# BMEG 230 Project
# Weighted Squat Jump Design
# Final Report

The Biomechanic Brainiacs

Ellie Smith 62673660
Elin Lee 16772683
Stacey Sholter 92672997

## 1.0 Introduction

### 1.1 Outline Design Problems

Patellofemoral pain syndrome (PFPS) is a common issue among athletes, particularly those who participate in sports involving squatting and jumping. This condition can be caused by several factors, including overuse of the knee joint, problems with kneecap alignment, and weak muscles surrounding the knee (Cleveland Clinic, 2018).

A major cause of PFPS is altered patellofemoral (PF) joint forces. This alteration can lead to an imbalance in the distribution of forces across the knee joint, which can result in pain and discomfort. Additionally, compression of the PF joint is also a significant issue. This compression can lead to increased stress on the joint, further exacerbating the pain and discomfort associated with PFPS. Despite these challenges, exercise is often a favourable treatment for PFPS. By strengthening the muscles surrounding the knee, individuals can help to improve the alignment of the kneecap and reduce the strain on the PF joint. However, it is important to note that the effectiveness of exercise as a treatment can vary depending on the individual's specific condition and needs (Meil et al., nd).

In designing solutions to address these issues, it is crucial to consider the unique challenges associated with PFPS. Any design must take into account the need to balance forces across the knee joint, reduce compression of the PF joint, and strengthen the surrounding muscles. Furthermore, the design must be adaptable to accommodate the diverse needs of individuals with PFPS. This includes considering the specific movements involved in the individual's sport or activity, as well as their unique physiological characteristics.

### 1.2 Discuss Movement Under Study

The squat jump, a versatile lower-body strengthening exercise, caters to individuals across diverse fitness levels, from novices embarking on their fitness journey to elite athletes (Lorenzen, 2018). Engaging the ankle, knee, and hip joints, this exercise taps into the power of key muscle groups, including the quadriceps, gluteal muscles, hamstrings, core muscles, and gastrocnemius. Beyond its primary focus on strength-building, the squat jump also contributes to cardiovascular fitness.

Structured in three phases within the sagittal plane, the exercise unfolds seamlessly. The initial phase involves a squat, with flexion occurring in the torso, hip, knees, and ankles. Upper leg muscles and ankle muscles are activated to maintain stability and balance. The subsequent phase propels the individual upward through a powerful push-off, where the ankles move into a plantarflexion position. Concurrently, extension in the knees, hips, and elbows facilitates upward propulsion. The final phase entails a controlled landing, with flexion in the ankle and knee joints providing a cushioned return to the original squat position.

Extending beyond its practical application, research papers delve into the biomechanics of the squat jump, shedding light on specific aspects related to functional movements and performance. For instance, studies such as "A Comparison of Biomechanical Outcomes in Single Leg Squat and Vertical Drop Jump" by Kristin Nicole Lorenzen explore kinematic and kinetic differences in individuals with a history of intra-articular knee injury (2018). Other research, like "Analysis and Comparison of Motion Biomechanics Characteristics of Squat Jump and Half-Squat Jump" by Manman Zhao and Jinjin Zhang, delves into the kinematics and dynamics of squat jumps in young men (2022). Additionally, studies investigate the nuances of squat jumps in specialized contexts, such as the "Biomechanical Analysis of Squat and Counter Movement Jump in Skater," which explores differences between skaters and control subjects.

### 1.3 Review Existing Solutions

The exploration of knee braces encompasses various types, each tailored to address specific conditions and requirements. According to research, patellar straps prove effective when the condition is isolated to the patellar tendon. These straps utilize pressure, enhancing proprioception and providing targeted support. Soft knee braces, on the other hand, focus on applying compression around the knee. Typically employed preventively, these braces lack the ability to offload joint pressure. Another innovative option is the Levitation knee brace, featuring a spring-loaded hinge that absorbs energy when the leg is bent. This design incorporates a hard exterior for durability and robust support, making it a noteworthy choice for those seeking comprehensive knee assistance (Kerekes, 2021).

