BE 436 - Biomechanics of Human Movement

Lab #2: Analyzing Biomechanics of Squats, Lunges, and Side Lunges

April 22nd, 2022
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Group Monday - B2

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Acknowledgments:

We would like to express our gratitude to Dr. Stefanovic for teaching us the skills needed to complete this study and giving us the opportunity to work with the motion capture lab.

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Project Overview:

This report will include background on the biomechanics of the body as well as a description of experiments conducted. The methods to carry out these experiments are explained and then the results of each experiment are explained and reported. Following this, there is a discussion on the importance of our experiments and calculations.

Introduction:

The goal of this lab was to analyze the biomechanics of three similar forms of exercise, squats, lunges, and side lunges. These three exercises are all lower body exercises and should display some similarities in the forces produced while being performed. To complete this lab, we assigned one member to be the motion capture subject, two members to operate the computer, and the rest to help place the markers on the subject and take pictures.

Using the same motion capture suit and marker placement as the last lab, we collected data points corresponding to the human body while performing the selected exercises. Due to the movement of the exercises, the markers moved on the suit which created noise in our data. This noise can lead to noticeable outliers in the graphs, even after removing any clear erroneous data points.

Despite the noise, we were able to show similarities and differences in the ground reaction forces and torques generated during squats, lunges, and side lunges.

We chose the three exercises of squats, lunges, and side lunges because they all use most of the same muscles. The muscles used where the quadriceps (Rectus Femoris, Vastus Lateralis, Vastus Medialis, and Vastus Intermedius) [5], the hamstrings (Semitendinosus, Semimembranosus, and Biceps Femoris) [3], the Adductors (Adductor Longus, Adductor Brevis, Adductor Magnus, and Gracilis) [4], the Calves (Gastrocnemius and Soleus) [1], and the Gluteus (Gluteus Maximus, Gluteus Minimus, and Gluteus Medius) [2]. This experiment allows us to see which exercise is the most beneficial for working out your legs.

Methods:

1. Begin the lab by completing basic setup tasks
    a. Start the Vicon Motion Capture software
        i. Create a folder to collect data, which was stored under a database, then the following folders: Courses, be436, be436_sp22, Group 13, Experiment 2, Patient 1, and finally, Session 1.
    b. Assist one group member in putting on the motion capture suit
        i. Attach velcro motion trackers to the motion capture suit by following the Marker Placement Guide on UBLearns

2. Calibrate the motion capture software
    a. Allow the test subject to stand in the viewing area to confirm that the software is accurately tracking the motion of the subject, and all markers are visible
    b. Have the test subject move towards each outer bound of the viewing area until the software begins to lose sight of suit markers. Place some type of marker on the border of each viewing area to denote where the motion capture cameras begin to lose sign of the test subject
    c. Use the Auto Initializing Labeling pipeline for the calibration
3. Begin analysis of exercises
    a. Once data collection has started, perform ten full squats while maintaining the same general position. Stop data collection after the completion of the ten squats. Label this data “Squats 1”.
    b. Repeat the previous step to record the second set of data for the squats trial. Label this data “Squats 2”.
    c. Repeat steps 3A and 3B for lunges and side lunges and label them respectively. When complete, you should have two sets of data for each motion totalling to six total datasets.
4. Process and save recorded data
    a. Once all data is collected, save and apply the Export pipeline to all six trials
    b. Upload collected data to UBBox and share with the group.

Results:

In this section, we will be using the positions we have obtained from the motion capture lab to calculate the velocity and acceleration of our subject. Then, we will use those values to determine the ground reaction forces and torques that our subject creates.

Section 1 - Linear Speed

We first calculated the linear speed of our subject. We did this by using the sternum marker of our subject, estimating this to be their center of mass. For each exercise– squat, lunge and side lunge– we did our calculations using only one of the trials. For squats, we used the second trial, while lunges and side lunges both used the first trial.

We took the x, y and z positions for the sternum marker and converted these to meters by multiplying by 0.001. After we had that data converted, we took the difference from each data point to the next and then divided that by our time interval of 0.01 seconds. This gave us our subject’s speed. The example equation is for the x axis speed.

$$v_x = \frac{x_2 - x_1}{0.01s} \qquad \text{Equation 1.1}$$

We then graphed linear speed in each direction, as well as the magnitude of the linear speed for each exercise. Figures 1.1-1.12 display this data. To get a better grasp on our data, we calculated the maximum, minimum and averages for the speed in each direction, using the built-in functions in Excel (“max()”, “min()”, and “average()”).

Squat: Linear Speed

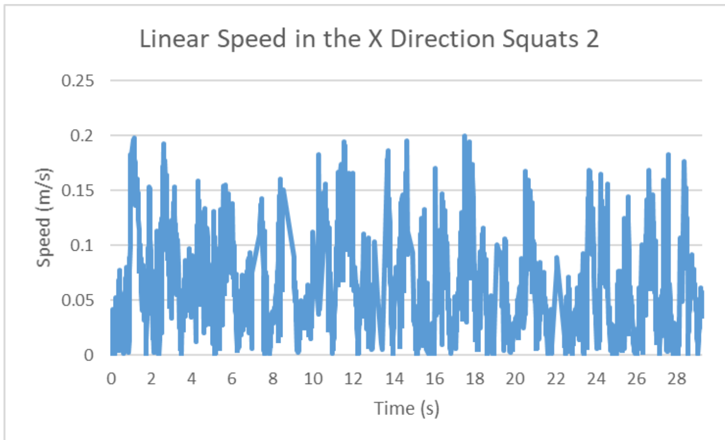

Figure 1.1 - The linear speed of the center of gravity in the X direction during the second squats trial.

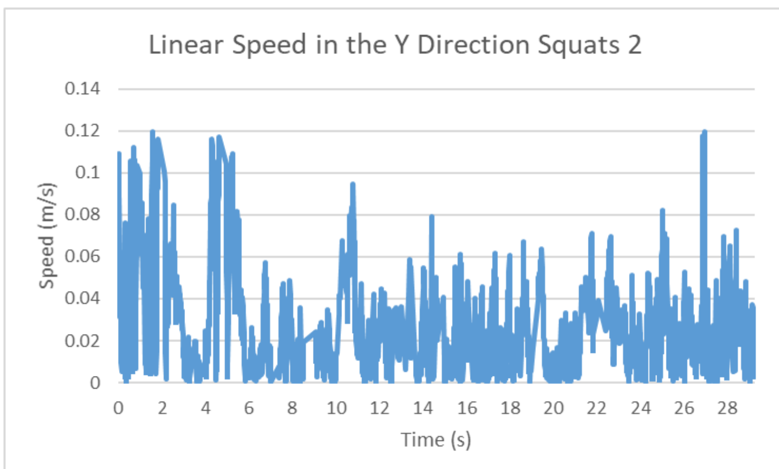

Figure 1.2 - The linear speed of the center of gravity in the Y direction during the second squats trial.

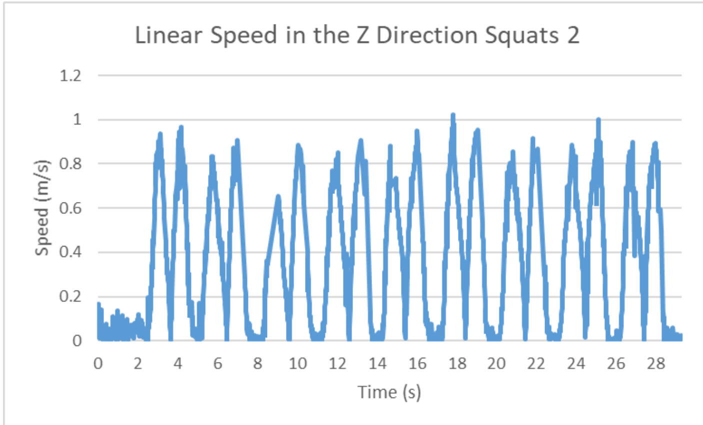

Figure 1.3 - The linear speed of the center of gravity in the Z direction during the second squats trial.

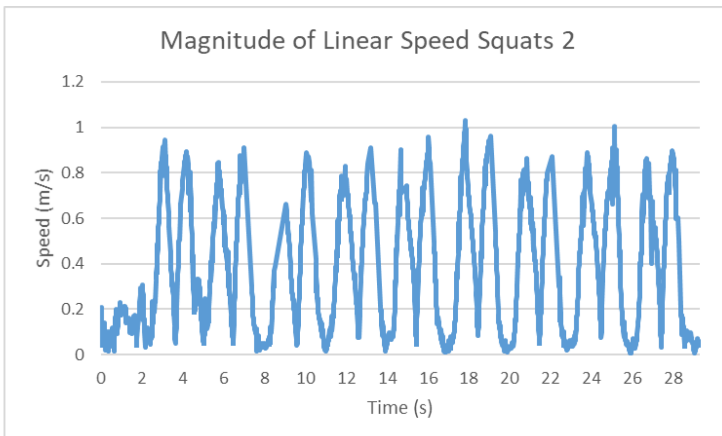

Figure 1.4 - The total magnitude of linear speed of the center of gravity during the second squats trial.

These values seem accurate for the overall magnitude and Z axis, but they are affected by noisy data for the X and Y axes. Based on the graph for the X axis, there does not appear to be any outliers, but the overall noise makes it hard to analyze. The data for the Y axis does contain outliers, but removing them would delete significant portions of the data.

Lunge: Linear Speed

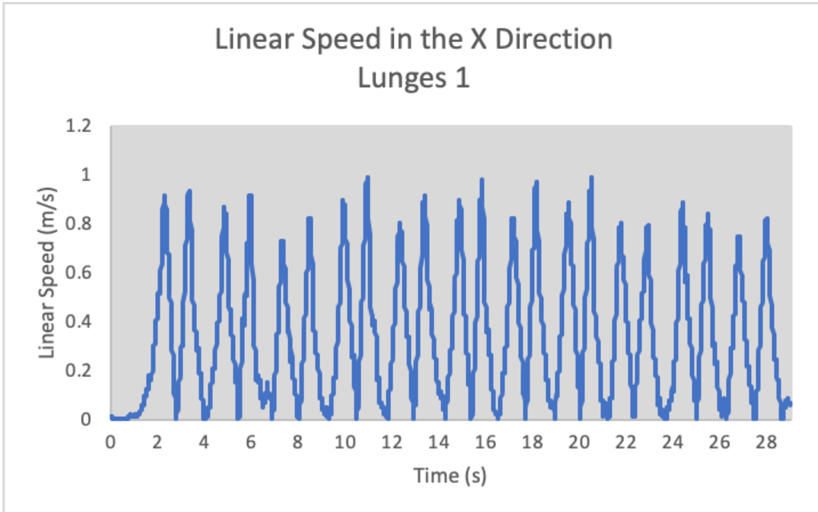

Figure 1.5 - The linear speed of the center of gravity in the X direction during the first lunges trial.

