents the vertical response. The ankle saw the greatest vertical displacement then the knee and finally the hip (least), which is expected since during the gait cycle the AJC will be lifted with the foot off the ground through by knee joint flexion, followed by a step of progression, which requires sufficient toe clearance height, which is executed by the knee. This means that the AJC and KJC have the greatest vertical displacement, which agrees with the data. The HJC position shows the smallest vertical displacement, which makes sense as well, when considering the movement of the gait cycle. The larger displacements of the AJC and KJC compared to the HJC, give larger velocity and acceleration ranges as expected.

Regarding the Z-position, the results for all three joint centres are expected, considering that the Z-axis represents the lateral response. Looking at the graphs for Z-displacement across all joint centres, we see a generally negative values, with a positive slope, indicating that the participant began away from the origin and walked along a trajectory angled slightly away from the X/-Z plane rather than parallel with the X-axis. In addition to this movement, it does appear that each joint had minor movement in the lateral and medial direction, which is not necessarily conducive with a forward progression during gait but makes sense when considering the variance that exists between gait styles and the movement of joints during the cycle. Despite the lateral and medial changes in position, the results are still expected. This behavior is also reflected in the velocities of the joints which show similar ranges of translational values for all joints. However, I would have expected the HJC to have the largest response range for all values as the torso tends to “sway” medially and laterally while walking, which is not necessarily reflected in the data. The participant had to alter their gait slightly during experimentation by controlling their hand and arm movement to prevent occlusion of some of the hip and pelvis clusters, which may have made them stray away from their traditional gait.

12. What potential sources of inaccuracy exist for locating joint centres? (4)

When doing this sort of experimentation and analysis, several potential sources of inaccuracy can occur. Interpolation is a point during the analysis where errors can occur. If there are several large gaps of missing data, the interpolation may produce odd results. This is ultimately caused by poor data collection methods, where the cameras' visibility of the markers on the participant may be obstructed. This is further exacerbated by poor data managing techniques, where when cleaning the data, large gaps were left or the beginning and ends of the data still have holes.

One error from the data collection phase may include skin and muscle artifacts. Since the markers are attached to the skin or wrapped around segments in clusters, they will shift with the skin and muscle during movement and give false locations for the digitized bony landmarks. During digitization of these landmarks, it is also possible that the probe is not positioned perfectly in the intended location when compared to the positions of the landmarks in the literature.

When deciding how to define your joint centre, most of the decisions come from previous literature, which always has a degree of inaccuracy, which is typically reported in the source. This can lead to additional issues when locating joint centres. Since the three joint centres were all approximated from bony landmarks, there will inevitably be some error associated with the reported method. The HJC is a particularly difficult joint to estimate based on bony landmarks due to its complex geometry and varying degrees of superficiality. Comparatively speaking, the error for the AJC and KJC will be smaller than that of HJC simply due to their superficial anatomical positions of the bony landmarks.

Finally, the camera system calibration, if done improperly, can give inaccuracies in the collected data. The same will occur if a camera is shifted after registration and calibration. During our data collection, a reported inaccuracy of marker position of 0.451 mm was reported, which is within the tolerable range, but will inevitably skew results.

13. Describe how you could attempt to minimize the sources of inaccuracy in your experimental setup and/or calculations. (4)

To reduce inaccuracy during data collection, several steps can be taken to maximize success. Increasing the marker count on each segment can help reduce gaps of missing data and make interpolation and identification of bony landmarks more seamless. Each segment needs at least three markers as discussed in class; however, more can be used in case some get blocked from the camera's view during experimentation. Additionally, it is important during the experimental setup to ensure that all markers and clusters are secured in place, and not obstructed from the camera's view as much as possible.

To minimize calculation inaccuracy, it is best to research for the most up-to-date standards and methods that yield the most accurate joint centres with the smallest reported error. It may also be useful to understand the limitations and simplifications of each reported method to understand what your data can and cannot do.

Another way to reduce error during data collection is to ensure that your camera calibration has a tolerable and minimized reported marker inaccuracy. To do so, the calibration should be done to represent the motion being captured. For example, as we did, during the analysis of the lower limbs, the calibration cube was waved in the lower portion of the capture volume.

Construct local coordinate systems for the foot, shank, and thigh, using the joint centres calculated earlier and additional tracked landmarks.

14. Describe your methodology and rationale for decisions on axes for your segment coordinate systems. (12)

All my LCS definitions are based on source [3]. Note that the source defined a different LCS axes orientation so I will be adjusting their equations to match my orientation, which is based on ISB standards [2]. I used ISB standards because they established an industry standard to keep data analysis and practice consistent between research, ultimately enabling more accurate comparisons between different literature [2]. The reason this method was used is because it was recommended in class as an assigned reading and aligned with all the collected markers that were taken during experimentation [3]. This was the case for all the segment LCS. This source also had clear directions and came from a reliable source [3].

<u>Foot LCS [3]:</u>

First, Set the origin of the foot as the heel. Define the local x-axis of the foot as a line going through the 2nd metatarsal from the heel origin with the positive direction facing the anteriorly. Also, calculate its unit vector. Calculate the midpoints of the malleoli (using the foot markers). Create a temporary unit vector (v) as a line going through the middle of the malleoli from the heel origin. Take the cross-product of the temporary vector and the x-vector to get the z-axis. Calculate the unit vector for z. Finally, take the cross-product of the z and x axes to obtain a perpendicular y-axis. Calculate its unit vector. This results in a fully defined foot LCS. he mathematical steps implemented into MATLAB can be seen below.

$\vec{O_F} = \overrightarrow{Heel_F}$
$\vec{x_F} = \overrightarrow{2M} - \vec{O_F}$ $\widehat{(\iota_F)} = \frac{\vec{x_F}}{norm(\vec{x_F})}$
$Mal_{MID,X} = \frac{MM_x + LM_x}{2}$ $Mal_{MID,Y} = \frac{MM_y + LL_y}{2}$ $Mal_{MID,Z} = \frac{MM_z + LL_z}{2}$ $\overrightarrow{Mal_{mid}} = (Mal_{MID,X}\ Mal_{MID,Y}\ Mal_{MID,Z})$
$\vec{v_F} = \overrightarrow{Mal_{mid}} - \vec{O_F}$
$\vec{z_F} = cross(\vec{x_F}, \vec{v_F})$ $\widehat{(k_F)} = \frac{\vec{z_F}}{norm(\vec{z_F})}$
$\vec{y_F} = cross(\vec{z_F}, \vec{x_F})$ $\widehat{(y_F)} = \frac{\vec{y_F}}{norm(\vec{y_F})}$

Shank LCS [3]:

First, define the origin of the shank as the midpoint between femoral condyles for x, y and z points. Calculate the midpoints of the malleoli (using shank markers). Define the local y-axis of the shank as a line going through the origin of the shank from the malleoli midpoint. Take the unit vector. Create a temporary unit vector (v) as a line going through the lateral femoral epicondyle from the medial femoral epicondyle. Take the cross-product of the y vector and the temporary vector to get the x-axis. Calculate the unit vector. Take the cross-product of the x and y axes to obtain a perpendicular z-axis. Calculate the unit vector. The mathematical steps implemented into MATLAB can be seen below.

$\vec{O}_S = \frac{\overrightarrow{LFC_T} + \overrightarrow{MFC_T}}{2}$
$Mal_{MID,X} = \frac{MM_x + LM_x}{2}$ $Mal_{MID,Y} = \frac{MM_y + LL_y}{2}$ $Mal_{MID,Z} = \frac{MM_z + LL_z}{2}$ $\overrightarrow{Mal_{mid}} = (Mal_{MID,X}\ \ Mal_{MID,Y}\ Mal_{MID,Z})$
$\overrightarrow{y_F} = \overrightarrow{O_S} - \overrightarrow{Mal_{mid}}$ $(\widehat{\jmath_S}) = \frac{\overrightarrow{y_S}}{norm(\overrightarrow{y_S})}$
$\overrightarrow{v_S} = \overrightarrow{LFC} - \overrightarrow{MFC}$
$\overrightarrow{x_S} = cross(\overrightarrow{y_S}, \overrightarrow{v_S})$ $(\widehat{\imath_S}) = \frac{\overrightarrow{x_S}}{norm(\overrightarrow{x_S})}$
$\overrightarrow{z_S} = cross(\overrightarrow{x_S}, \overrightarrow{y_S})$ $(\widehat{k_S}) = \frac{\overrightarrow{z_S}}{norm(\overrightarrow{z_S})}$

Thigh LCS [3]:

First define the local y-axis of the thigh as a line going through the origin of the thigh (which is equal to the hip joint centre) from the femoral condyles' midpoint. The HJC was determined earlier. Take the unit vector. Create a temporary unit vector (v) as a line going through the lateral femoral epicondyle from the medial femoral epicondyle. Take the cross-product of the y vector and the temporary vector to get the x-axis. Calculate the unit vector. Take the cross-product of the x and y axes to obtain a perpendicular z-axis. Calculate the unit vector. The mathematical steps implemented into MATLAB can be seen below.