Shifting the focus to exoskeleton research, passive knee exoskeletons emerge as promising aids in functional tasks, particularly in load lifting and stress reduction during activities like squats. The biomechanical effects of a specific springexo coilspring exoskeleton, as detailed in a study (Hidayah et al., 2021), showcase its impact on knee extension through thigh and shank cuffs, with a spring encircling the knee. Furthermore, a separate proposal (Ben-David et al., 2022) emphasizes the advantages of passive knee exoskeletons in enhancing vertical jump height. This particular device utilizes springs that collaborate with the quadriceps, storing mechanical energy during knee flexion and releasing it during knee extension, resulting in a notable increase in jump height. The study reports a 6.4% higher jump with the exoskeleton compared to participants without it.

In line with this, a single-leg exoskeleton design, as discussed in another research article (Moon et al., 2019), contributes to the expanding realm of exoskeleton technology. While specific details of this design are not provided, the research underscores the diverse approaches within exoskeleton development, hinting at potential advancements and applications in the realm of knee assistance and biomechanical enhancement. Collectively, these research findings showcase the multifaceted landscape of knee braces and exoskeletons, offering insights into the varied options available for individuals seeking solutions to knee-related challenges.

### 1.4 Describe Client Needs

In addressing the unique needs of athletes with knee problems who still seek effective workouts, the utilization of wearable biomechanical devices presents a promising solution. However, several factors, as highlighted by McDevitt et al. (2022), need careful consideration, including cost, availability, and adoption.

To make these devices more appealing and accessible to athletes, a paramount concern is their cost-effectiveness. Incorporating affordable materials in the construction of the device not only lowers the overall cost but also enhances its availability. Another crucial aspect is the practicality of the device during a workout routine. Given that squat jumps are typically just one exercise within a broader regimen, the device must be easy to put on and take off swiftly. This ease of use ensures that athletes can seamlessly integrate the wearable into their workouts without disrupting the flow or consuming excessive time, thereby enhancing its practical utility.

Comfort emerges as a non-negotiable criterion for the wearable device. Athletes with knee problems need assurance that the device is comfortable enough to be worn consistently throughout their workouts. This comfort factor contributes significantly to user compliance and satisfaction, key elements for the sustained adoption of such technology. Lastly, the primary focus of the wearable biomechanical device is to address and mitigate joint forces and alignment issues, with particular emphasis on alleviating concerns related to knee problems. This functionality ranks highest in the priority list for the wearable device's design and features.

By prioritizing the reduction of joint forces and ensuring proper alignment, the device becomes a targeted solution for athletes seeking to engage in strenuous workouts while managing knee-related challenges.

In essence, the success of a wearable biomechanical device tailored for athletes with knee problems lies in its affordability, ease of use during workouts, overall comfort, and, most critically, its ability to effectively reduce joint forces and ensure proper alignment. Meeting these client needs will not only enhance the device's acceptance but also contribute significantly to the well-being and performance of athletes facing knee-related concerns.

### 1.5 Objective
Our study seeks to design a device to augment the squat-jump movement for better, more comfortable performance by athletes with patellofemoral joint syndrome.

## 2.0 Methods
### 2.1 Biomechanical Data Collection Approach
In conducting the biomechanical study, the collection of data is a critical aspect that involves meticulous planning and precise execution. The equipment and setup play a pivotal role in ensuring the accuracy of the biomechanical data acquired. To achieve this, a high-quality camera capable of recording at a high frame rate is employed. The camera is strategically positioned on a stable tripod to guarantee steady recordings, and its orientation is adjusted to capture the sagittal plane of motion.

Prior to recording, participant preparation is essential. Basic participant information, including weight, is gathered, and participants are thoroughly briefed on the specific motions they will be performing, including any added weights. This preparation phase is crucial to standardize the conditions and variables across the study.

The video recording process was then carefully executed. Each video starts from a static posture to establish a baseline, and the movements progress in a controlled manner with consistent velocity. Three videos are recorded for each participant and motion: unweighted motion, weighted motion with weight 1, and weighted motion with weight 2, where weight 2 is greater than weight 1. Following the recording, a rigorous video testing phase was implemented to ensure the quality and accuracy of the collected data. Each video undergoes visual inspection for clarity, focus, and proper framing, guaranteeing that the recorded material meets the study's high standards.