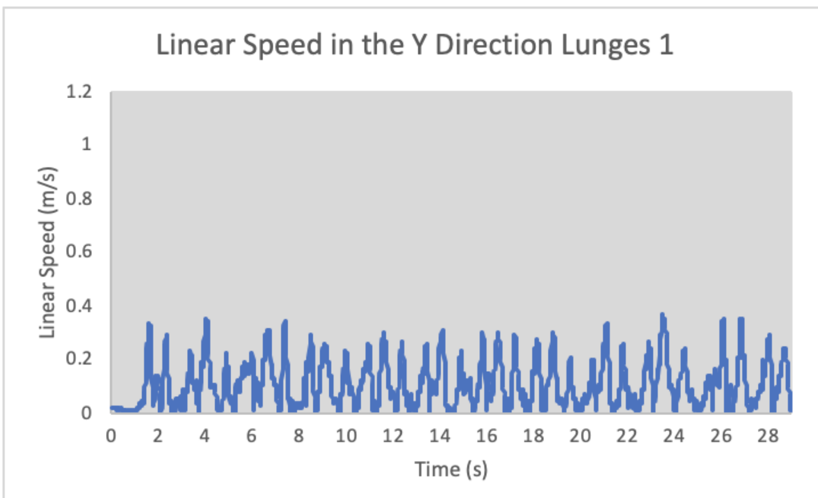

Figure 1.6 - The linear speed of the center of gravity in the Y direction during the first lunges trial.

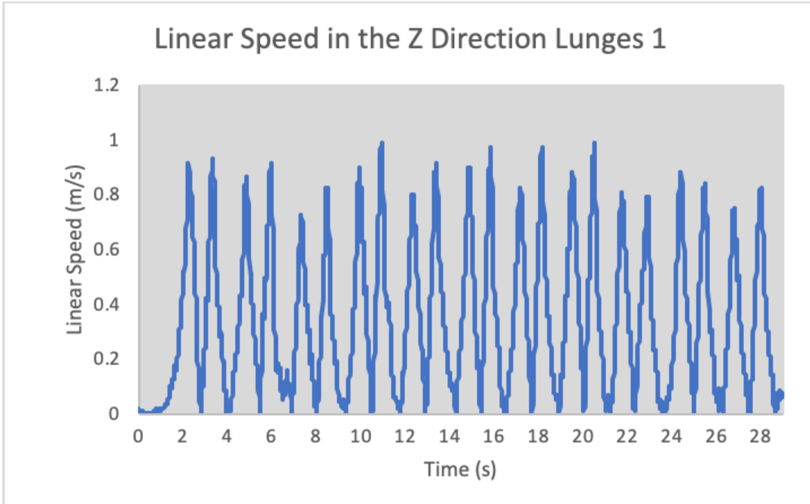

Figure 1.7 - The linear speed of the center of gravity in the Z direction during the first lunges trial.

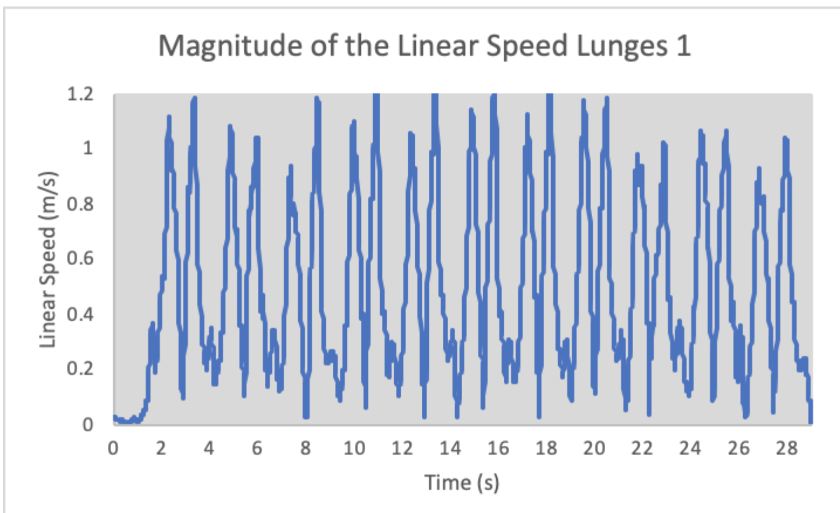

Figure 1.8 - The total magnitude of linear speed of the center of gravity during the first lunges trial.

	x	y	z	Magnitude
Max Linear Speed (m/s)	0.992	0.369	0.814	1.27
Minimum Linear Speed (m/s)	$1.5x10^{-6}$	$2.44x10^{-5}$	$1.22x10^{-5}$	0
Average Linear Speed (m/s)	0.339	0.108	0.288	0.496

Side Lunge: Linear Speed

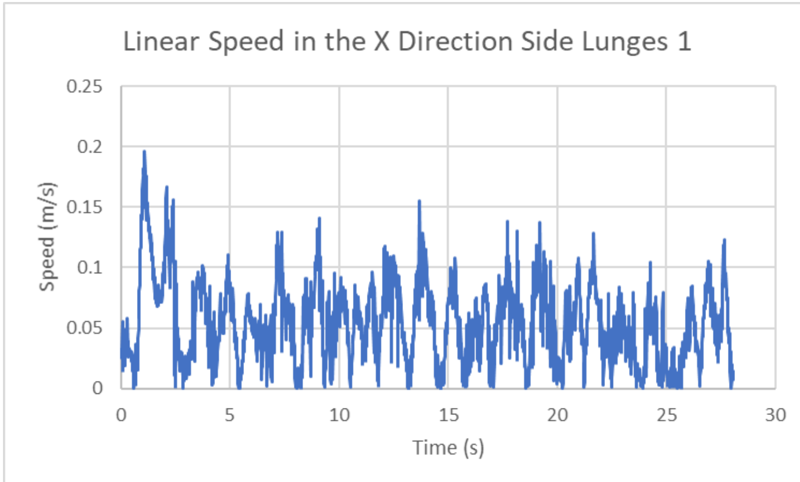

Figure 1.9 - The linear speed of the center of gravity in the X direction during the first side lunge trial.

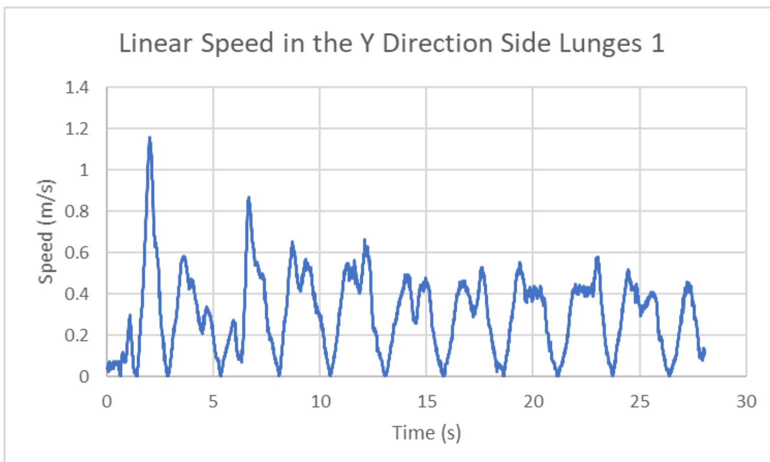

Figure 1.10 - The linear speed of the center of gravity in the Y direction during the first side lunge trial.

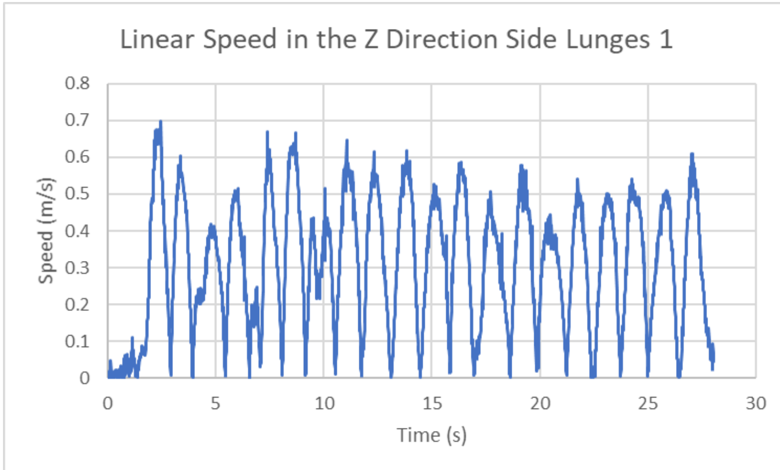

Figure 1.11 - The linear speed of the center of gravity in the Z direction during the first side lunge trial.

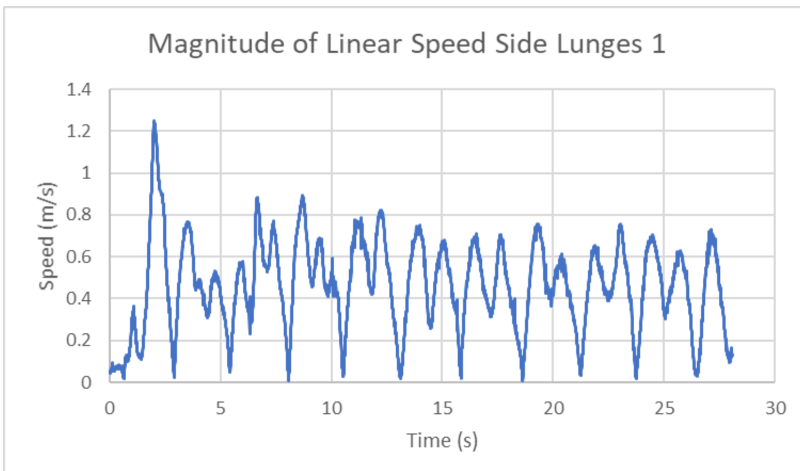

Figure 1.12 - The total magnitude of linear speed of the center of gravity during the first side lunge trial.

	x	y	z	Magnitude
Max Linear Speed (m/s)	0.196	1.156	0.698	1.250
Minimum Linear Speed (m/s)	1.83x10-5	7.32x10-5	0.000696	0.00834
Average Linear Speed (m/s)	0.0541	0.304	0.311	0.464

Section 2 - Acceleration

In this section, we calculated the acceleration of our subject over time. Using the speed from the previous section, we took the difference between two speed data points and divided that by 0.01 seconds, to get acceleration in each direction of each trial. The example equation is for the x axis acceleration.

$$a_x = \frac{v_{x2} - v_{x1}}{0.01s} \quad \text{Equation 2.1}$$

We performed this calculation for every direction and for each exercise, and graphed our results. Figures 2.1-2.12 display this data. To get a better grasp on our data, we calculated the maximum, minimum and averages for the acceleration in each direction, using the built-in functions in excel (“max()”, “min()”, and “average()”).