$\vec{O}_T = \vec{H}_{JC,global}$ $\overrightarrow{FC}_{mid} = \vec{O}_S$ $\overrightarrow{y_T} = \overrightarrow{O_T} - \overrightarrow{FC}_{mid}$ $\widehat{(j_T)} = \frac{\overrightarrow{y_T}}{norm(\overrightarrow{y_T})}$
$\overrightarrow{v_T} = \overrightarrow{LFC} - \overrightarrow{MFC}$ $\widehat{(v_T)} = \frac{\overrightarrow{v_T}}{norm(\overrightarrow{v_T})}$
$\overrightarrow{x_T} = cross(\overrightarrow{y_T}, \overrightarrow{v_T})$ $\widehat{(\imath_T)} = \frac{\overrightarrow{x_T}}{norm(\overrightarrow{x_T})}$
$\overrightarrow{z_T} = cross(\overrightarrow{x_T}, \overrightarrow{y_T})$ $\widehat{(k_T)} = \frac{\overrightarrow{z_T}}{norm(\overrightarrow{z_T})}$

15. Show figures of the local coordinate system of each segment in your report. (3)

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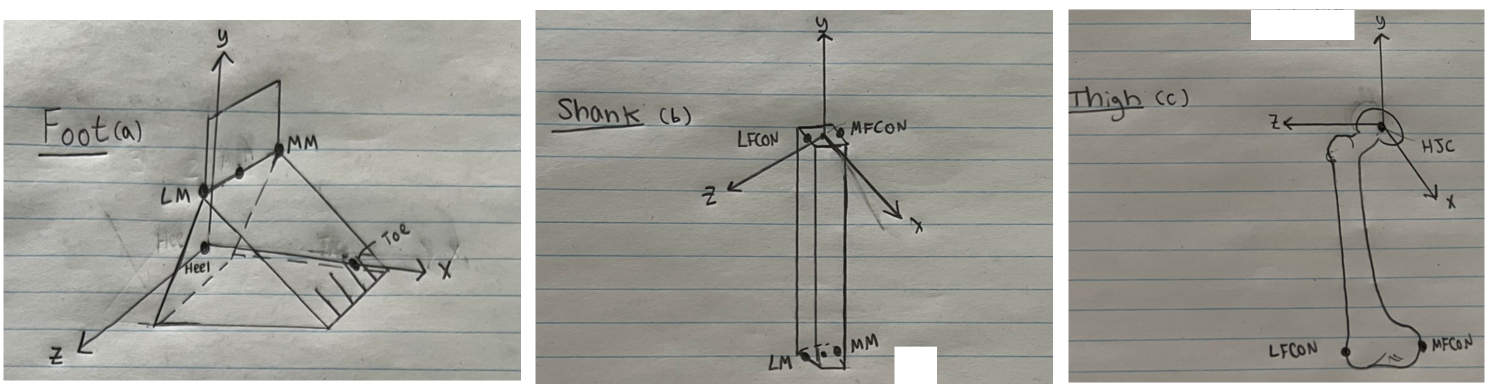

Figure 4: LCS for foot (a), shank (b), and thigh (c).

16. For the walking task, calculate segment angles for each of the segments and present them as time-series data for the walking task. (4)

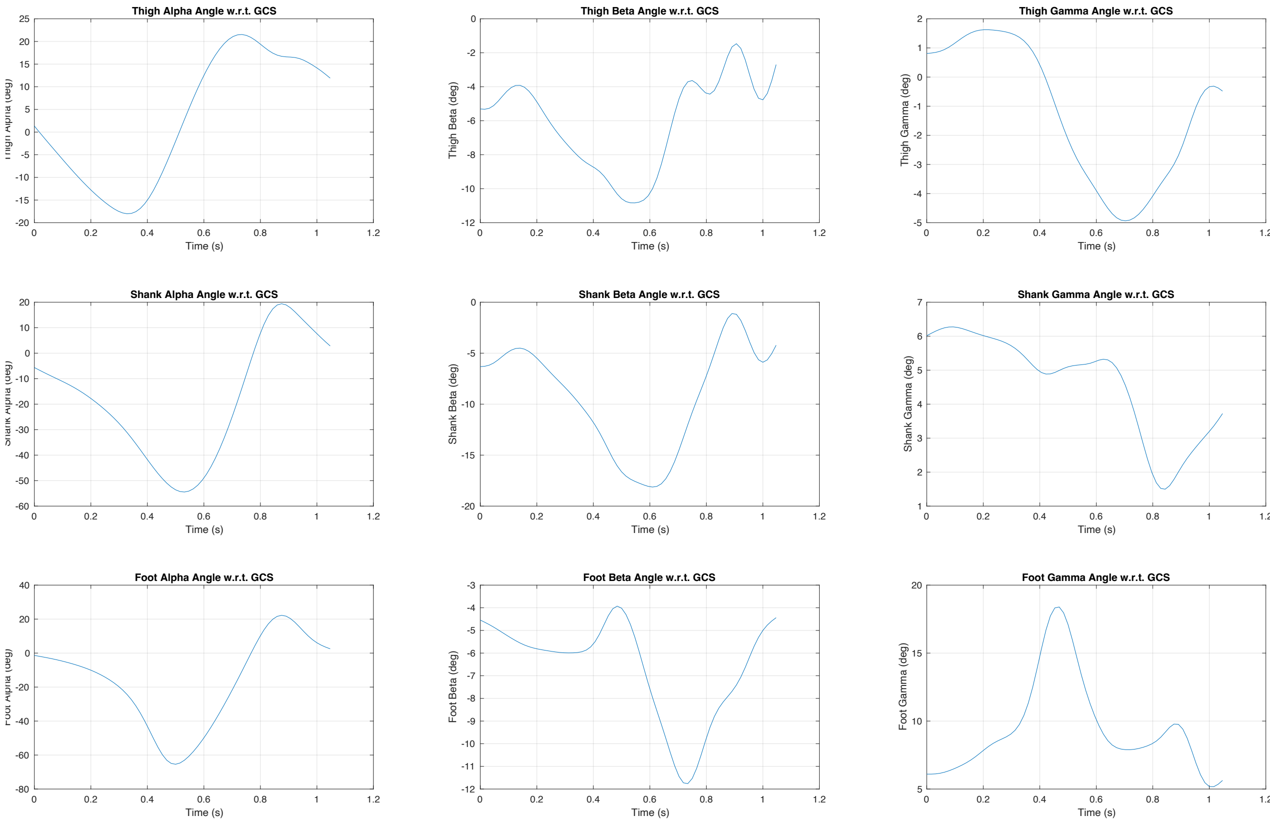

Figure 5: Segments angles alpha, beta and gamma for the gait trial.

17. For the static tasks, calculate segment angles for each of the segments (foot, shank, thigh) and determine the mean and standard deviation for each task. (2)

Task	Segment	Angle	Mean [deg.]	Standard Deviation [deg.]
Standing	Foot	Alpha	-3.2047	0.058759
		Beta	-11.6922	0.017422
		Gamma	0.87415	0.020266
	Shank	Alpha	-7.8309	0.12831
		Beta	-1.5968	0.027751
		Gamma	-0.27038	0.026434
	Thigh	Alpha	-7.731	0.17781
		Beta	-1.5775	0.03276
		Gamma	-1.4484	0.028515
Squatting	Foot	Alpha	-7.8093	0.44284
		Beta	-29.7458	0.25669
		Gamma	-10.0809	0.22261
	Shank	Alpha	-31.0265	1.028
		Beta	-33.7044	0.33268
		Gamma	7.5672	0.39847
	Thigh	Alpha	73.8978	0.78358
		Beta	4.0373	0.32274
		Gamma	-22.5947	0.34844
Unilateral Kneeling	Foot	Alpha	-5.7432	0.029763
		Beta	-1.6558	0.03988
		Gamma	0.34892	0.057406
	Shank	Alpha	-19.3464	0.15874
		Beta	-19.6096	0.13716
		Gamma	4.1421	0.33702
	Thigh	Alpha	85.9737	0.1622
		Beta	-1.3601	0.29474
		Gamma	-9.9949	0.21696
Single Arm Supported Kneeling	Foot	Alpha	-66.4063	0.095836
		Beta	-4.9182	0.048088
		Gamma	-57.3848	0.10021
	Shank	Alpha	-59.4341	0.045026
		Beta	-4.8948	0.026694
		Gamma	-57.5506	0.051144
	Thigh	Alpha	-18.3962	0.31572
		Beta	60.5315	0.16854
		Gamma	7.2577	0.20528