The subsequent step involves data processing using OpenPose, a computer vision library, to extract kinematic data from the videos. The extracted data is then exported to CSV files, facilitating further in-depth analysis. A meticulous approach is maintained in data organization, where detailed records of each participant, including weight, added weights, and conditions, are documented. Additionally, the frequency of the camera during recording is noted for future reporting purposes. Post-processing steps involve trimming the videos to include only the necessary portions for analysis. Consistency is ensured across all videos in terms of the selected segments, contributing to the reliability of the data.

In the reporting phase, comprehensive details are provided, including the camera frequency used for recording. The collected data is presented in a clear and organized manner, specifying the conditions for each participant and motion. This meticulous approach to data collection and processing ensures the study's reliability and contributes to the overall scientific rigour of the biomechanical analysis.

**2.2 Data Analysis**
A video of each participant performing the squat jump was analyzed in OpenPose. This gave an estimate of each joint during the entire motion by tracking about 25 different anatomical markers. This data was then presented in a CSV file and a video overlay. For each participant and trial, a time array was initially set. The time array took into account that the video was filmed at a frame rate of 30 Hz. To calculate the joint angles, vectors from the CSV file data were created. The vectors included, for both the x and y directions, a heel-to-toe vector and an ankle-to-knee vector. In order to determine the angles between these vectors another variable, angles_deg was calculated using the inverse tan of the calculated vectors.

```
angles_deg = atan2d(heeltoe_Vector(:, 1).*ankleknee_Vector(:, 2) -
heeltoe_Vector(:, 2).*ankleknee_Vector(:, 1), heeltoe_Vector(:,
1).*ankleknee_Vector(:, 1) + heeltoe_Vector(:, 2).*ankleknee_Vector(:, 2));
```
**Equation 2.1** Matlab code used to calculate the angle between the heel-toe vector and ankle-knee vector for each frame of the given video.

The angles_deg represented the angle of the participants' ankle-knee segment during the squat jumps. Before the data was plotted it was filtered using a lowpass Butterworth frequency in order to remove high-frequency noise. For certain trials, the data files contained additional data before and after the jump. This was removed by changing the time vector being plotted, in order only to plot the squat jump itself. The filtered angle between the ankle and knee joint was then plotted against the time vector for the selected time. The sample rate was 30 Hz as the videos were taken on an iPhone. The cutoff frequency was set to 5 after trial and error to determine the best-fit frequency.

From the angle vs time plot angular velocity angular velocity was able to be calculated by taking the approximate time derivative of the filtered angles using MatLab's 'diff' function. [1]

```
angular_velocity = diff(filtered_angles_deg) / time_interval;
```
**Equation 2.2** Angular velocity using the approximate derivative function from MatLab.

The angular acceleration was found in a similar method by taking the approximate time derivative of the angular velocity.

```
angular_acceleration = diff(angular_velocity) / time_interval;
```
**Equation 2.3** Angular acceleration calculation using the approximate derivative function from MatLab.

To calculate the knee to hip angles a very similar process was used. After the time vector was set, the vectors from the knee to the hip in both the x and y direction were calculated and set. For this segment since there were no points to be used as reference points a reference vector was created. From there the angles in each frame were calculated using the same format as Equation 1. Again, the data was filtered using the same low pass filter as the ankle-knee segment. The angular velocity and angular acceleration were also calculated with the same function as in equations 2 and 3.

Each of these calculations was done for each participant's 3 different trials at each of the 3 different weighted conditions.

To collect temporal and spatial metrics, Matlab was once again used. The range of motion of each joint was calculated by setting each joint involved, the mid hip, hip, knee, ankle, and hip, as a marker. From this, the vectors between each were calculated. The angle between each during each frame of the video was calculated by a helper function that found the angle using the function acosd from the Matlab library.

```
angle = acosd(dot(v1, v2) / (norm(v1) * norm(v2)));
```

**Equation 2.4** Calculation used to find the angle between the vectors set between each of the selected markers.

To calculate the total time of the motion the time of the motion within the video was divided by the frame rate.

Both the spatial and temporal metrics were calculated on each of the participants for each of the different trials.