Squat: Acceleration

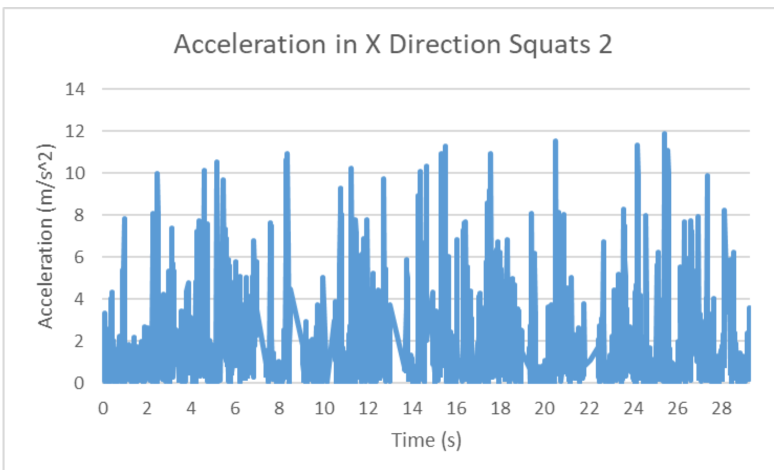

Figure 2.1 - The linear acceleration of the center of gravity in the X direction during the second squats trial.

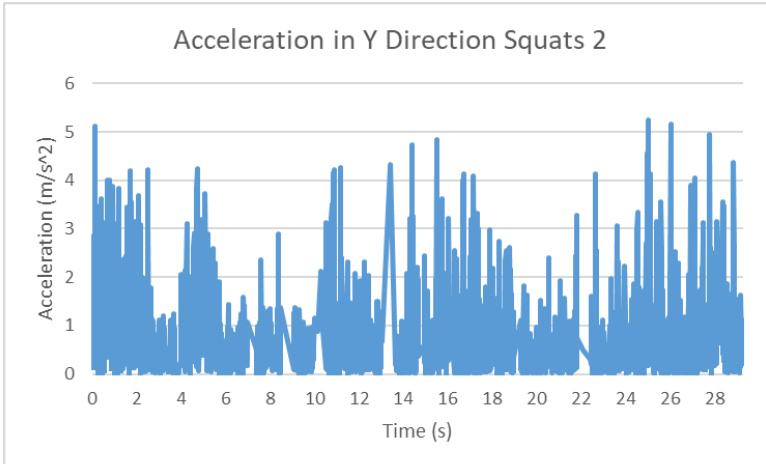

Figure 2.2 - The linear acceleration of the center of gravity in the Y direction during the second squats trial.

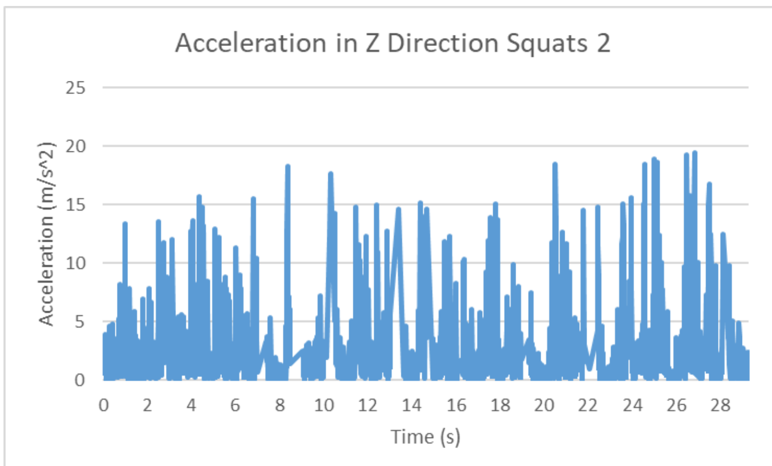

Figure 2.3 - The linear acceleration of the center of gravity in the Z direction during the second squats trial.

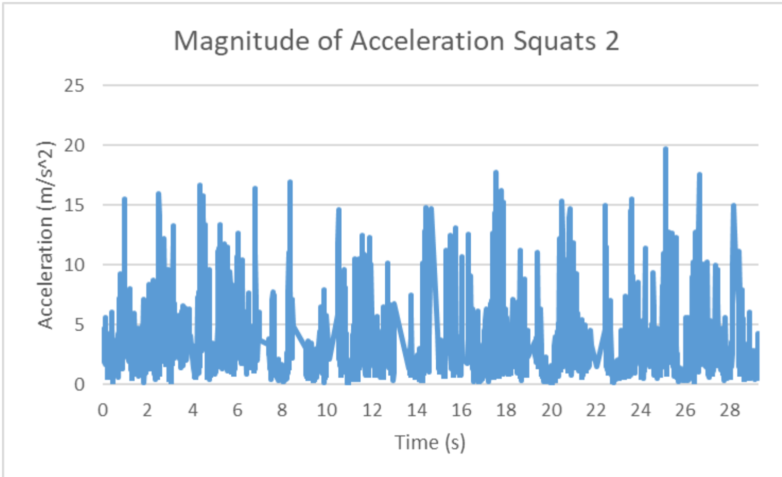

Figure 2.4 - The magnitude of linear acceleration of the center of gravity during the second squats trial.

	x	y	z	Magnitude
Max Linear Acceleration (m/s^2)	11.874	5.253	19.402	19.702
Minimum Linear Acceleration (m/s^2)	0.00038	0	$1.11x10^{-12}$	$1.11x10^{-12}$
Average Linear Acceleration (m/s^2)	1.697	0.774	2.467	3.293

Lunge: Acceleration

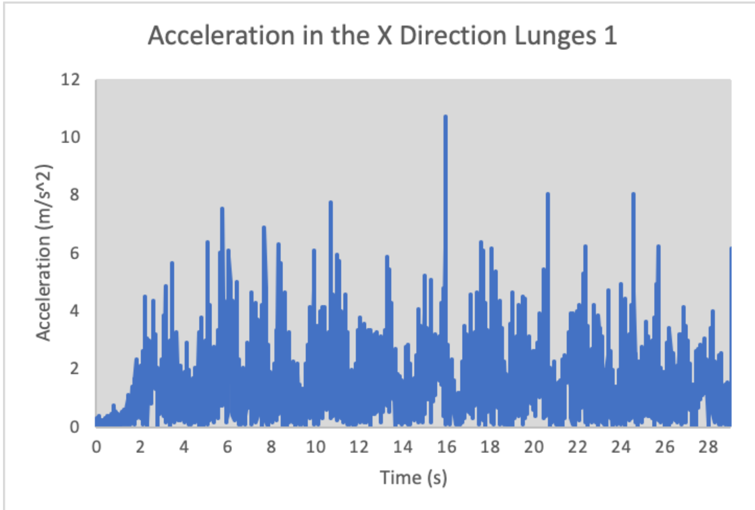

Figure 2.5 - The linear acceleration of the center of gravity in the X direction during the first lunges trial.

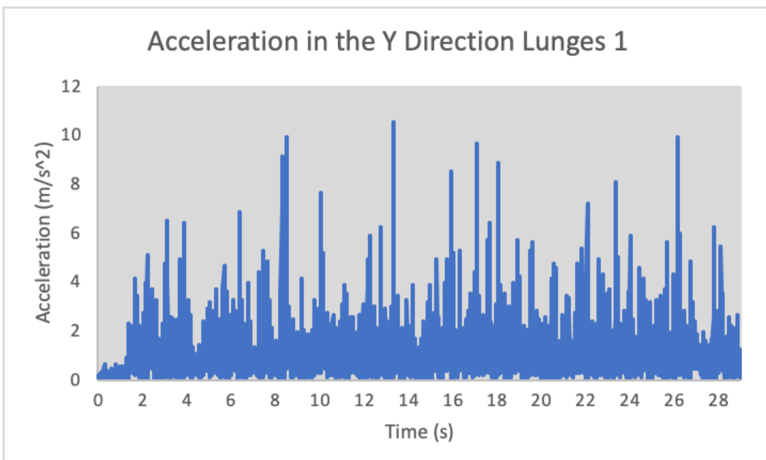

Figure 2.6 - The linear acceleration of the center of gravity in the Y direction during the first lunges trial.

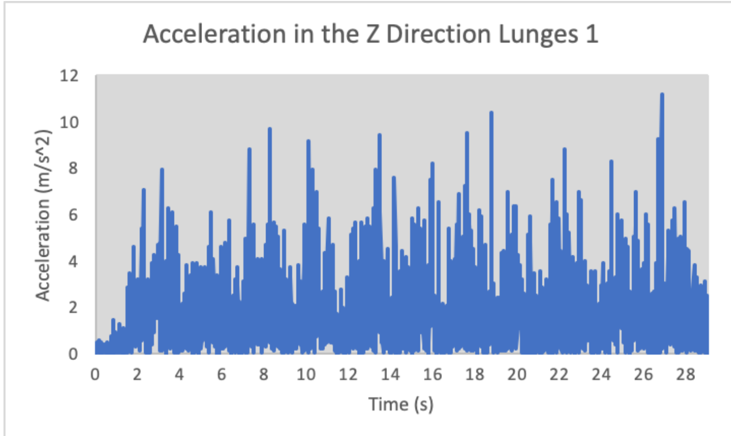

Figure 2.7 - The linear acceleration of the center of gravity in the Z direction during the first lunges trial.

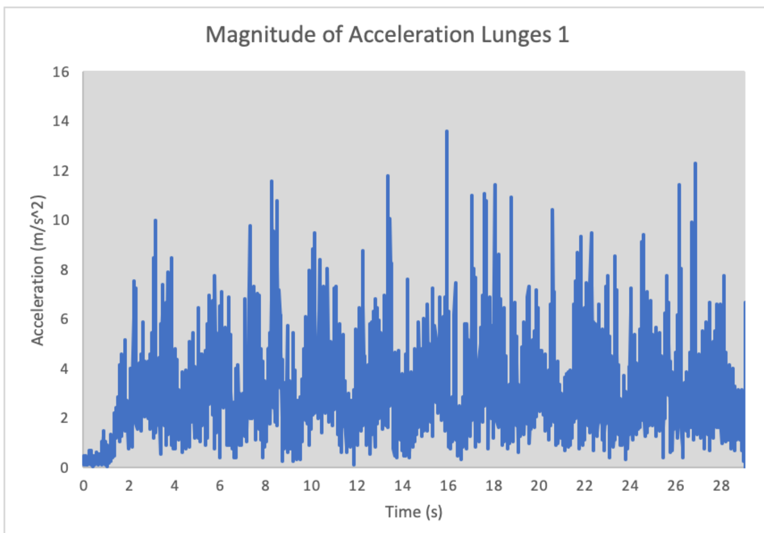

Figure 2.8 - The magnitude linear acceleration of the center of gravity during the first lunge trial.

	x	y	z	Magnitude
Max Linear Acceleration (m/s^2)	10.8	10.5	11.2	13.6
Minimum Linear Acceleration (m/s^2)	0	0	0	0
Average Linear Acceleration (m/s^2)	1.53	1.22	1.80	3.02

Side Lunge: Acceleration

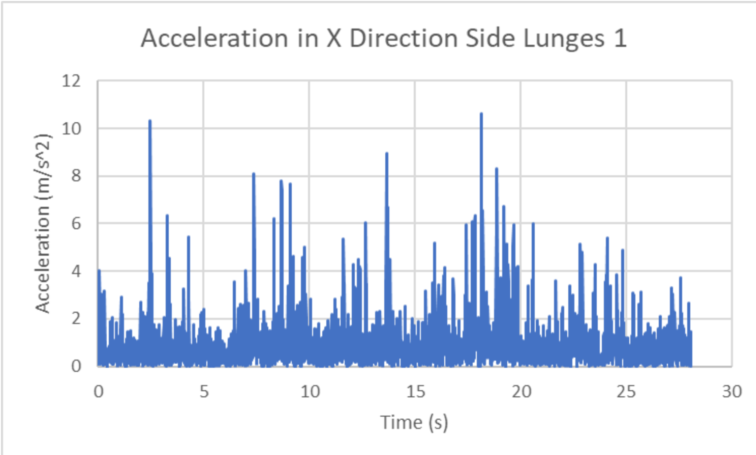

Figure 2.9 - The linear acceleration of the center of gravity in the X direction during the first side lunge trial.