18. Using ISB guidelines and appropriate rotation sequences, calculate the joint angles (ankle and knee angles) for the walking task and present them as time-series data (4)

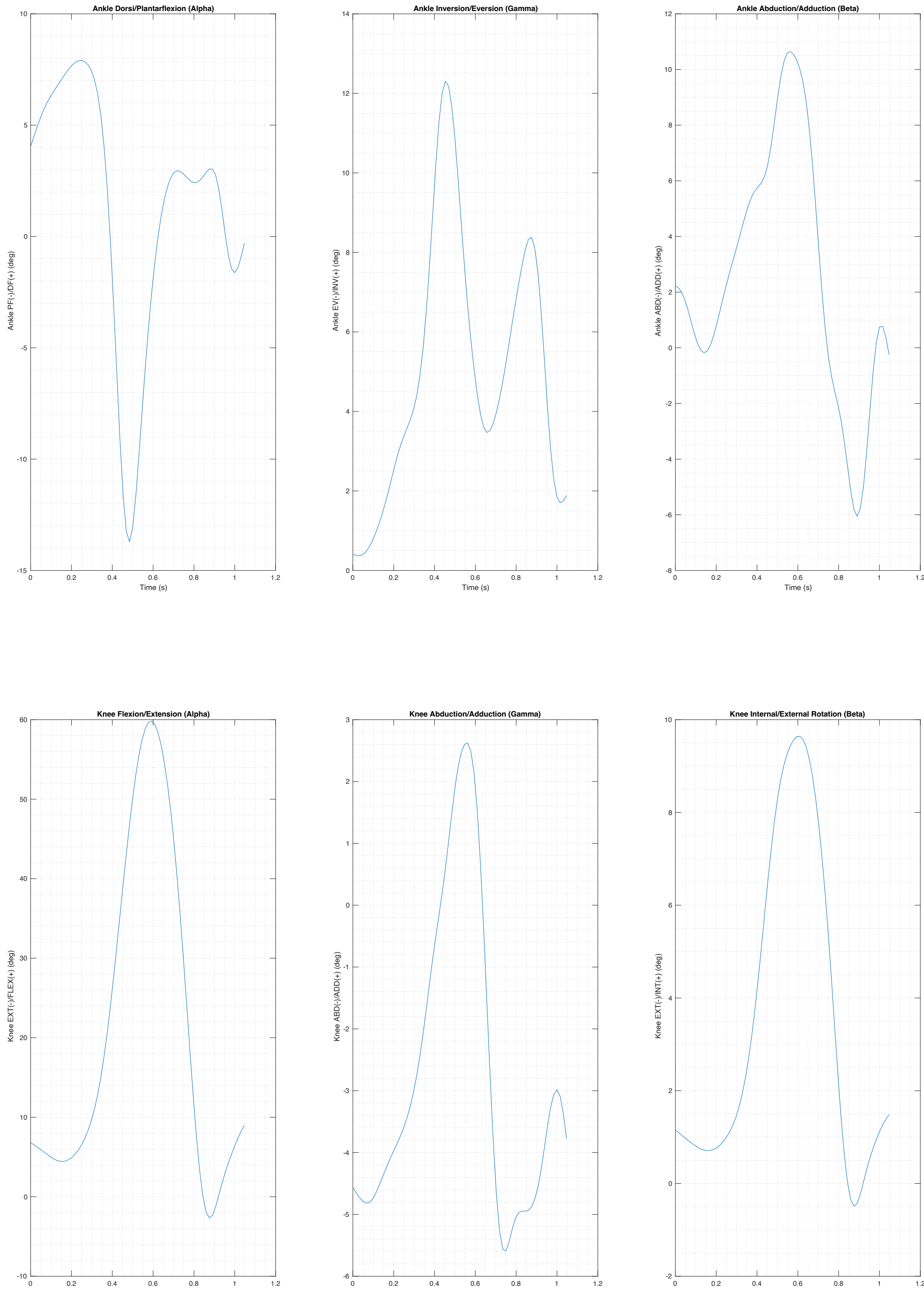

Figure 6: Ankle (top) and Knee (bottom) Joint Angles.

19. For walking, compare your measured joint angles to those in the literature for level walking (include citations and figures/data from the literature). What differences exist? What do you think is the source of these differences? (4)

An excellent piece of literature to compare to my data came from [5]. In this work, the authors presented a publicly available dataset of 42 healthy volunteers (24 young adults and 18 older adults) who walked both overground and on a treadmill at a range of gait speeds [5]. The results included both raw and processed kinematic and kinetic data from the lower extremities, in addition to plots of the data, making it a good choice for comparison [5]. Figure 7, highlights the average ankle joint angles of the participants at three different walking speeds, indicated by the different line styles, at various percentages of the gait cycle [5]. Figure 8, highlights the average knee joint angles of the participants at three different walking speeds, indicated by the different line styles, at various percentages of the gait cycle [5]. It is important to note that one crucial difference is that the plots in the literature encapsulate a complete gait cycle while our collected data likely does not. Even more important is the fact that they plotted the angle against the percentage of the gait cycle while I used time. I believe they chose to use percent gait because it is more interpretable and meaningful when doing analysis than just using time.

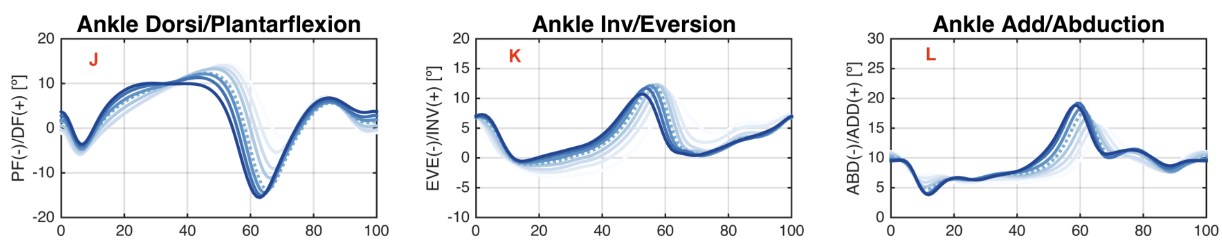

Figure 7: Ankle joint angles from source [5].

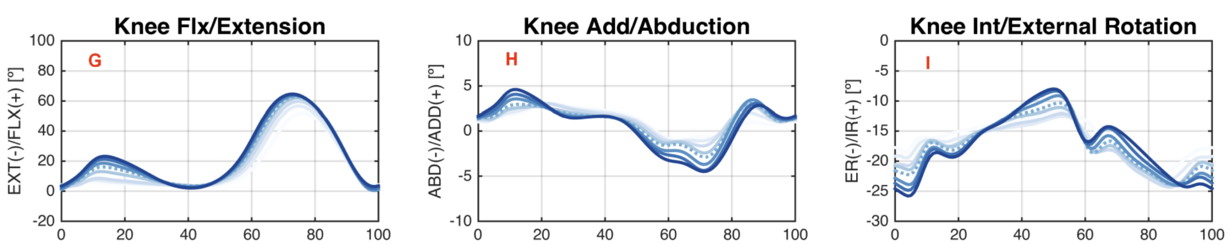

Figure 8: Knee joint angles from source [5].

When comparing the ankle angles from this study to the literature, the overall trends for all three angles appear to be similar, however, there are occasional differences, and the ranges and minimums/maximums vary as well. The dorsi/plantarflexion minimum shows a plantarflexion angle greater which seems very similar to the literature at ~15 degrees of plantarflexion [5]. The ankle inversion/eversion trajectory from our experiments has two peaks versus the one in the literature but the maximum is the same for both at about 12 degrees of inversion [5]. When looking at the abduction/adduction of the ankle, both plots have a very similar trajectory but completely different ranges, where the literature seems to have less abduction than my plots. The differences can likely be attributed to the different methods used to establish the LCS. The LCS may be orientated differently to one another at the same pose in the studies. This study also used a non-arm swing gait, which could have altered the subjects' normal gait, skewing results. The differences in the range of motion and the shape of the plots can be attributed to the fact that this study only looked at one participant, while the literature averaged the gait cycles of 42 individuals.

The flexion/extension angles are nearly identical between this study and literature; however, the other two movements differ greatly. The abduction/adduction and internal/external graphs differ significantly, however, the range of motion for abduction/adduction appears to be similar for both graphs at about 10 degrees. The range of motion for internal/external do not match the literature at all in trajectory or range. The different calculation methods used to obtain these angles, and different joint centre definitions may have caused such discrepancies.

20. Using ISB guidelines and rotation sequences, calculate the joint angles (ankle and knee angles) for the static tasks and determine their means and standard deviations. (2)

Create a table that includes the task name and the means and standard deviations of the joint angles for each task.