For the phase 5 analysis, segment analysis of the dynamic movements was calculated at the squat phase, take-off phase, and in-air phase using Newton's second law. A generalized participant was used using averages of the participants' gender and age group. The equations used can be seen in figures 2.5, 2.6, and 2.7 in the appendix. Assumptions were made for the ground reaction forces and the accelerations. Gravity was assumed to be $9.81 m/s^2$ in the negative y direction. These values were chosen based on common values. Segment analysis was then calculated by hand and using Matlab to find the values in tables 3.11, 3.12, and 3.13 in the Results section.

## 2.3 Device Concept Selection

### 2.3.1 Brainstorming Session

In the course of our brainstorming session, our group employed a collaborative approach to develop design alternatives. The session, conducted together, spanned approximately one hour, allowing for in-depth exploration and discussion. We began by outlining the problems we aimed to address, such as achieving a softer landing, optimizing muscle work and force, and mitigating knee pain or the effects of force. Through open dialogue and creative input from each member, we generated ideas to enhance the explosive jump motion while maintaining the effectiveness of workouts for athletes without imposing additional strain on their bodies and joints. Our main points of focus involved reducing joint forces, and improving joint alignment. Our exploration extended to investigating the potential of spring exoskeletons for achieving higher jumps. Specifically focusing on knee-related solutions, we examined features of passive knee exoskeletons tailored for elevated jumps and patellofemoral knee braces designed to reduce forces on the joint while enhancing alignment.

### 2.3.2 Screening, Ranking, and Scoring

In the selection process for the optimal knee brace design, instead of a pros/cons table, we utilized screening, ranking and scoring tables to evaluate three preliminary designs produced earlier. These designs are annotated with key features and brief explanations of each in Appendix Table 2.1.

Initially, rather than conducting elimination, the screening process served to confirm that all three designs were viable and deserved a more thorough evaluation, which was done in the subsequent ranking and scoring stages. In the Ranking table (Table 2.2), all three designs – Hard Knee Brace, Soft Knee Brace, and Patellar Strap – received equal total results of 8 points each when evaluated based on cost or availability, comfort, practicality, and their effectiveness in reducing joint forces and alignments. However, a more detailed next assessment was conducted using a weighted decision matrix (WDM) as shown in Table 2.3. The criteria were weighted according to their importance: cost at 10%, comfort at 25%, practicality at 25%, and reducing joint forces and alignments at 40%. The Hard Knee Brace scored highest with a total score of 2.3 due to its superior performance in reducing joint forces and alignments. The Soft Knee Brace followed closely with a score of 2 owing to its comfort level while the Patellar Strap lagged behind with a score of 1.7 mainly because it excelled only in cost. Biomechanically relevant considerations played an essential role; the Hard Knee Brace's ability to significantly reduce joint forces made it stand out despite not being the most comfortable or practical option. This factor is crucial for patients requiring substantial support post-injury or surgery.

In conclusion, based on our comprehensive evaluation process that considered various factors including biomechanical benefits, cost-effectiveness, comfort level, and ease of use; we selected the Hard Knee Brace as our winning concept design. Its outstanding performance in providing a significant reduction in joint forces outweighed other factors, making it an optimal choice for ensuring both safety and support for users.

## 3.0 Results

### 3.1 Biomechanical

The range of motion of each joint is highly dependent on the amount of weight each participant is jumping with. Additionally, the ROM is also highly dependent on each participant's motion within the squat. Discrepancies between each participant can include the minimum height within their squat. Throughout each participant, it can be seen that the angles of the ROM are more consistent throughout each of their own trials than compared to the other participants. The time of each movement depended on the participants' jump style. Participant one took a slower squat than participant 2 or 3 therefore making their jump time longer.

**Table 3.1** Range of motion of each participant showcasing spatial metrics and the total time of each motion showcasing temporal metrics.