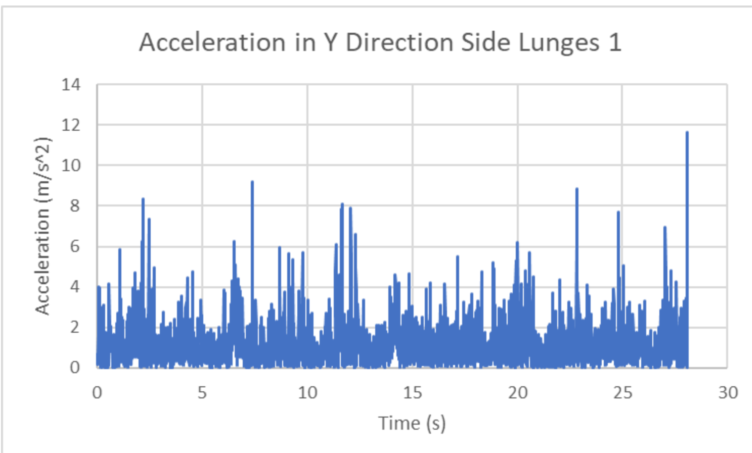

Figure 2.10 - The linear acceleration of the center of gravity in the Y direction during the first side lunge trial.

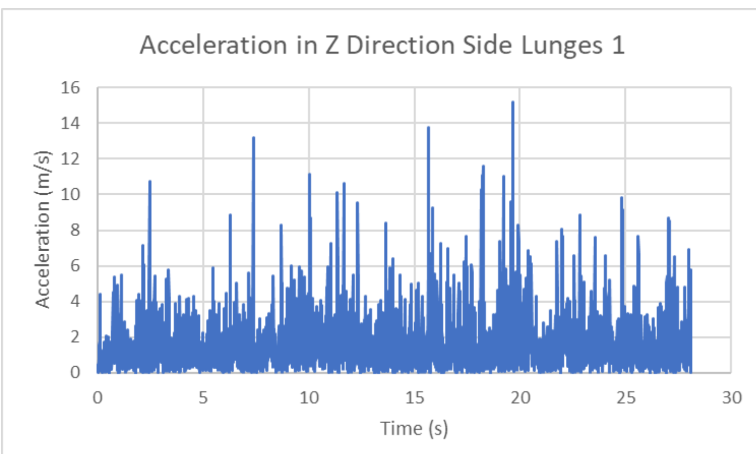

Figure 2.11 - The linear acceleration of the center of gravity in the Z direction during the first side lunge trial.

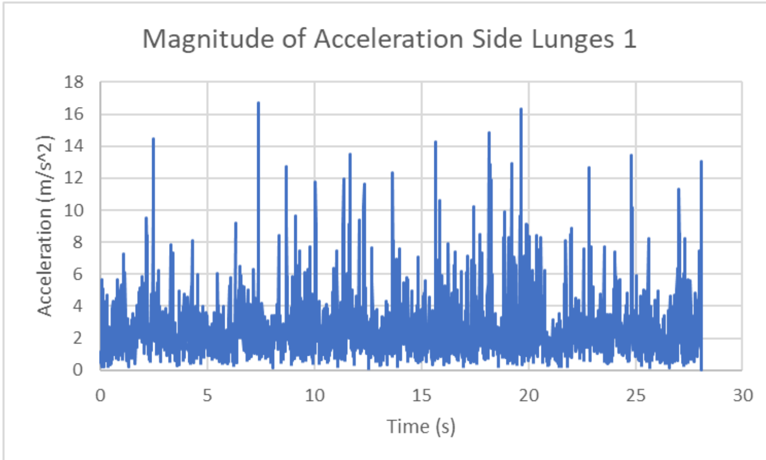

Figure 2.12 - The magnitude of the linear acceleration of the center of gravity during the first side lunge trial.

	x	y	z	Magnitude
Max Linear Acceleration (m/s^2)	10.614	11.660	15.209	16.696
Minimum Linear Acceleration (m/s^2)	0	0	0	0
Average Linear Acceleration (m/s^2)	0.951	1.209	1.714	2.623

Section 3 - Ground Reaction Forces

In this next section, we used the acceleration we just obtained, and found the ground reaction forces by multiplying acceleration and the mass of our subject.

$$Ground\ Reaction\ Force = mass\ of\ subject\ (56.7kg) * acceleration(m/s^2) \qquad \text{Equation 3.1}$$

We then graphed our results for these ground reaction forces. Figures 3.1-3.12 are the results for each direction (x, y and z), in squats, lunges, and side lunges respectively. For all the datasets, we used the sternum marker as our center of gravity. Also, same as we did for speed and acceleration, we found the maximums, minimums and averages for the ground reaction forces in each direction for every exercise. This allows us to get a better understanding of our data.

Squat: Ground Reaction Force

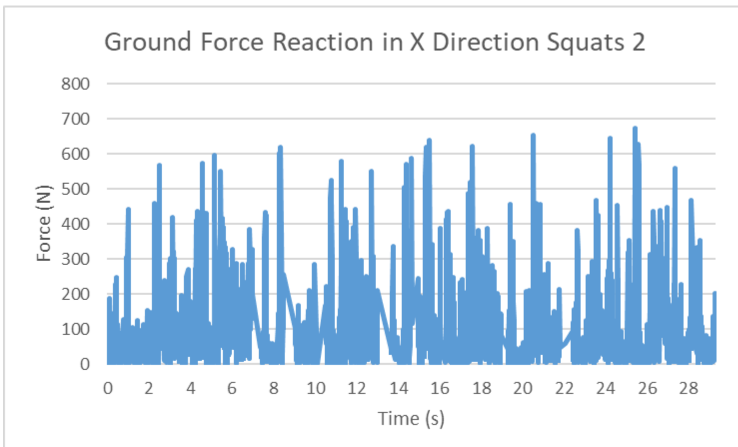

Figure 3.1 - The ground reaction force in the X direction during the second squats trial.

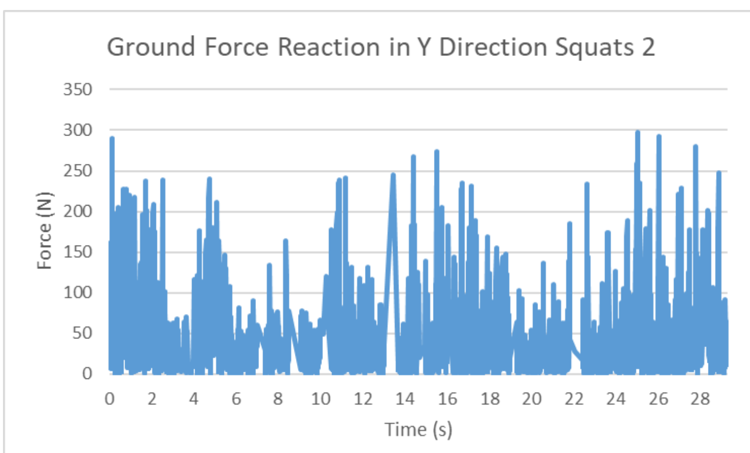

Figure 3.2 - The ground reaction force in the Y direction during the second squats trial.

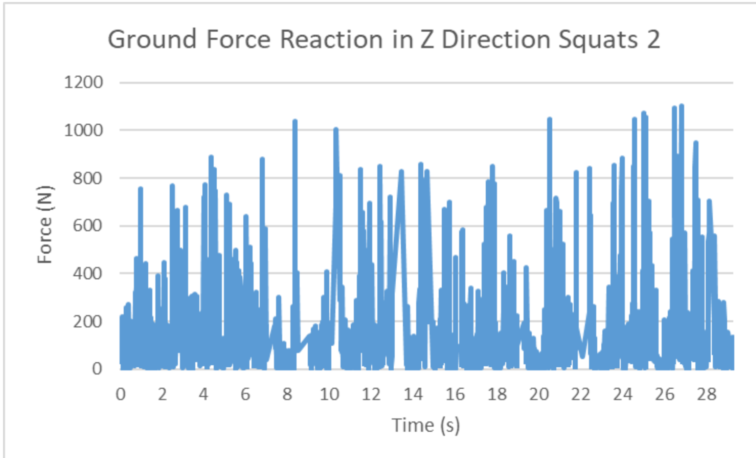

Figure 3.3 - The ground reaction force in the Z direction during the second squats trial.

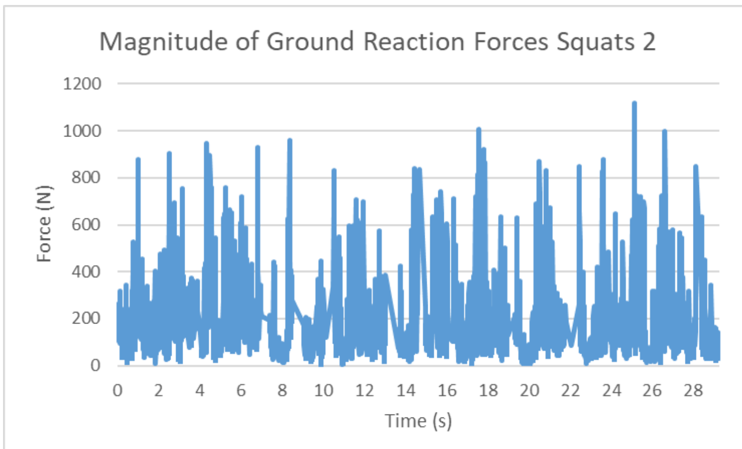

Figure 3.4 - The magnitude of the ground reaction force during the second squats trial.

	x	y	z	Magnitude
Max Ground Reaction Force (N)	673.252	297.823	1100.12	1117.09
Minimum Ground Reaction Force (N)	0.0215	0	$6.29x10^{-11}$	5.319
Average Ground Reaction Force (N)	96.198	43.907	139.894	186.705

Lunge: Ground Reaction Force

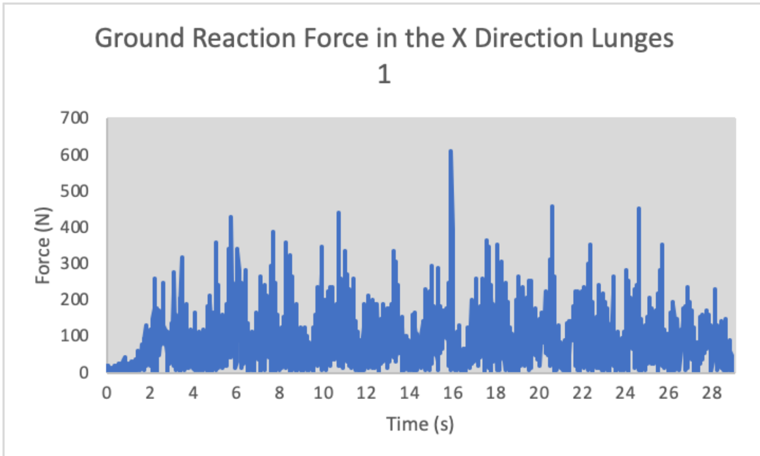

Figure 3.5 - The ground reaction force in the X direction during the first lunges trial.