Task	Joint	Angle	Mean [deg.]	Standard Deviation [deg.]
Standing	Ankle	Alpha	4.4854	0.066134
		Beta	-9.9909	0.022353
		Gamma	2.0743	0.018407
	Knee	Alpha	0.10003	0.053862
		Beta	0.016796	0.0090275
		Gamma	-1.1753	0.022788
Squatting	Ankle	Alpha	19.6946	0.48415
		Beta	2.505	0.40821
		Gamma	-5.7418	0.16769
	Knee	Alpha	76.1162	1.2046
		Beta	10.9017	0.10807
		Gamma	-5.3555	0.38244
Unilateral Kneeling	Ankle	Alpha	12.312	0.074766
		Beta	18.1104	0.12669
		Gamma	-3.2089	0.28535
	Knee	Alpha	75.8585	0.1694
		Beta	10.2866	0.1341
		Gamma	-0.15374	0.27829
Single Arm Supported Kneeling	Ankle	Alpha	3.6709	0.01471
		Beta	5.8409	0.10818
		Gamma	-0.95022	0.13627
	Knee	Alpha	79.7174	0.14586
		Beta	0.95966	0.095842
		Gamma	3.0236	0.18071

21. Based on your calculated outputs, which of the tasks create the most substantial risks/demands for the Plant Operations workers? Provide information from the literature to support your answer. (4)

When considering all the tasks, it is safe to say that walking and standing provided the lowest risk of all the movements, since these tasks are undergone daily, and the body is used to these movements. This is because walking and standing do not require the ankle or knee to reach angles near their range of motion limits [7][8]. Additionally, the joint loading at these points is standard and does not exceed ranges that are undergone in during a daily routine [8]. The squat, unilateral and sing arm supported kneels create a greater amount of kinematic demand for the workers. All three of these tasks require the knee to be at a high flexion angle and particularly with the squat, the ankle is required to be at a high dorsiflexion angle. This creates very high loading on these joints that may be further exacerbated if the plant workers are carrying something or performing a task [8]. Going through the literature, it is stated that suggests that repeated flexion of the knee throughout the workday can increase the risk of musculoskeletal injury, which would certainly be the case for plant workers, who require the use of dynamic movements under heavy loads to complete their work [9]. In addition, repeated dorsiflexion motion near the range of motion limit of the ankle can cause anterior ankle nerve impingement, which can be painful and reduce the range of motion for the joint [10]. Ultimately, based on our experimentation and analysis, we see that the squatting and the two kneeling positions incur the highest degrees of joint flexion and plantarflexion, for the knee and ankle respectively, thus making these the most dangerous tasks, according to literature [9][10].

22. Comment on the usefulness of segment angles (questions 16 and 17) vs. joint angles (questions 18-20) in terms of conveying pertinent (useful) information to others. (2)

Explain which angles (segment or joint) you think are more useful (and to whom they might be useful) and why you think they are more useful.

In general, joint angles are evidently better at conveying useful information to others, especially when considering the musculoskeletal risks associated of a task, as was done in this assignment. Simply knowing a segment angle provides its orientation in space but does not really translate to useful conclusions. Understanding how each segment relates to another is essential to understanding human kinematics and kinetics as well as analyzing joint loads. Visualizing a segment angle is also quite convoluted and joint angles are much easier to interpret when considering human biomechanics. The average individual can relate joint angles to their own body better as well, making this information more interpretable and thus useful to others.

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Appendix

List of variables (3):

Type your list of variables here (what you'll call them in your code and a description of what they are.)

Table 1: Calculated Variable Definitions and Descriptions

Variable Abbreviation	**Variable Name**	**Variable Description**
$A_{JC,x}$	Ankle Joint Centre x-position	Array quantity of 1 column and as many rows as frames collected.
$A_{JC,y}$	Ankle Joint Centre y-position	Array quantity of 1 column and as many rows as frames collected.
$A_{JC,z}$	Ankle Joint Centre z-position	Array quantity of 1 column and as many rows as frames collected. Used to
$K_{JC,x}$	Knee Joint Centre x-position	Array quantity of 1 column and as many rows as frames collected.
$K_{JC,y}$	Knee Joint Centre y-position	Array quantity of 1 column and as many rows as frames collected.
$K_{JC,z}$	Knee Joint Centre z-position	Array quantity of 1 column and as many rows as frames collected.
$H_{JC,x}$	Hip Joint Centre x-position	Array quantity of 1 column and as many rows as frames collected.
$H_{JC,y}$	Hip Joint Centre y-position	Array quantity of 1 column and as many rows as frames collected.
$H_{JC,z}$	Hip Joint Centre z-position	Array quantity of 1 column and as many rows as frames collected.
$\dot{A}_{JC,x}$	Ankle Joint Centre translational x-velocity	Derivative of respective position quantity for a given set of frames. Taking the derivative means that a frame will be lost. Array quantity of 1 column and same number rows as frames collected minus the 1 lost.
$\dot{A}_{JC,y}$	Ankle Joint Centre translational y-velocity	Derivative of respective position quantity for a given set of frames. Taking the derivative means that a frame will be lost. Array quantity of 1 column and same number rows as frames collected minus the 1 lost.
$\dot{A}_{JC,z}$	Ankle Joint Centre translational z-velocity	Derivative of respective position quantity for a given set of frames. Taking the derivative means that a frame will be lost. Array quantity of 1 column and same number rows as frames collected minus the 1 lost.
$\dot{K}_{JC,x}$	Knee Joint Centre translational x-velocity	Derivative of respective position quantity for a given set of frames. Taking the derivative means that a frame will be lost. Array quantity of 1 column and same number rows as frames collected minus the 1 lost.
$\dot{K}_{JC,y}$	Knee Joint Centre y-velocity	Derivative of respective position quantity for a given set of frames. Taking the derivative means that a frame will be lost. Array quantity

		of 1 column and same number rows as frames collected minus the 1 lost.
$\dot{K}_{JC,z}$	Knee Joint Centre translational z-velocity	Derivative of respective position quantity for a given set of frames. Taking the derivative means that a frame will be lost. Array quantity of 1 column and same number rows as frames collected minus the 1 lost.
$\dot{H}_{JC,x}$	Hip Joint Centre translational x-velocity	Derivative of respective position quantity for a given set of frames. Taking the derivative means that a frame will be lost. Array quantity of 1 column and same number rows as frames collected minus the 1 lost.
$\dot{H}_{JC,y}$	Hip Joint Centre translational y-velocity	Derivative of respective position quantity for a given set of frames. Taking the derivative means that a frame will be lost. Array quantity of 1 column and same number rows as frames collected minus the 1 lost.
$\dot{H}_{JC,z}$	Hip Joint Centre translational z-velocity	Derivative of respective position quantity for a given set of frames. Taking the derivative means that a frame will be lost. Array quantity of 1 column and same number rows as frames collected minus the 1 lost.
$\ddot{A}_{JC,x}$	Ankle Joint Centre translational x-acceleration	Derivative of respective velocity quantity for a given set of frames. Taking the derivative means that a frame will be lost. Array quantity of 1 column and same number rows as frames collected minus the 1 lost.
$\ddot{A}_{JC,y}$	Ankle Joint Centre translational y-acceleration	Derivative of respective velocity quantity for a given set of frames. Taking the derivative means that a frame will be lost. Array quantity of 1 column and same number rows as frames collected minus the 1 lost.
$\ddot{A}_{JC,z}$	Ankle Joint Centre translational z-acceleration	Derivative of respective velocity quantity for a given set of frames. Taking the derivative means that a frame will be lost. Array quantity of 1 column and same number rows as frames collected minus the 1 lost.
$\ddot{K}_{JC,x}$	Knee Joint Centre translational x-acceleration	Derivative of respective velocity quantity for a given set of frames. Taking the derivative means that a frame will be lost. Array quantity of 1 column and same number rows as frames collected minus the 1 lost.
$\ddot{K}_{JC,y}$	Knee Joint Centre translational y-acceleration	Derivative of respective velocity quantity for a given set of frames. Taking the derivative means that a frame will be lost. Array quantity of 1 column and same number rows as frames collected minus the 1 lost.
$\ddot{K}_{JC,z}$	Knee Joint Centre translational z-acceleration	Derivative of respective velocity quantity for a given set of frames. Taking the derivative means that a frame will be lost. Array quantity of 1 column and same number rows as frames collected minus the 1 lost.