| | Participant 1 | | | Participant 2 | | | Participant 3 | | |
|---|---|---|---|---|---|---|---|---|---|
| | No weight | 6 pounds | 10 pounds | No weight | 6 pounds | 10 pounds | No weight | 6 pounds | 10 pounds |
| Range of motion of Ankle (Degrees) | 79.837033 | 62.330308 | 43.804307 | 89.879420 | 89.879420 | 89.879420 | 87.699906 | 86.026071 | 86.024441 |
| Range of motion of Knee (Degrees) | 83.355340 | 18.895850 | 55.307146 | 58.368050 | 62.313428 | 62.313428 | 37.380457 | 58.368050 | 19.688646 |
| Range of motion of Hip (Degrees) | 106.206635 | 45.863804 | 45.863804 | 56.578222 | 100.487677 | 106.206635 | 25.153900 | 40.884728 | 21.147565 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Total time of movement (Seconds)** | 8.500000 seconds | 8.433333 seconds | 5.133333 seconds | 10.400000 seconds | 13.166667 seconds | 15.900000 seconds | 2.966667 seconds | 3.666667 seconds | 3.833333 seconds |

This section presents the results of the data analysis through Matlab. The same analysis was performed for each of the participants. Both the ankle-knee and knee-hip data tables for participant 1 and participant 2, tables 3.2 and 3.3, and tables 3.4 and 3.5 respectively, can be found in the appendix. Comparing the jumps of the different weighted trials of each participant it can be seen that when greater weight was added there was an overall change in the participants' jump style. A much greater discrepancy can be seen in the knee and hip angles. The added weight affects both the knee and hip to a much greater degree than the ankle joint. This can be seen in each of the participants' jumps in tables 3.3, 3.5, and 3.7. The angular velocities also show high variation at each of the different weighted conditions for the hip and knee segment analysis but remain more consistent for the ankle angle. The angular acceleration is inconsistent throughout each trial though this may be due to insufficient filtering of the data.

**Table 3.6** Ankle - Knee segment joint angle, angular velocity, and angular acceleration versus time graphs for participant 3 for each different weighted condition.

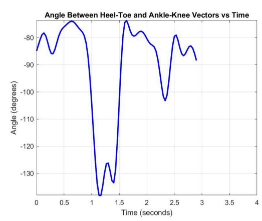
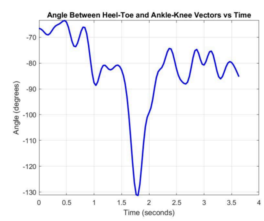
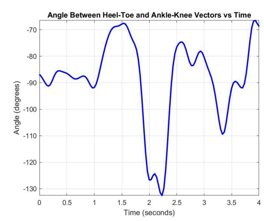
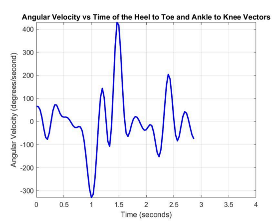
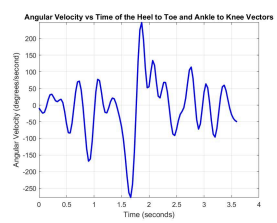
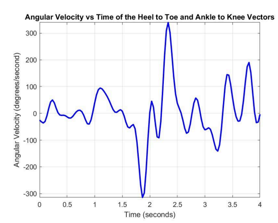
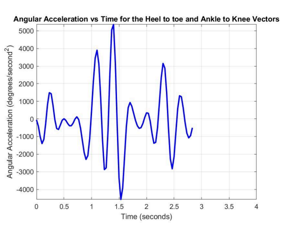
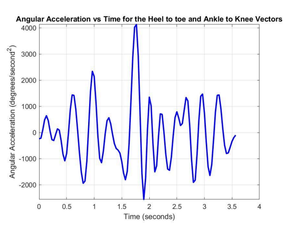
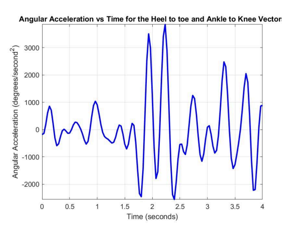
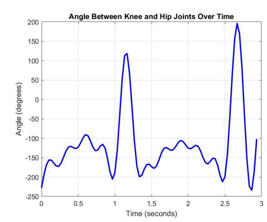
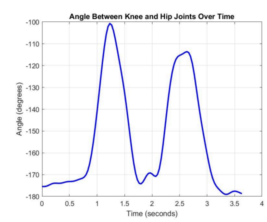
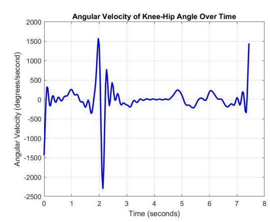
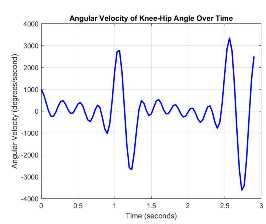
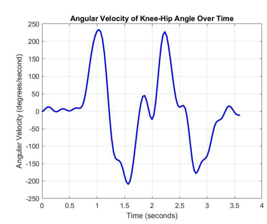
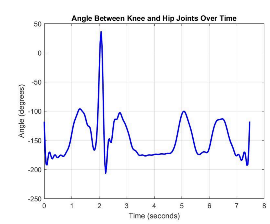
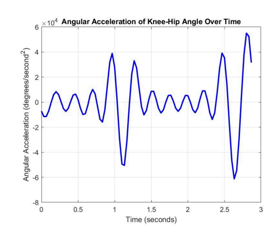
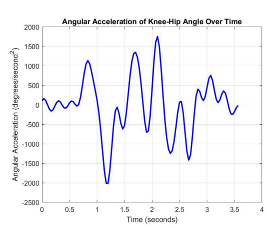
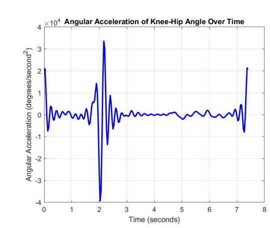
| | No Weight | 6 Pound Weight | 10 Pound Weight |
|---|---|---|---|
| **Joint angle versus Time** |  |  |  |
| **Angular Velocity versus Time** |  |  |  |
| **Angular Acceleration versus Time** |  |  |  |