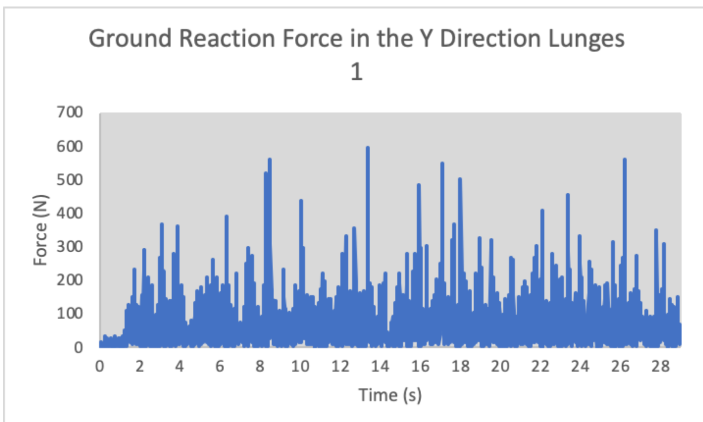

Figure 3.6 - The ground reaction force in the Y direction during the first lunges trial.

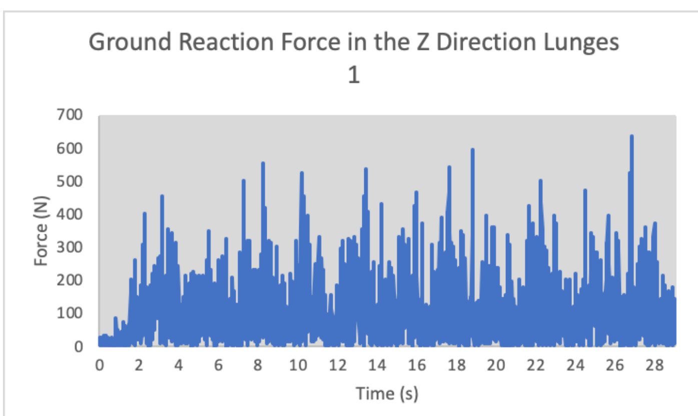

Figure 3.7 - The ground reaction force in the Z direction during the first lunges trial.

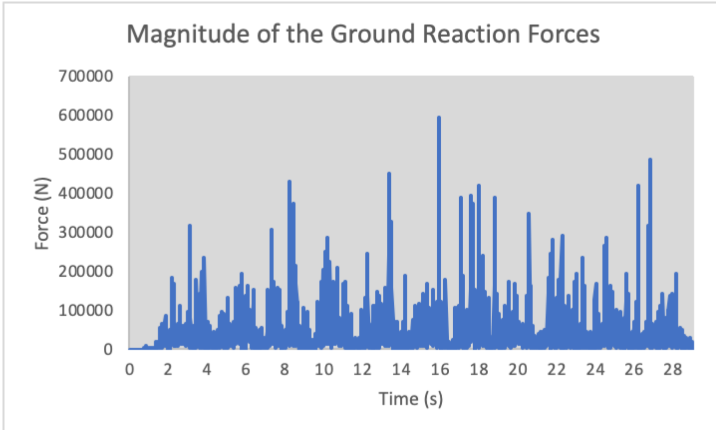

Figure 3.8 - The magnitude of the ground reaction force during the first lunges trial.

	x	y	z	Magnitude
Max Ground Reaction Force (N)	608	595	635	769
Minimum Ground Reaction Force (N)	0.120	0	0	0
Average Ground Reaction Force (N)	86.9	69.3	102	171

Side Lunge: Ground Reaction Force

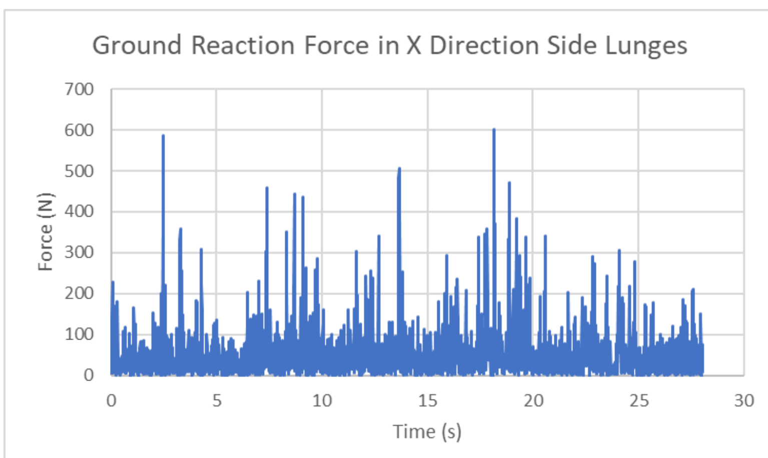

Figure 3.9 - The ground reaction force in the X direction during the first side lunge trial.

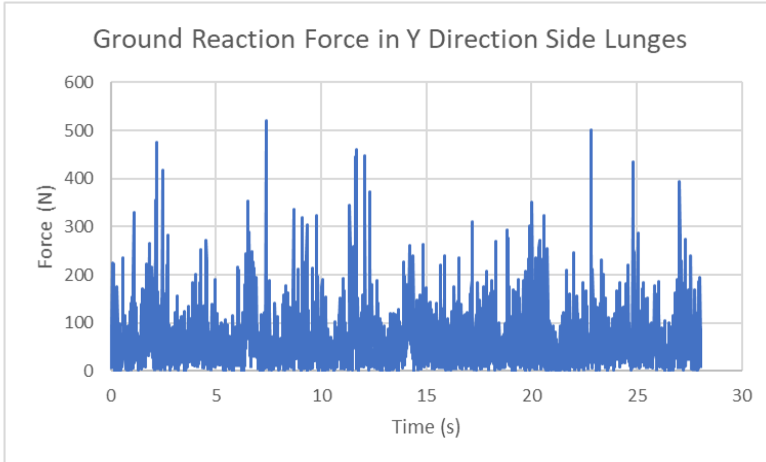

Figure 3.10 - The ground reaction force in the Y direction during the first side lunge trial.

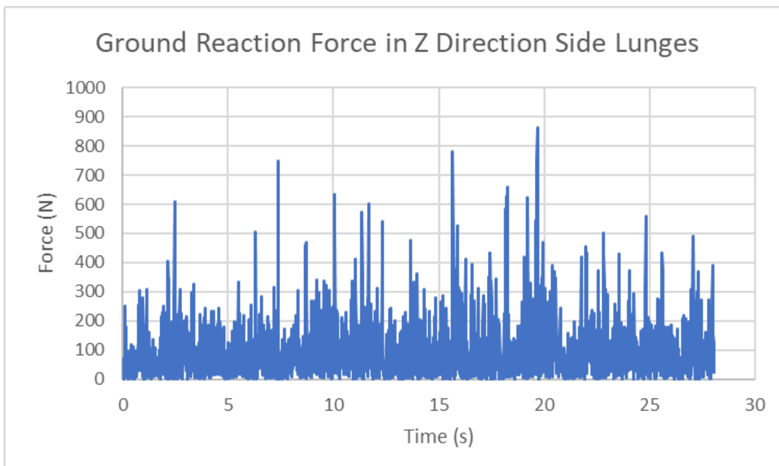

Figure 3.11 - The ground reaction force in the Z direction during the first side lunge trial.

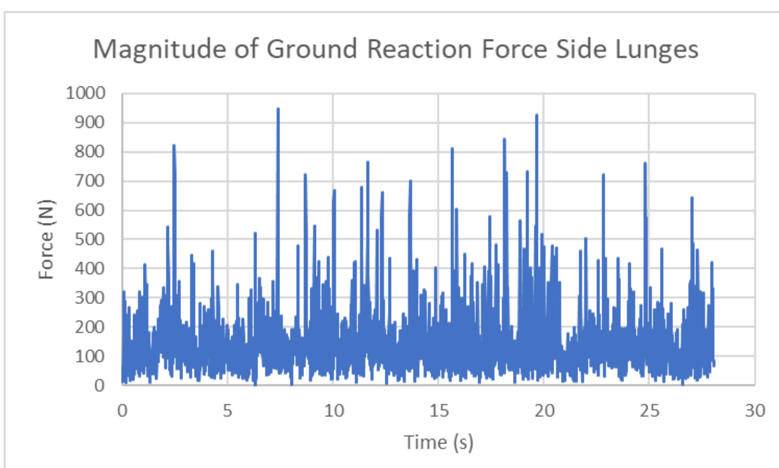

Figure 3.12 - The magnitude of the ground reaction force during the first side lunge trial.

	x	y	z	Magnitude
Max Ground Reaction Force (N)	601.797	520.402	862.405	946.687
Minimum Ground Reaction Force (N)	0	0	0	0
Average Ground Reaction Force (N)	53.915	68.335	97.079	148.451

Section 4 - Torque of the Hip and Knee Calculations and Net Values

In order to calculate the torque of the hip and the knee, we used the x and z components of the data collected for various markers on the body. For each movement recorded there are different calculations to determine the torque at the hip.

A few assumptions were used throughout this section. Firstly, our results from the squats data show that the net torques around the hip and the knee are equal and opposite in order to maintain equilibrium. While this may not be the case in a more detailed model, this makes sense for our simplified model. Secondly, we assume that movements between the left leg and right leg for asymmetric movements, our forward and side lunges, are also equal and opposite. Because of this, we are only examining the movement of the right leg in these two exercises, and the final net torque can be assumed to be half of the real world net torque where both legs are taken into account.