$\ddot{H}_{JC,x}$	Hip Joint Centre translational x-acceleration	Derivative of respective velocity quantity for a given set of frames. Taking the derivative means that a frame will be lost. Array quantity of 1 column and same number rows as frames collected minus the 1 lost.
$\ddot{H}_{JC,y}$	Hip Joint Centre translational y-acceleration	Derivative of respective velocity quantity for a given set of frames. Taking the derivative means that a frame will be lost. Array quantity of 1 column and same number rows as frames collected minus the 1 lost.
$\ddot{H}_{JC,z}$	Hip Joint Centre translational z-acceleration	Derivative of respective velocity quantity for a given set of frames. Taking the derivative means that a frame will be lost. Array quantity of 1 column and same number rows as frames collected minus the 1 lost.
α	Euler angle relating to rotation about z-axis	This variable will be used to calculate segment angles for each of the thigh (T), shank (S) and foot (F). Scalar quantities in an array of 1 column and as many rows as frames collected.
β	Euler angle relating to rotation about y-axis	This variable will be used to calculate segment angles for each of the thigh (T), shank (S) and foot (F). Scalar quantities in an array of 1 column and as many rows as frames collected.
γ	Euler angle relating to rotation about x-axis	This variable will be used to calculate segment angles for each of the thigh (T), shank (S) and foot (F). Scalar quantities in an array of 1 column and as many rows as frames collected.
α_{TS}	Angle relating to the Intersegmental rotation of the Thigh & Shank (Knee Joint) about z-axis	Used to calculate knee joint angles. Scalar quantities in an array of 1 column and as many rows as frames collected.
β_{TS}	Angle relating to the Intersegmental rotation of the Thigh & Shank (Knee Joint) about y-axis	Used to calculate knee joint angles. Scalar quantities in an array of 1 column and as many rows as frames collected.
γ_{TS}	Angle relating to the Intersegmental rotation of the Thigh & Shank (Knee Joint) about x-axis	Used to calculate knee joint angles. Scalar quantities in an array of 1 column and as many rows as frames collected.
α_{SF}	Angle relating to the Intersegmental rotation of the Shank & Foot (Ankle Joint) about z-axis	Used to calculate ankle joint angles. Scalar quantities in an array of 1 column and as many rows as frames collected.
β_{SF}	Angle relating to the Intersegmental rotation of the Shank & Foot (Ankle Joint) about y-axis	Used to calculate ankle joint angles. Scalar quantities in an array of 1 column and as many rows as frames collected.
γ_{SF}	Angle relating to the Intersegmental rotation of the Shank & Foot (Ankle Joint) about x-axis	Used to calculate ankle joint angles. Scalar quantities in an array of 1 column and as many rows as frames collected.

Table 2: Remaining Variable Definitions and Descriptions Needed for Calculations

Variable Abbreviation	**Variable Name**	**Variable Description**
I	Global x-axis unit vector	Unit vector scalar matrix with the values and dimensions indicated as follows: $\mathrm{I} = [1\ 0\ 0]^T$
J	Global y-axis unit vector	Unit vector scalar matrix with the values and dimensions indicated as follows: $\mathrm{J} = [0\ 1\ 0]^T$
K	Global z-axis unit vector	Unit vector scalar matrix with the values and dimensions indicated as follows: $\mathrm{I} = [0\ 0\ 1]^T$
i	Local x-axis unit vector	Unit vector scalar matrix with the values and dimensions indicated as follows: $\mathrm{i} = [1\ 0\ 0]^T$
j	Local y-axis unit vector	Unit vector scalar matrix with the values and dimensions indicated as follows: $\mathrm{j} = [0\ 1\ 0]^T$
k	Local z-axis unit vector	Unit vector scalar matrix with the values and dimensions indicated as follows: $\mathrm{k} = [0\ 0\ 1]^T$
O_P	Coordinates of the Pelvis' Origin	This coordinate variable will have x, y and z components. It is a scalar quantity array with 3 columns (For each direction) and as many rows as frames collected. Can be extracted from experimental data.
O_T	Coordinates of the Thigh's Origin	This coordinate variable will have x, y and z components. It is a scalar quantity array with 3 columns (For each direction) and as many rows as frames collected. Can be extracted from experimental data.
O_S	Coordinates of the Shank's Origin	This coordinate variable will have x, y and z components. It is a scalar quantity array with 3 columns (For each direction) and as many rows as frames collected. Can be extracted from experimental data.
O_F	Coordinates of the Foot's Origin	This coordinate variable will have x, y and z components. It is a scalar quantity array with 3 columns (For each direction) and as many rows as frames collected. Can be extracted from experimental data.
ASIS	Coordinates of the Anterior Superior Iliac Spine	This coordinate variable will have x, y and z components. It is a scalar quantity array with 3 columns (For each direction) and as many rows as frames collected. Can be extracted from experimental data.
IC	Coordinates of the Iliac Spine	This coordinate variable will have x, y and z components. It is a scalar quantity array with 3 columns (For each direction) and as many rows as frames collected. Can be extracted from experimental data.
PSIS	Coordinates of the Posterior Superior Iliac Spine	This coordinate variable will have x, y and z components. It is a scalar quantity array with 3 columns (For each direction) and as many rows as frames collected. Can be extracted from experimental data.
GT	Coordinates of the Greater Trochanter	This coordinate variable will have x, y and z components. It is a scalar quantity array with 3 columns (For each direction) and as many rows as frames collected. Can be extracted from experimental data.
LFC	Coordinates of the Lateral Femoral Condyle	This coordinate variable will have x, y and z components. It is a scalar quantity array with 3 columns (For each direction) and as many rows as frames collected. Can be extracted from experimental data.

MFC	Coordinates of the Medial Femoral Condyle	This coordinate variable will have x, y and z components. It is a scalar quantity array with 3 columns (For each direction) and as many rows as frames collected. Can be extracted from experimental data.
LTC	Coordinates of the Lateral Tibial Condyle	This coordinate variable will have x, y and z components. It is a scalar quantity array with 3 columns (For each direction) and as many rows as frames collected. Can be extracted from experimental data.
MTC	Coordinates of the Medial Tibial Condyle	This coordinate variable will have x, y and z components. It is a scalar quantity array with 3 columns (For each direction) and as many rows as frames collected. Can be extracted from experimental data.
TT	Coordinates of the Tibial Tuberosity	This coordinate variable will have x, y and z components. It is a scalar quantity array with 3 columns (For each direction) and as many rows as frames collected. Can be extracted from experimental data.
MM	Coordinates of the Medial Malleolus	This coordinate variable will have x, y and z components. It is a scalar quantity array with 3 columns (For each direction) and as many rows as frames collected. Can be extracted from experimental data.
LM	Coordinates of the Lateral Malleolus	This coordinate variable will have x, y and z components. It is a scalar quantity array with 3 columns (For each direction) and as many rows as frames collected. Can be extracted from experimental data.
H	Coordinates of the Heel	This coordinate variable will have x, y and z components. It is a scalar quantity array with 3 columns (For each direction) and as many rows as frames collected. Can be extracted from experimental data.
2M	Coordinates of the tip of the 2^{nd} Metatarsal	This coordinate variable will have x, y and z components. It is a scalar quantity array with 3 columns (For each direction) and as many rows as frames collected. Can be extracted from experimental data.
5M	Coordinates of the lateral side of the 5^{th} Metatarsal	This coordinate variable will have x, y and z components. It is a scalar quantity array with 3 columns (For each direction) and as many rows as frames collected. Can be extracted from experimental data.
1M	Coordinates of the medial side of the 1^{st} Metatarsal	This coordinate variable will have x, y and z components. It is a scalar quantity array with 3 columns (For each direction) and as many rows as frames collected. Can be extracted from experimental data.

NOTE: For the assignment, in the case of x, y, and z subscripts, a lower-case letter denotes a local coordinates system (LCS) while an upper-case subscript denotes a global coordinate system (GCS). In Table 1, LCS subscripts were used purely as an example but in application, some variables (including provided or literature variables) may be used in the GCS, which will be reflected with upper-case X, Y and Z subscripts in the subsequent work. Additionally, marker data is provided for both left and right limbs, but that is not considered when naming the variables. I will be using the right leg for analysis.

Planning Phase Draft 1:

1. Crop the experimental data to get usable data frames.
2. Assign experimental landmark data to defined variables from Tables 1 and 2
3. Define the rotation matrices and general axes as they relate to the global coordinate system.
4. Define joint centers and extract their coordinates.
    a. Ankle
    b. Knee
    c. Hip
5. Determine the joint centre positions for the hip, knee and thigh.
6. Determine the velocities and accelerations for all tasks.
    a. Differentiation using time intervals and coordinates (3-point central difference technique)
7. Define the local coordinate system for each segment.
    a. Foot
    b. Shank
    c. Thigh
8. For static trials:
    a. Calculate average segment angles and their standard deviation.
    b. Calculate average intersegmental angles and their standard deviation using ISB guidelines in each direction.
9. For walking trials:
    a. Calculate segment angles for the foot shank and thigh segments.
    b. Calculate intersegmental angles (ankle and knee joint) using ISB guidelines in each direction.
10. Plot time series graphs of walking trial's ankle, hip and knee joint centres positions, velocities, and accelerations. Compare the results to literature.
11. Plot segment angles versus time for walking task.
12. Plot time series graph of intersegmental angles versus time for walking task in each direction using ISB guidelines and rotation sequences.
    a. Compare to literature.