**Table 3.7** Knee - Hip segment joint angle, angular velocity, and angular acceleration versus time graphs for participant 3 for each different weighted condition.

| | No Weight | 6 Pound Weight | 10 Pound Weight |
|---|---|---|---|

| | | | |
|---|---|---|---|
| **Joint angle versus Time** |  |  |  |
| **Angular Velocity versus Time** |  |  |  |
| **Angular Acceleration versus Time** |  |  |  |

## 3.2 Phase 5 Results

The following Free Body Diagram (FBD) is for the initial squat of the motion. This FBD has been generalized to a person without any mass or additional weight. Further FBDs for the take-off phase and the landing phase can be found in Table 3.10 in the appendix.

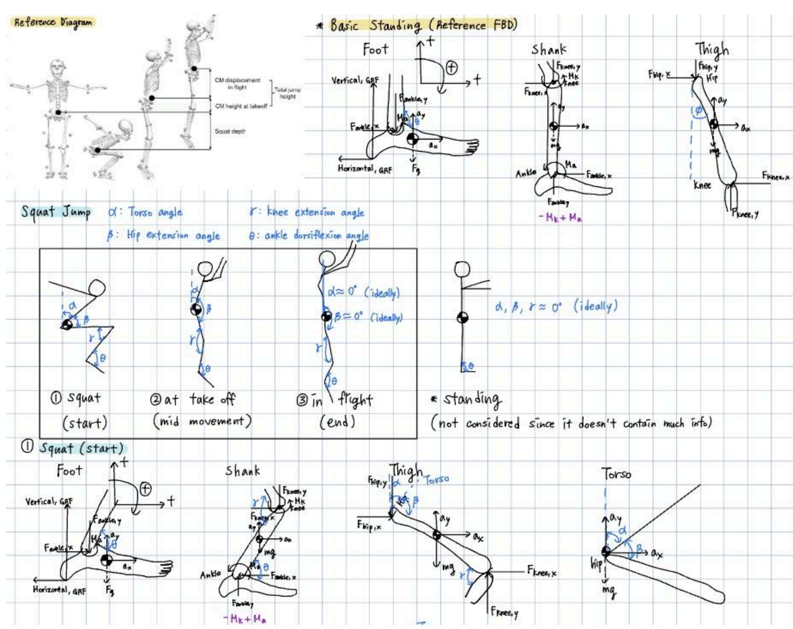



**Figure 3.9** Free Body Diagram of the jump squat motion. Detailed FBD of the squat (start) phase of the jump.

**Table 3.11** Properties of the lower body segments for squat jumps at start (squat)

| | Ankle (Foot) | Knee (Shank) | Hip (Thigh) |
|---|---|---|---|
| Mass (M = 50 kg) | m = 0.0145M | m = 0.0465M | m = 0.100M |
| Linear Acceleration (x) | Ax = 2 m/s^2 | Ax = 1.5 m/s^2 | Ax = 1 m/s^2 |
| Linear Acceleration (y) | Ay = - 9.8 m/s^2 | Ay = - 9.8 m/s^2 | Ay = - 9.8 m/s^2 |
| Angular Acceleration | α = 10 rad/s^2 | α = 15 rad/s^2 | α = 20 rad/s^2 |
| Moment of inertia at COM | Iankle = 0.01 kg*m^2 | Iknee = 0.02 kg*m^2 | Ihip = 0.03 kg*m^2 |
| Length of segment | L = 0.25 m | L = 0.45 m | L = 0.55 m |
| Angle of inclination from vertical | Θ = - 30° | Θ = - 45° | Θ = - 60° |
| Distance of COM from proximal joint | Xcom = 2 cm<br>Ycom = 3 cm | Xcom = 4 cm<br>Ycom = 6 cm | Xcom = 6 cm<br>Ycom = 8 cm |
| Joint Moment (M = 50 kg) | M = 0.09434M N*m | M = 0.30015M N*m | M = 0.6004M N*m |