For the Squats trial we determined mathematically that the calculations for the torque of the knee result in equal but opposite values when compared to the torque of the hip. This can be seen from the data as well as in the graphs of the calculated torque (Figures 4.2, 4.3, 4.5, 4.7). This phenomena occurs because when doing our calculations and approximations of the body measurements, we made the assumption that the ground reaction forces extend from the exact middle of the thigh. This measurement of 8 inches (0.2032 m) was used for both the distance of the force from the hip (d_1) and the distance of the force from the knee (d_2). In actuality,the distance of the knee/hip moment may differ throughout the movement of our given exercises, but for the sake of this project this assumption was applied to each trial. Therefore, it can be assumed that the graphs and values for the knee torque calculations can be inferred from the hip torque graphs and values.

Squats 2 - Torque of the Hip and Knee Calculations

To calculate the torque of the hip during the Squat trial, we first averaged the left and right markers for the thigh, knee, ankle, and pelvis (THI, KNE, ANK, ASI respectively). This essentially saves us the trouble of averaging left and right leg data at the end of their individual calculations by creating a theoretical single leg that is central to the body and an average of each leg's position. Then, to determine the location of the hip, the ASI and THI markers were averaged. To determine the middle of the thigh, the calculated location of the hip and the KNE marker were averaged.

The next step was to create a vertical vector to represent the ground reaction forces acting on the thigh. This vector was created from the x and z components leading from the middle of the thigh to the sternum marker (STRN). This vector was labeled U. Then, the vector from the middle of the thigh to the hip was determined using the x and z components and labeled V. The magnitude of each of these vectors was determined by Equation 4.1. The dot product of these two vectors was determined by Equation 4.2.

$$Magnitude\ of\ Vector\ = \sqrt{x^2 + z^2} \quad \text{Equation 4.1}$$
$$U \bullet V = (U(x) * V(x)) + (U(y) * V(y)) \quad \text{Equation 4.2}$$
$$\frac{U \bullet V}{|U| \times |V|} = cos(\theta) \quad \text{Equation 4.3}$$
$$\frac{U \bullet V}{|U| \times |V|} = cos(\Delta) \quad \text{Equation 4.4}$$

These values were combined in Equation 4.3 in order to determine the angle of gamma. To find the angle of theta, we used Equation 4.6 and then graphed theta with respect to time as seen in Figure 4.1. To find the value of the shifted ground reaction force (F_{shift}) we used Equation 4.7. Lastly, the torque of the hip and the torque of the knee were calculated from Equation 4.8 and graphed with respect to time as seen in Figures 4.2 and 4.3.

$$\theta = -90 - \Delta \quad \text{Equation 4.5}$$
$$\theta = 90 - \gamma \quad \text{Equation 4.6}$$
$$F_{shift} = Fcos(\theta) \quad \text{Equation 4.7}$$
$$T = Fd \quad \text{Equation 4.8}$$

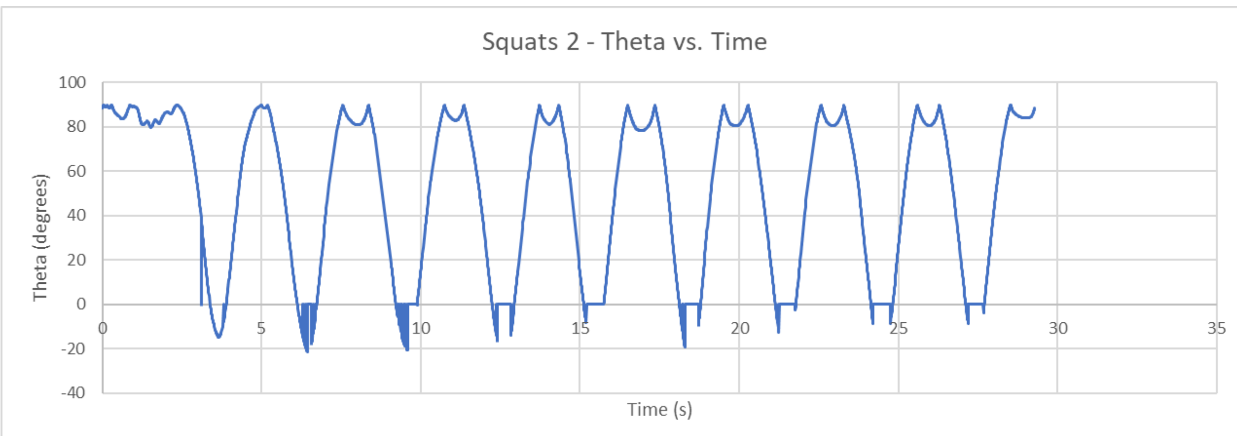

Figure 4.1 - Angle (theta) that the ground reaction force is shifted throughout the Squat 2 trial.

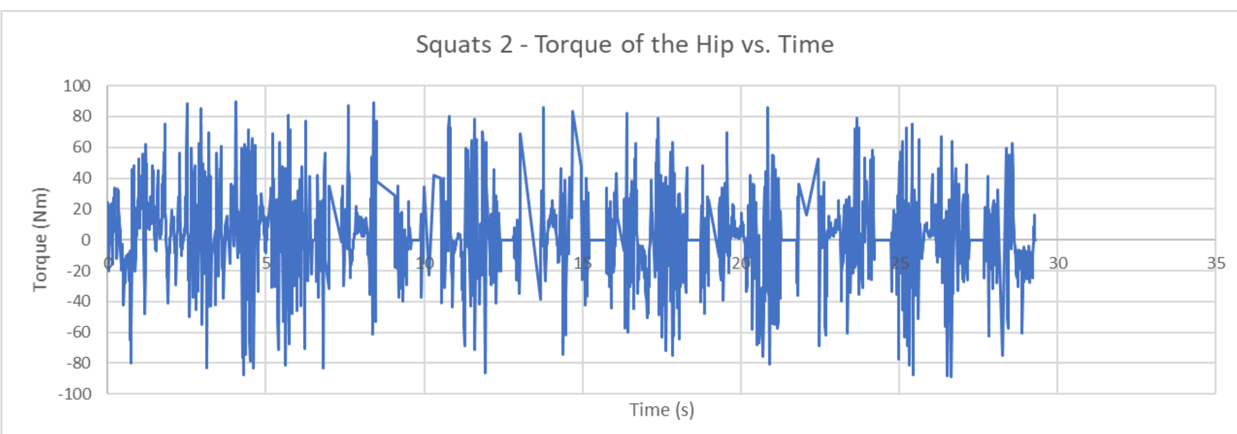

Figure 4.2 - Represents the torque of the hip calculated throughout the duration of the Squat 2 trial.

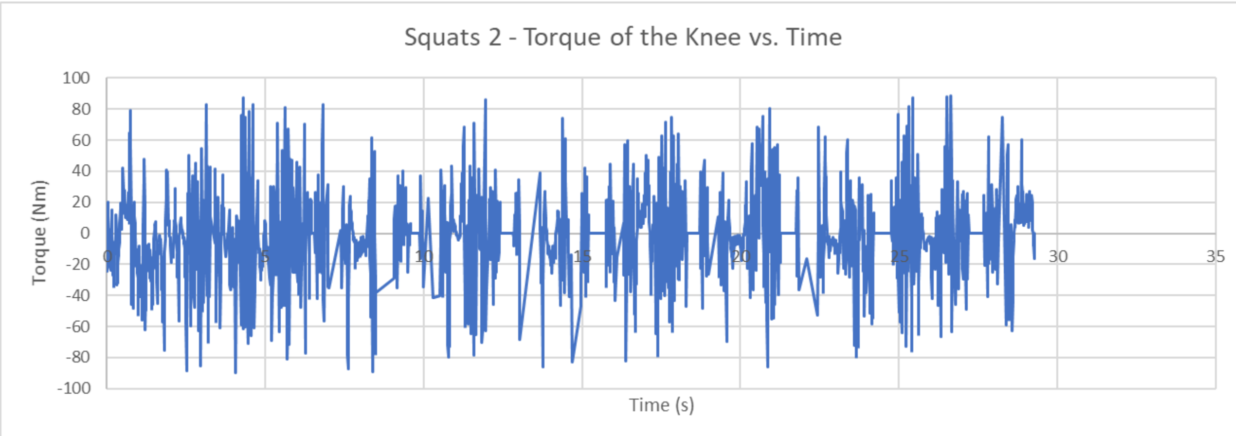

Figure 4.3 - Represents the torque of the knee calculated throughout the duration of the Squat 2 trial.

It can be seen that figures 4.2 and 4.3 are mirrored along the x axis, which shows further proof of our assumption that the hip and knee have equal and opposite forces and torques. In subsequent data sets where the movements are asymmetric, we will only be showing the torque and angular data for the hip, as we can reasonably assume equal and opposite data for the knee when an equally distanced moment arm is applied.

Squats 2 - Net Torque Data

The following charts of torque statistics for the hip and knee were determined from the data collected using Excel functions. Again, we can see that our hip and knee torques are equal and opposite. Due to this, we will show only the hip torques in subsequent datasets for conciseness.

Squat - Torque of the Hip

Net Thip (Nm)	4589.237037
Mean Thip (Nm)	1.781536117
Max Thip (Nm)	89.90957651
Min Thip (Nm)	-88.8422167
Median Thip (Nm)	0

Squat - Torque of the Knee

Net Tknee (Nm)	-4589.237037
Mean Tknee (Nm)	-1.781536117
Max Tknee (Nm)	88.8422167
Min Tknee (Nm)	-89.90957651
Median Tknee (Nm)	0

Forward Lunges 1 - Torque of the Hip and Knee Calculations

To calculate the torque of the hip during the Squat trial, we utilized the markers indicating the right side of the body. To determine the location of the right hip, the RASI and RTHI markers were averaged. To determine the middle of the right thigh, this location of the right hip and the RKNE marker were averaged.

The next step was to create a vertical vector to represent the ground reaction forces acting on the thigh. This vector was created from the x and z components leading from the right hip to the sternum marker (STRN). This vector was labeled U. Then, the vector from the hip to the middle of the thigh was determined using the x and z components and labeled V. The magnitude of each of these vectors was determined by Equation 4.1. The dot product of these two vectors was determined by Equation 4.2.

These values were combined in Equation 4.4 in order to determine the angle of delta. To find the angle of theta, we used Equation 4.5(delta-theta) and then graphed theta with respect to time as seen in Figure 4.4. To find the value of the shifted ground reaction force (F_{shift}) we used Equation 4.7. Lastly, the torque of the hip and the torque of the knee were calculated from Equation 4.8 and graphed with respect to time as seen in Figure 4.5. This graph had outlier values outside the range of (-100<n<100) excluded for clarity.