Planning Phase Draft 2:

Objective	Steps to accomplish the objective	Associated formulas / MATLAB commands
Import CSV experimental Data into MATLAB.	1. Specify path/directory to files (the files should be downloaded from LEARN and placed in same folder as the MATLAB script)	`filePath = "ExampleGaitData.csv";`
	2. Assign file to an array	`dataArray = readtable(FilePath);`
Crop beginning and end of the data where large gaps are present.	1. This step may vary from trial to trial. Visually inspect the data and manually identify rows at the beginning and end of the data that do not contain any data.	
	2. Manually deleted the rows identified so that there are no empty indices at the beginning or end of the data for any landmark. Also delete the columns pertaining to the cluster markers.	
Interpolate missing data points.	1. Extract the numbers of rows and columns of the dataArray	`[rows, cols] = size(dataArray);`

	2. Loop through the rows and columns	`%Cubic spline interpolation`
		`interpolatedData = zeros(rowsSize, colsSize);`
		`interpolatedData(:,1)= dataArray(:,1);`
		`for j = 2:colsSize`
		`    interpolatedData(:,j) =`
		`fillmissing(dataArray(:,j),'spline'); %% cubic`
		`spline interp`
		`end`

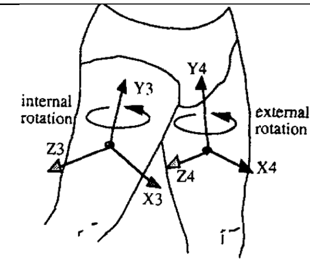
	3. Within the loop identify the values that have a value of NaN, using filmissing function.	
	4. If that index is NaN,fillmissing will interpolate using a cubic spline.	

Plot edited data to confirm cropping and interpolation functioned as intended.	1. In a separate MATLAB script, make a rough and manual plot of the cropped and interpolated data, to check if the data seems reasonable, compared to the original data. Select a couple of markers that seem troublesome and have distinct graphical features (i.e., heel y position	`figure`
		`plot(interpolatedData(:,1),`
		`interpolatedData(:,51),'b',dataArray(:,1),`
		`dataArray(:,51), 'r', 'linewidth', 5);`
		`title('pelvis ASIS Y');`
		
		Example for the Pelvis' right ASIS

	during gait). Also, used markers of edited data that have holes so that there are clear gaps that can be checked.	
	2. If there are large gaps that persist, crop that data again or interpolate as needed.	
	3. If data is altered again, repeat the plotting,	`figure` `plot(rough_frames,rough_data);`
Filter the data.	1. Use a second order lowpass Butterworth filter with a cut-off frequency of 6Hz for each column of the interpolated data [1]. Use filter function afterwards.	`[b,a] = butter(2,6/(64/2),"low")` Where 2 represents the filter order, 6 represents the 6Hz cut-off frequency, 64 is the sampling frequency, and low is the lowpass filter. We then apply this filter to the data using the `filtfilt` MATLAB function.
Collect sets of landmarks and assign them into arrays.	1. Using the column titles in the given file, separate all the filtered data into individual x,y,z arrays.	For example: `P_R_ASIS = dataArray(:,50:52)`
Create a time series.	1. Calculate time interval between data points based on sampling frequency.	$$\Delta t = \frac{1}{f} = \frac{1}{64} = 0.015625\ s$$

	2. Create an array from 0 to the number of frames that increments by this interval to make a time series. Use `rows-1` to because the first timestep is 0.	`[rows, cols] = size(dataArray);`
		`frames = rows;`
		`freq = 64;`
		`deltaT = 1/freq;`
		`timeSeries = 0+(0:frames-1)*deltaT;`

Define the axes directions and rotation matrices relative to the global coordinate system [2].	1. Define the global unit vectors which will be used to calculate the local to global Euler angles in following steps.	$\vec{I} = [1\ 0\ 0]$ $\vec{J} = [0\ 1\ 0]$ $\vec{K} = [0\ 0\ 1]$ Recall that lowercase i, j, k are in the LCS.
	2. Define the local to global rotation matrix per ISB recommendations [2]. A ZYX (local to global) matrix is recommended from the cited literature and provides me with the equation for the rotation	$$[{}^{L}R_G] = \begin{bmatrix} \cos\alpha\cos\beta & \cos\alpha\sin\beta\sin\gamma - \sin\alpha\cos\gamma & \cos\alpha\sin\beta\cos\gamma + \sin\alpha\sin\gamma \\ \sin\alpha\cos\beta & \sin\alpha\sin\beta\sin\gamma + \cos\alpha\cos\gamma & \sin\alpha\sin\beta\cos\gamma - \cos\alpha\sin\gamma \\ -\sin\beta & \cos\beta\sin\gamma & \cos\beta\cos\gamma \end{bmatrix}$$ $$\beta = -\sin^{-1}(\vec{K}\cdot\vec{\imath})$$ $$\alpha = \sin^{-1}\frac{\vec{J}\cdot\vec{\imath}}{cos\beta}$$

	matrix and Euler angles α, β, and γ.	$\gamma = \sin^{-1}\frac{\vec{K}\cdot\vec{j}}{cos\beta}$
	3. Per ISB recommendations, the LCS axes will be oriented as follows [2]: x – anteriorly, y – upwards, z – laterally.	 [2]
Define the ankle joint center and determine position.	1. Define the ankle joint center (A_{JC}) as the midpoint of the malleoli [3].	$A_{JC,x} = \frac{LM_x + MM_x}{2}$ $A_{JC,y} = \frac{LM_y + MM_y}{2}$ $A_{JC,z} = \frac{LM_z + MM_z}{2}$ $\vec{A}_{JC,Global} = [A_{JC,x} \quad A_{JC,y} \quad A_{JC,z}]$

	2. Create and fill an array with the ankle joint center data.	`F_R_L_MAL = dataArray(:,92:94);`
		`F_R_M_MAL = dataArray(:,95:97);`
		
		`AJC = ones(frames,3);`
		`for j=1:frames`
		`    AJC(j,:) = (F_R_L_MAL(j,:) + F_R_M_MAL(j,:))/2;`
		`end`

Define the knee joint center and determine position.	1. Define the knee joint center (K_{JC}) as the midpoint between the femoral condyles [3].	$K_{JC,x} = \frac{LFC_x + MFC_x}{2}$ $K_{JC,y} = \frac{LFC_y + MFC_y}{2}$ $K_{JC,z} = \frac{LFC_z + MFC_z}{2}$ $\vec{K}_{JC,Global} = [K_{JC,x} \quad K_{JC,y} \quad K_{JC,z}]$

	2. Create and fill an array with the ankle joint center data.	`T_R_L_FCON = dataArray(:,71:73);`
		`T_R_M_FCON = dataArray(:,74:76);`
		
		`KJC = ones(frames,3);`

<table>
<tr><td></td><td></td><td><pre><code>for j=1:frames
  KJC(j,:) = (T_R_L_FCON(j,:) + T_R_M_FCON(j,:))/2;
end</code></pre></td></tr>
<tr><td rowspan="5">Define the hip joint center and determine position. Adapted from [2]-[4].</td><td>1. Using the cited sources' methods, I calculated the hip joint center [3]. Note that they defined a different LCS axes orientation so I will be adjusting their equations to match my orientation (ISB Standard [2][3]. Now to convert the local hip joint center to a global one.</td><td>$$H_{JC,x} = -0.19 * (|\overrightarrow{RASIS} - \overrightarrow{LASIS}|)$$ $$H_{JC,y} = -0.30 * (|\overrightarrow{RASIS} - \overrightarrow{LASIS}|)$$ $$H_{JC,z} = 0.36 * (|\overrightarrow{RASIS} - \overrightarrow{LASIS}|)$$ $$\vec{H}_{JC,local} = [HJC_x \quad HJC_y \quad HJC_z]$$</td></tr>
<tr><td>2. Define the origin for a reference LCS for the pelvis. Place the origin at the midpoint between the left and right anterior superior iliac spines [4].</td><td>$$O_{p,x} = \frac{LASIS_X + RASIS_X}{2}$$ $$O_{p,y} = \frac{LASIS_y + RASIS_y}{2}$$ $$O_{p,z} = \frac{LASIS_z + RASIS_z}{2}$$ $$\vec{O}_p = (O_{p,x}, O_{p,y}, O_{p,z})$$</td></tr>
<tr><td>3. Find the midpoint of the left and right posterior superior iliac spines [4].</td><td>$$PSIS_{MID,X} = \frac{LPSIS_x + RPSIS_x}{2}$$ $$PSIS_{MID,Y} = \frac{LPSIS_y + RPSIS_y}{2}$$ $$PSIS_{MID,Z} = \frac{LPSIS_z + RPSIS_z}{2}$$ $$\overrightarrow{PSIS}_{MID} = (PSIS_{MID,X}, PSIS_{MID,Y}, PSIS_{MID,Z})$$</td></tr>
<tr><td>4. Define the local z-axis of the pelvis as a line going through the right ASIS from the pelvic origin with the positive direction facing the right. Also calculate its unit vector [4].</td><td>$$\overrightarrow{z_P} = \overrightarrow{RASIS} - \overrightarrow{O_P}$$ $$\widehat{(k_p)} = \frac{\overrightarrow{z_P}}{norm(\overrightarrow{z_P})}$$ <code>norm()</code> is a MATLAB function.</td></tr>
<tr><td>5. Define a temporary vector for the pelvis as a line going through pelvic origin from the</td><td>$$\overrightarrow{v_P} = \overrightarrow{O_P} - \overrightarrow{PSIS}_{MID}$$</td></tr>
</table>

	mid PSIS with the positive direction facing anteriorly [4].	
	6. Take the cross-product of the z and v axes ($\overrightarrow{z_P}$ X $\overrightarrow{x_P}$) to obtain a perpendicular y axis. Calculate its unit vector.	$\overrightarrow{y_P} = cross(\overrightarrow{z_P}, \overrightarrow{v_P})$ $\widehat{(J_p)} = \frac{\overrightarrow{y_P}}{norm(\vec{y})}$ `cross()` is a MATLAB function.
	7. Take the cross-product of the y and z axes ($\overrightarrow{y_P}$ X $\overrightarrow{z_P}$) to obtain a perpendicular x axis. Calculate its unit vector.	$\overrightarrow{x_P} = cross(\overrightarrow{y_P}, \overrightarrow{z_P})$ $\widehat{(\iota_p)} = \frac{\overrightarrow{x_P}}{norm(\overrightarrow{\overrightarrow{x_P}})}$
	8. Using the ZYX rotation matrix and Euler angle equations defined earlier, calculate α, β, and γ between the local pelvis and global coordinate systems [2].	$\beta_P = -\sin^{-1}(\vec{K} \cdot \overrightarrow{\iota_P})$ $\alpha_P = \sin^{-1}\frac{\vec{J} \cdot \overrightarrow{\iota_P}}{cos\beta}$ $\gamma_P = \sin^{-1}\frac{\vec{K} \cdot \overrightarrow{J_P}}{cos\beta}$
	9. Calculate the local to global rotation matrix with the α, β, and γ from step 8 [2].	$[{}^P R_G] = \begin{bmatrix} \cos\alpha\cos\beta & \cos\alpha\sin\beta\sin\gamma - \sin\alpha\cos\gamma & \cos\alpha\sin\beta\cos\gamma + \sin\alpha\sin\gamma \\ \sin\alpha\cos\beta & \sin\alpha\sin\beta\sin\gamma + \cos\alpha\cos\gamma & \sin\alpha\sin\beta\cos\gamma - \cos\alpha\sin\gamma \\ -\sin\beta & \cos\beta\sin\gamma & \cos\beta\cos\gamma \end{bmatrix}$
	10. Use the equation from the literature to convert the local hip joint centre to the global one [3].	$\vec{H}_{JC,global} = \vec{O}_p + [{}^P R_G][H_{JC,local}]^T$
Determine the velocity and acceleration of the ankle, knee, and hip joint centers.	1. Using the time interval determined earlier, calculate the velocity and acceleration of each joint using the 3-point central difference technique, which was shown in class.	$v_{mJC,X,n} = \frac{mJC_{X,n+1} - mJC_{X,n-1}}{2\Delta t}$ $v_{mJC,Y,n} = \frac{mJC_{Y,n+1} - mJC_{Y,n-1}}{2\Delta t}$ $v_{mJC,Z,n} = \frac{mJC_{Z,n+1} - mJC_{Z,n-1}}{2\Delta t}$ $a_{mJC,X,n} = \frac{mJC_{X,n+1} - 2mJC_{X,n} + mJC_{X,n-1}}{\Delta t^2}$ $a_{mJC,X,n} = \frac{mJC_{X,n+1} - 2mJC_{X,n} + mJC_{X,n-1}}{\Delta t^2}$ $a_{mJC,X,n} = \frac{mJC_{X,n+1} - 2mJC_{X,n} + mJC_{X,n-1}}{\Delta t^2}$

		Where m represents a given joint and n is the frame number.
Define the local coordinate system for the foot. Based on [3]. Note that the source defined a different LCS axes orientation so I will be adjusting their equations to match my orientation.	1. Set the origin of the foot as the heel.	$\vec{O_F} = \overrightarrow{Heel_F}$
	2. Define the local x-axis of the foot as a line going through the 2nd metatarsal from the heel origin with the positive direction facing the anteriorly. Also calculate its unit vector.	$\overrightarrow{x_F} = \overrightarrow{2M} - \overrightarrow{O_F}$ $\widehat{(\iota_F)} = \frac{\overrightarrow{x_F}}{norm(\overrightarrow{x_F})}$
	3. Calculate the midpoints of the malleoli (use foot markers).	$Mal_{MID,X} = \frac{MM_x + LM_x}{2}$ $Mal_{MID,Y} = \frac{MM_y + LL_y}{2}$ $Mal_{MID,Z} = \frac{MM_z + LL_z}{2}$ $\overrightarrow{Mal_{mid}} = (Mal_{MID,X}\ Mal_{MID,Y}\ Mal_{MID,Z})$
	4. Create a temporary unit vector (v) as a line going through the middle of the malleoli from the heel origin.	$\overrightarrow{v_F} = \overrightarrow{Mal_{mid}} - \overrightarrow{O_F}$
	5. Take the cross-product of the temporary vector and the x unit vector to get the z axis ($\overrightarrow{x_F}$ X $\overrightarrow{v_F}$). Calculate the unit vector.	$\overrightarrow{z_F} = cross(\overrightarrow{x_F}, \overrightarrow{v_F})$ $\widehat{(k_F)} = \frac{\overrightarrow{z_F}}{norm(\overrightarrow{z_F})}$
	6. Take the cross-product of the z and x axes ($\overrightarrow{z_F}$ X $\overrightarrow{x_F}$) to obtain a perpendicular y axis. Calculate its unit vector.	$\overrightarrow{y_F} = cross(\overrightarrow{z_F}, \overrightarrow{x_F})$ $\widehat{(J_F)} = \frac{\overrightarrow{y_F}}{norm(\overrightarrow{y_F})}$
Define the local coordinate system for the shank [3]. Note that the source defined a different LCS axes orientation so I will be adjusting their equations to match my orientation.	1. Define the origin of the shank as the midpoint between femoral condyles for x, y and z points.	$\vec{O_S} = \frac{\overrightarrow{LFC_T} + \overrightarrow{MFC_T}}{2}$
	2. Calculate the midpoints of the malleoli (use shank markers).	$Mal_{MID,X} = \frac{MM_x + LM_x}{2}$ $Mal_{MID,Y} = \frac{MM_y + LL_y}{2}$ $Mal_{MID,Z} = \frac{MM_z + LL_z}{2}$ $\overrightarrow{Mal_{mid}} = (Mal_{MID,X}\ Mal_{MID,Y}\ Mal_{MID,Z})$