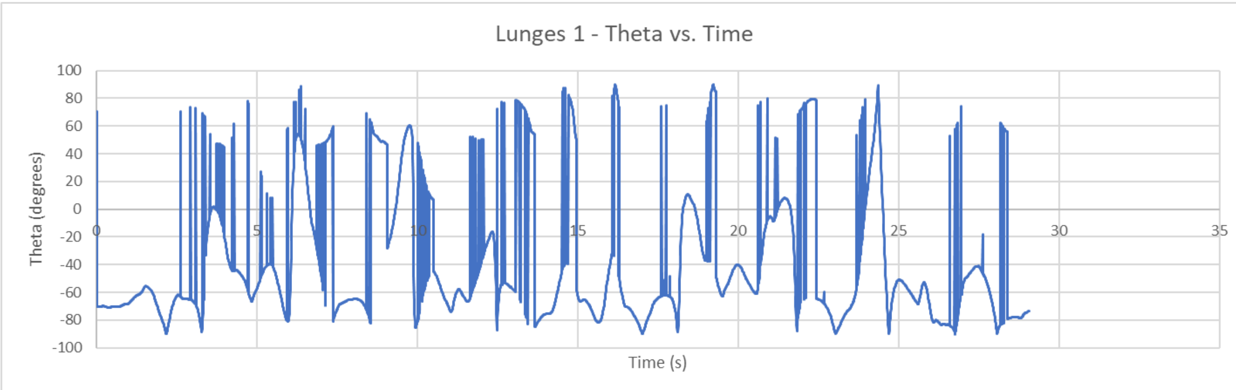

Figure 4.4 - Angle (theta) that the ground reaction force is shifted throughout the Forward Lunge 1 trial.

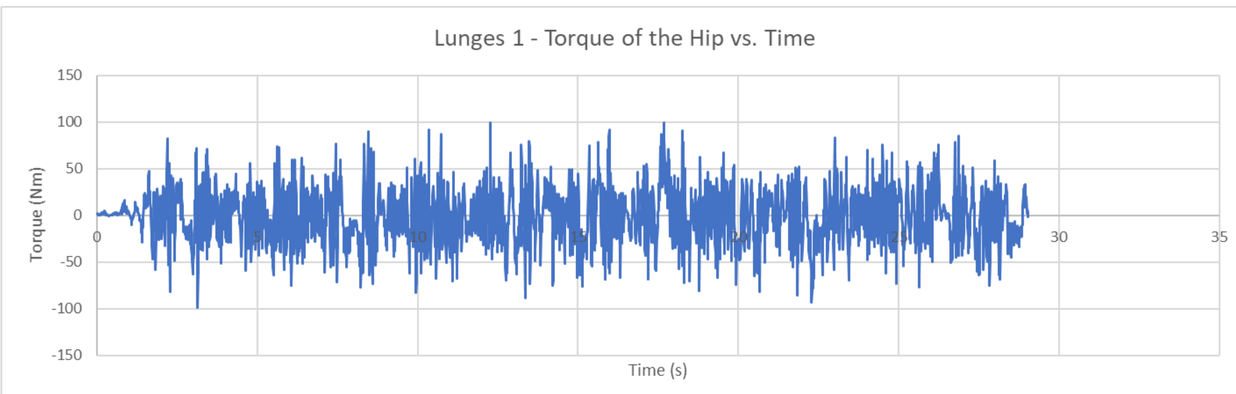

Figure 4.5 - Represents the torque of the hip calculated throughout the duration of the Forward Lunge 1 trial.

Forward Lunges 1 - Net Torque Data

The following charts of torque statistics for the hip were determined from the data collected using excel functions. It can be inferred that the torque statistics regarding the torque of the knee are essentially equal and opposite to these values due to the previously mentioned assumptions claiming d_1 is equal to d_2.

Forward Lunge - Torque of the Hip

Net Thip (Nm)	-4643.85
Mean Thip (Nm)	-1.59802
Max Thip (Nm)	99.32364
Min Thip (Nm)	-98.7981
Median Thip (Nm)	-0.7022

Side Lunge 1 - Torque of the Hip and Knee Calculations

The torque at the hip during our side lunge trials were calculated using similar methods as previously stated. A hip marker was calculated from the averaged RASI and RTHI markers, and a mid-thigh marker was calculated by averaging RHIP and RKNE. This allowed us to calculate a vector from the hip to mid-thigh, which was used in conjunction with a vector from the hip to sternum which was inferred to be the marker most in-line with our ground reaction forces.

The angle between these vectors was calculated in the same way as previous tests, calculating the difference of angle gamma in radians, converting to degrees, and then finding the opposing angle theta. The plot of the angle theta during the side lunge test can be seen below

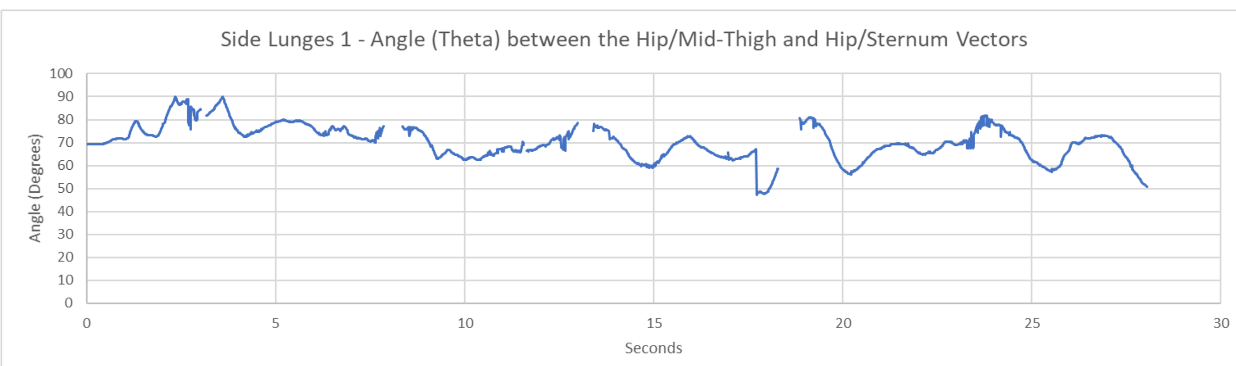

Figure 4.6 - Angle (theta) that the ground reaction force is shifted throughout the Side Lunge 2 trial.

One thing of note for this plot is that its inconsistency is due to the fact that we are seeing a full cycle of only one leg. This means each rep has two phases, the lunge and the extension for when the other leg is lunging. This coupled with the fact that our side lunge form was not ideal at first gives us a somewhat chaotic plot.

Additionally, the hip torque was also calculated in the same way as the lunge and forward lunge experiments. This plot has a clear, yet somewhat inconsistent cyclical pattern. Extreme outliers (-80Nm<n<80Nm) were eliminated from the dataset for clarity.

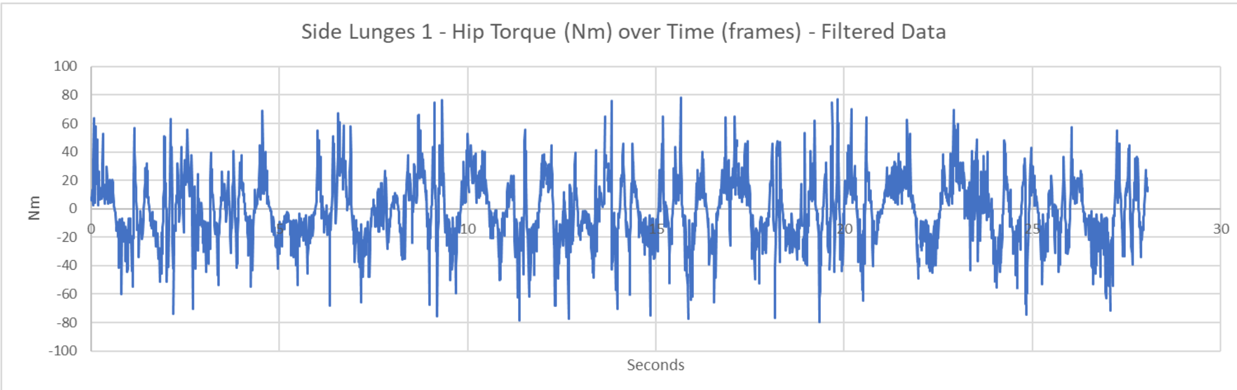

Figure 4.7 - Represents the torque of the hip calculated throughout the duration of the Side Lunge 2 trial.

Side Lunges 1 - Net Torque Data

The following charts of torque statistics for the hip were determined from the data collected using excel functions. It can be inferred that the torque statistics regarding the torque of the knee are essentially equal and opposite to these values due to the previously mentioned assumptions claiming d_1 is equal to d_2.

Side Lunge - Torque of the Hip

Net Thip (Nm)	-4756.9
Mean Thip (Nm)	-1.69526
Max Thip (Nm)	127.144
Min Thip (Nm)	-157.398
Median Thip (Nm)	-2.67701

Section 5 - Force Produced by the Muscle

The force produced by the muscle on the muscle is equal to the force vector of the ground reaction force relative to the angle of the hip/knee vector. Because we assume this occurs at the midpoint of the leg between the hip and knee, we can assume the forces on both body parts are equal and opposite.

Force Produced by the Muscle

	Squats 2	Lunge 1	Side Lunge 1
Net Force (N)	22584.82794	-22853.6	-16825.4
Max Force (N)	442.4683883	488.7974	383.9288
Min Force (N)	-437.2156333	-486.211	-391.991
Mean Force (N)	7.710764062	-7.86428	-6.4062
Median Force (N)	0	-3.45571	-11.028

Section 6 - Movement of the Center of Gravity

Lastly, we graphed the position of the sternum marker, estimated to be our center of gravity. By showing the movement in all three axes, we can see the predominant axis of movement for each exercise as well as any cyclical patterns. Comparing the graphs shows how the body moves differently for each exercise.

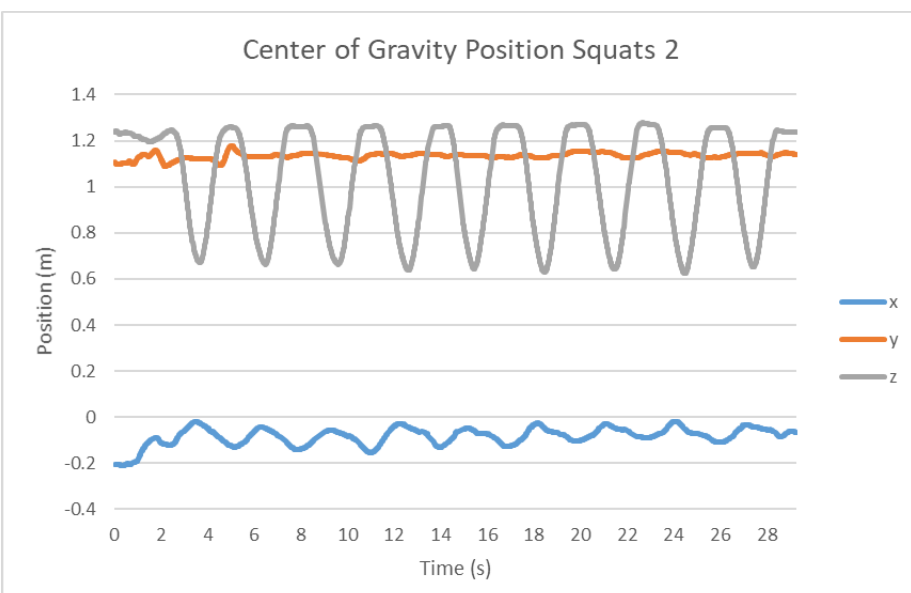

Figure 6.1 - The position of the center of gravity in all three axes during the second squats trial.