	3. Define the local y-axis of the shank as a line going through the origin of the shank from the malleoli midpoint. Take the unit vector.	$\overrightarrow{y_F} = \overrightarrow{O_S} - \overrightarrow{Mal_{mid}}$ $\widehat{(J_S)} = \frac{\overrightarrow{y_S}}{norm(\overrightarrow{y_S})}$
	4. Create a temporary unit vector (v) as a line going through the lateral femoral epicondyle from the medial femoral epicondyle.	$\overrightarrow{v_S} = \overrightarrow{LFC} - \overrightarrow{MFC}$
	5. Take the cross-product of the y vector and the temporary vector to get the x axis ($\overrightarrow{y_F}$ X $\overrightarrow{v_F}$). Calculate the unit vector.	$\overrightarrow{x_S} = cross(\overrightarrow{y_S}, \overrightarrow{v_S})$ $\widehat{(\imath_S)} = \frac{\overrightarrow{x_S}}{norm(\overrightarrow{x_S})}$
	6. Take the cross-product of the x and y axes ($\overrightarrow{x_S}$ X $\overrightarrow{y_S}$) to obtain a perpendicular z axis. Calculate the unit vector.	$\overrightarrow{z_S} = cross(\overrightarrow{x_S}, \overrightarrow{y_S})$ $\widehat{(k_S)} = \frac{\overrightarrow{z_S}}{norm(\overrightarrow{z_S})}$
Define the local coordinate system for the thigh [3]. Note that the source defined a different LCS axes orientation so I will be adjusting their equations to match my orientation.	1. Define the local y-axis of the thigh as a line going through the origin of the thigh (which is equal to the hip joint centre) from the femoral condyles' midpoint. Take the unit vector.	$\vec{O}_T = \vec{H}_{JC,global}$ $\overrightarrow{FC}_{mid} = \vec{O}_S$ $\overrightarrow{y_T} = \overrightarrow{O_T} - \overrightarrow{FC}_{mid}$ $\widehat{(J_T)} = \frac{\overrightarrow{y_T}}{norm(\overrightarrow{y_T})}$
	2. Create a temporary unit vector (v) as a line going through the lateral femoral epicondyle from the medial femoral epicondyle.	$\overrightarrow{v_T} = \overrightarrow{LFC} - \overrightarrow{MFC}$ $\widehat{(v_T)} = \frac{\overrightarrow{v_T}}{norm(\overrightarrow{v_T})}$
	3. Take the cross-product of the y vector and the temporary vector to get the x axis ($\overrightarrow{y_T}$ X $\overrightarrow{v_T}$). Calculate the unit vector.	$\overrightarrow{x_T} = cross(\overrightarrow{y_T}, \overrightarrow{v_T})$ $\widehat{(\imath_T)} = \frac{\overrightarrow{x_T}}{norm(\overrightarrow{x_T})}$
	4. Take the cross-product of the x and y axes ($\overrightarrow{x_T}$ X $\overrightarrow{y_T}$) to obtain a perpendicular z axis. Calculate the unit vector.	$\overrightarrow{z_T} = cross(\overrightarrow{x_T}, \overrightarrow{y_T})$ $\widehat{(k_T)} = \frac{\overrightarrow{z_T}}{norm(\overrightarrow{z_T})}$

Calculate the segment angles for the foot, shank, and thigh [2].	1. For the foot, use the ISB recommended ZYX rotation matrix and solve for α, β, and γ [2].	$\beta_F = -\sin^{-1}(\vec{K} \cdot \vec{\imath_F})$ $\alpha_F = \sin^{-1}\frac{\vec{J} \cdot \vec{\imath_F}}{cos\beta}$ $\gamma_F = \sin^{-1}\frac{\vec{K} \cdot \vec{J_F}}{cos\beta}$
	2. For the shank, use the ISB recommended ZYX rotation matrix and solve for α, β, and γ [2].	$\beta_S = -\sin^{-1}(\vec{K} \cdot \vec{\imath_S})$ $\alpha_S = \sin^{-1}\frac{\vec{J} \cdot \vec{\imath_S}}{cos\beta}$ $\gamma_S = \sin^{-1}\frac{\vec{K} \cdot \vec{J_S}}{cos\beta}$
	3. For the thigh, use the ISB recommended ZYX rotation matrix and solve for α, β, and γ [2].	$\beta_T = -\sin^{-1}(\vec{K} \cdot \vec{\imath_T})$ $\alpha_T = \sin^{-1}\frac{\vec{J} \cdot \vec{\imath_T}}{cos\beta}$ $\gamma_T = \sin^{-1}\frac{\vec{K} \cdot \vec{J_T}}{cos\beta}$
Relate the local coordinate systems of the shank relative to the thigh to establish and extract intersegmental (knee joint) angles for the walking task. Use ISB guidelines [2][5].	1. Using the method outline in [5] along with the ISB guidelines [2], I will calculate knee joint angles. First, define the floating axis as the cross product of the shank's y-axis unit vector and the thigh's z-axis unit vector which are both segment fixed.	$\overrightarrow{e_{2,TS}} = \frac{cross(\vec{J_S}, \vec{k_T})}{norm\left(cross(\vec{J_S}, \vec{k_T})\right)}$
	2. Calculate alpha, which is the flexion (+)/extension(-) angle.	${}^T\alpha_S = \sin^{-1}(-\overrightarrow{e_{2,TS}} \cdot \vec{J_T})$
	3. Calculate the beta, which is the internal(+)/external (-) rotation angle.	${}^T\beta_S = \sin^{-1}(-\overrightarrow{e_{2,TS}} \cdot \vec{k_S})$
	4. Calculate the gamma, which is the adduction (+)/abduction (-) angle.	${}^T\gamma_S = \cos^{-1}(\vec{k_T} \cdot \vec{J_S}) - 90°$
Relate the local coordinate systems of the foot relative to the shank to establish and extract intersegmental (ankle joint) angles for the walking task [2][5].	1. Using the method outline in [5] along with the ISB guidelines [2], I will calculate ankle joint angles. First define the floating axis as the cross product of the shank's y-axis unit	$\overrightarrow{e_{2,SF}} = \frac{cross(\vec{J_S}, \vec{k_F})}{norm\left(cross(\vec{J_S}, \vec{k_F})\right)}$

	vector and the foot's z-axis unit vector which are both segment-fixed	
	2. Calculate alpha, which is the dorsi (+)/plantarflexion (-) angle.	$^{S}\alpha_F = \sin^{-1}(-\overrightarrow{e_{2,SF}} \cdot \overrightarrow{J_F})$
	3. Calculate the beta, which is the adduction (+)/abduction (-) angle.	$^{S}\beta_F = \sin^{-1}(-\overrightarrow{e_{2,SF}} \cdot \overrightarrow{k_S})$
	4. Calculate the gamma, which is the inversion (+)/eversion (-) angle.	$^{S}\gamma_F = \cos^{-1}(\overrightarrow{k_F} \cdot \overrightarrow{J_S}) - 90°$
For static trials, calculate the average segment angles and standard deviation.	1. For the foot, shank and thigh calculate the average of the alpha, beta, and gamma angles.	$Angle_{Segement,mean} = mean(Angle_{Segment})$ Where $Angle_{Segment}$ is an array containing an angle (alpha, beta, or gamma) for a given segment (foot, shank, or thigh), at each frame. This produces a single value for the mean. `mean()` is a MATLAB function used to calculate the average.
	2. For the foot, shank and thigh calculate the standard deviation of the alpha, beta, and gamma angles.	$Angle_{Segment,SD} = std(Angle_{Segment})$ Where $Angle_{Segment}$ is an array containing an angle (alpha, beta, or gamma) for a given segment (foot, shank, or thigh), at each frame. This produces a single value for the standard deviation. `std()` is a MATLAB function used to calculate the standard deviation.
For static trials, calculate the average intersegmental angles and standard deviation.	1. For the foot, shank and thigh calculate the average of the alpha, beta, and gamma angles.	$Angle_{Intersegement,mean} = mean(Angle_{Intersegment})$ Where $Angle_{Intersegment}$ is an array containing an angle (alpha, beta, or gamma) for a given intersegment (knee or ankle joint), at each frame. This produces a single value for the mean.
	2. For the foot, shank and thigh calculate the standard deviation of the alpha, beta, and gamma angles.	$Angle_{interegment,SD} = std(Angle_{intersegment})$ Where $Angle_{intersegment}$ is an array containing an angle (alpha, beta, or gamma) for a given intersegment (knee or ankle joint), at each frame. This produces a single value for the standard deviation. `std()` is a MATLAB function used to calculate the standard deviation.

For walking trials, plot position, velocity, and acceleration of each of the joint centres against time.	1. Create a time array that starts at the time of the second frame and ends one frame before the last. This is needed for the velocity and accelerations since there is a loss of frames when deriving.	`timeSeriesDer =  deltaT + (0:frames-1)*deltaT;`

	2. Plot data for displacement (first row), velocity (second row) and acceleration (third row), with each column representing X, Y, or Z directions. Note that the displacement will use the normal time series while velocity and acceleration will use the derived time series. Repeat this for each joint centre.	`figure`
		`subplot(3,3,1)`
		`plot(timeseries, AJC(:,1))`
		`title('AJC Y-Displacement in GCS)`
		`xlabel('Time (s))`
		`ylabel('Y Position (mm)')`
		
		This is just an example for AJC displacement. Repeat for each case.

For walking trials, plot segment angles against time.	1. Plot data for thigh (first row), shank (second row) and foot (third row), with each column representing alpha, beta, or gamma.	`figure`
		`subplot(3,3,1)`
		`plot(timeseries, α_S (:,1))`
		`title(Shank Alpha')`
		`xlabel('Time (s)' )`
		`ylabel(Shank Alpha (deg)')`
		
		This is just an example for Shank alpha angle. Repeat for each case.

For walking trials, plot intersegmental angles against time.	1. Plot data for alpha (first column), beta (second column), and gamma (third column) for the ankle (first row) and knee (second row) joints.	`figure`
		`subplot(1,3,1)`
		`plot(timeseries, α_TS (:,1))`
		`title(Knee Flexion(+)/Extension(-))`
		`xlabel('Time (s)')`
		`ylabel(Knee Alpha (deg)')`
		⋮