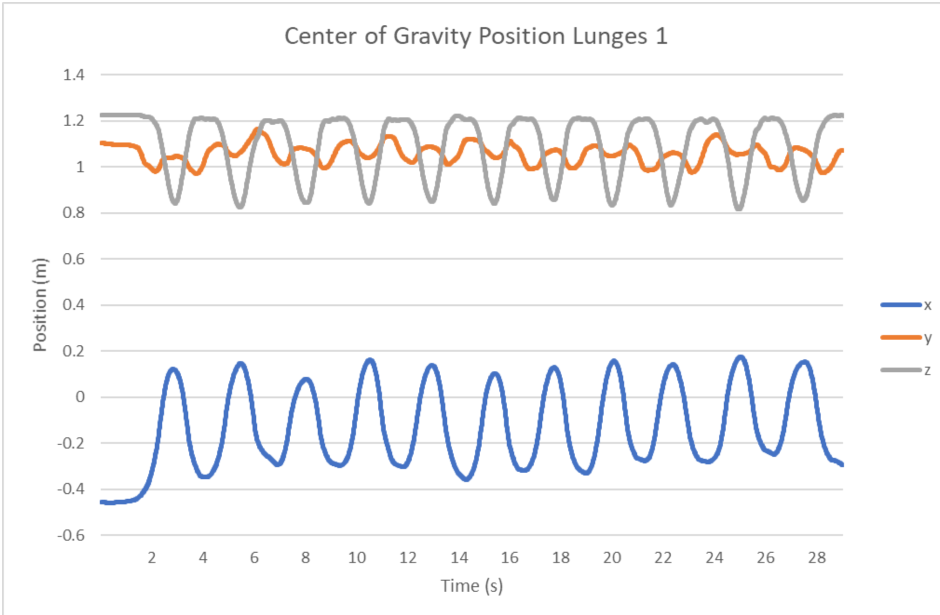

Figure 6.2 - The position of the center of gravity in all three axes during the first lunges trial.

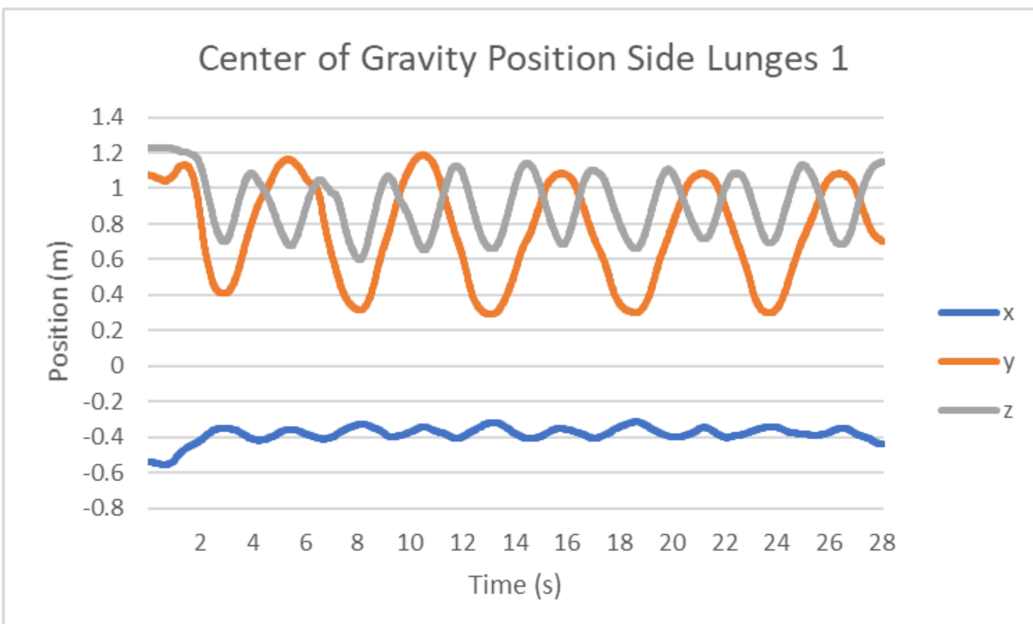

Figure 6.3 - The position of the center of gravity in all three axes during the first side lunges trial

Discussion:

Our ground reaction forces were taken for each direction of every trial, and by doing this we were able to calculate the averages of the ground reaction forces per step varied for each trial. We first started by calculating the linear speed by dividing the distance/meters by time. The linear speed of lunges 1 was greatest in the x direction and the average speed was 0.339 m/s. We then calculated the acceleration by dividing the linear speed by time. The acceleration for lunges 1 was greatest in the z direction and the minimum acceleration was zero in the x, y, and z directions. We then calculated the ground reaction forces by multiplying the acceleration by the mass of the subject. The ground reaction forces for lunges 1 were greatest in the z direction and smallest in both the y and z directions.

In our graphs for ground reaction force and linear speed, there are some outliers present, and this can be due to noise of the motion capture system. Not including the outliers, you can see that for our lunge 1 ground reaction forces, the maximum force for the x and y directions are around 600N, the maximum acceleration is 10.8 m/s^2, and the maximum linear speed is about 0.992 m/s. For our lunge 1 ground reaction forces, the average force for the x and y directions are around 77.5N, the average acceleration is 1.38 m/s^2, and the average linear speed is about 0.224 m/s.

During the side lunges trial, we can see some of the following trends. When referring to the linear speed during the side lunges exercise, it can be seen that average linear speed of the y and z directions are relatively the same, as they are 0.304 m/s and 0.311 m/s, respectively. You can also see from Figure 1.10 that linear speed in the y direction is a good indicator on how the subject is moving throughout these side lunges, as the subject has a speed of about 0 each time they do a side lunge (for a total of 10 times). As far as acceleration goes, the z direction has the highest maximum acceleration and the highest average acceleration for side lunges; these values are 15.209 m/s^2 and 1.714 m/s^2, respectively. The ground reaction forces for side lunges also follow this trend as well. The ground reaction forces have the highest maximum and average in the z direction. The maximum ground reaction force in the z direction is 862.405N and the average ground reaction force in the z direction is 97.079N.

The graphs for ground reaction force and linear speed during squats shows similar noise as during lunges and side lunges. As mentioned previously, this noise mainly affected the y and possibly x axes data. Our collected data for squats in the x axis gives a maximum speed of 0.199 m/s, maximum acceleration of 11.874 m/s^2, and maximum ground reaction force of 673.252 N. The y axis values, 0.119 m/s, 5.253 m/s^2, and 297.823 N, are roughly half of the corresponding x axis value. This trend is the same for the average values. The x axis had an average speed of 0.0606 m/s, average acceleration of 1.697 m/s^2, and average ground reaction force of 96.198 N. The y axis had average values of 0.0254 m/s, 0.774 m/s^2, and 43.907 N. This matches the fact that the center of gravity was moving about twice as much in the x axis as in the y axis, as shown in Figure 6.1.

Figure 6.1 also shows that the z axis contains the majority of the movement during a squat. Due to this, the calculated speed and ground reaction forces are greater in the z direction than the x and y directions. The z direction had a maximum speed of 1.021 m/s, maximum acceleration of 19.402 m/s^2, and maximum ground reaction force of 1100.12 N. These values are similar to the maximum of the overall magnitude 1.032 m/s, 19.702 m/s^2, and 1117.09 N,which makes sense since an ideal squat form would involve movement only in the z direction. The average values for just the z direction are 0.328 m/s, 2.467 m/s^2, and 139.894 N. The averages for the overall magnitude, 0.355 m/s, 3.293 m/s^2, and 186.705 N, are similar but overall greater since the x and y axes are also being considered.

When analyzing the statistical torque data from the three trials, the total net torque of the hip ranges in magnitude from approximately 4589 Nm to 4756 Nm. It would make sense that these values are similar considering that the trials were each performed the same amount of times. The mean of the torque lies around zero which aligns with the trials because each trial consisted of the subject bending their hip and knees in a repetitive motion as they move up and down. Therefore, the average torque would equate to zero as the positive and negative values would cancel out.

The oscillating theta plots for each experiment have somewhat messy data. We believe this is due to the data taking into account the motion of the left leg in asymmetric movements, like forward and side lunges. Aside from these erroneous fragments in the data, our values confirm the hypothesis set after our assumptions that the hip and knee would have equal and opposite reaction forces and torques along an equal moment arm.

When looking at the force produced by the muscle for the three trials, the lunges have the largest maximum force, followed by the squats and side lunges respectively. This would mean that forward lunges would require the most force with regards to the quadricep muscles when compared to squats and side lunges. The net force produced by the muscle is also largest for forward lunges along with the mean, although these values are a bit closer.

The graphs in Section 6 show the predominant axes of movement for each exercise. Squats involve movement almost entirely in the Z axis, while lunges and side lunges involve multiple axes. Lunges involve movement mainly in the X and Z axes, while side lunges involve the Y and Z axes. This is reflected in our calculated data when looking at the speed and forces in each individual axis.

References:

[1] "Calf Muscle: Anatomy, Function and Common Conditions." *Cleveland Clinic*, my.clevelandclinic.org/health/body/21662-calf-muscle#:~:text=Your%20calf%20muscle%20consists%20of.

[2] Elzanie, Adel, and Judith Borger. "Anatomy, Bony Pelvis and Lower Limb, Gluteus Maximus Muscle." *PubMed*, StatPearls Publishing, 2021, www.ncbi.nlm.nih.gov/books/NBK538193/.

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[4] "Hip Adductors." *Physiopedia*, www.physio-pedia.com/Hip_Adductors#:~:text=Adductor%20Magnus%20is%20a%20broad. Accessed 12 May 2022.

[5] "Quadriceps Muscle." *Physiopedia*, www.physio-pedia.com/Quadriceps_Muscle#:~:text=The%20quadriceps%20femoris%20is%20a.

Distribution of work:

1. **Linear Speed**
   - Calcs: MF, CC, LMK graph: MF, CC, LMK max/min: MF, CC, LMK
2. **Acceleration**
   - Calcs: MF, CC, LMK graph: MF, CC, LMKmax/min: MF, CC, LMK
3. **Ground Reaction Forces**
   - Calcs: MF, CC, LMK graph: MF, CC, LMK max/min: MF, CC, LMK
4. **Torque of the Hip**
   - Calcs: SS, CB graph: SS, CB max/min: SS, CB
5. **Torque of the Knee**
   - Calcs: SS, CB graph: SS, CB max/min: SS, CB
6. **Net Torques**
   - Calcs: SS, CB graph: SS, CB max/min: SS, CB
7. **Force of the muscles**
   - Calcs: SS, CB graph: SS, CB max/min: SS, CB
8. **Position of center of gravity**
   - Graph: MF
9. **Introduction, Methods, and Formatting**
   - CB, CC, LMK, MF, SS

Everyone helped write the results and discussion for the sections they worked on.