**Table 3.12** Properties of the lower body segments for squat jumps at mid movement (at take off)

| | Ankle (Foot) | Knee (Shank) | Hip (Thigh) |
|---|---|---|---|
| Mass (M = 50 kg) | m = 0.0145M | m = 0.0465M | m = 0.100M |
| Linear Acceleration (x) | Ax = 3 m/s^2 | Ax = 2 m/s^2 | Ax = 1.5 m/s^2 |
| Linear Acceleration (y) | Ay = - 9.8 m/s^2 | Ay = - 9.8 m/s^2 | Ay = - 9.8 m/s^2 |
| Angular Acceleration | α = 15 rad/s^2 | α = 20 rad/s^2 | α = 25 rad/s^2 |
| Moment of inertia at COM | Iankle = 0.01 kg*m^2 | Iknee = 0.02 kg*m^2 | Ihip = 0.03 kg*m^2 |
| Length of segment | L = 0.25 m | L = 0.45 m | L = 0.55 m |
| Angle of inclination from vertical | Θ = - 15° | Θ = - 30° | Θ = - 45° |
| Distance of COM from proximal joint | Xcom = 3 cm<br>Ycom = 4 cm | Xcom = 5 cm<br>Ycom = 7 cm | Xcom = 7 cm<br>Ycom = 9 cm |

| | | | |
|---|---|---|---|
| Joint Moment (M = 50 kg) | M = 0.001305M N*m | M = 0.00372M N*m | M =  0.0105M N*m |

**Table 3.13** Properties of the lower body segments for squat jumps at end (in flight)

| | Ankle (Foot) | Knee (Shank) | Hip (Thigh) |
|---|---|---|---|
| Mass (M = 50 kg) | m = 0.0145M | m = 0.0465M | m = 0.100M |
| Linear Acceleration (x) | Ax = 0 m/s^2 | Ax = 0 m/s^2 | Ax = 0 m/s^2 |
| Linear Acceleration (y) | Ay = - 9.8 m/s^2 | Ay = - 9.8 m/s^2 | Ay = - 9.8 m/s^2 |
| Angular Acceleration | α = 0 rad/s^2 | α = 0 rad/s^2 | α = 0 rad/s^2 |
| Moment of inertia at COM | Iankle = 0.01 kg*m^2 | Iknee = 0.02 kg*m^2 | Ihip = 0.03 kg*m^2 |
| Length of segment | L = 0.25 m | L = 0.45 m | L = 0.55 m |
| Angle of inclination from vertical | Θ = - 10° | Θ = - 25° | Θ = - 30° |
| Distance of COM from proximal joint | Xcom = 4 cm<br>Ycom = 5 cm | Xcom = 6 cm<br>Ycom = 8 cm | Xcom = 8 cm<br>Ycom = 10 cm |
| Joint Moment (M = 50 kg) | M =  - 0.00566M N*m | M =  - 0.02739M N*m | M =  - 0.0784M N*m |

### 3.3 Final Design

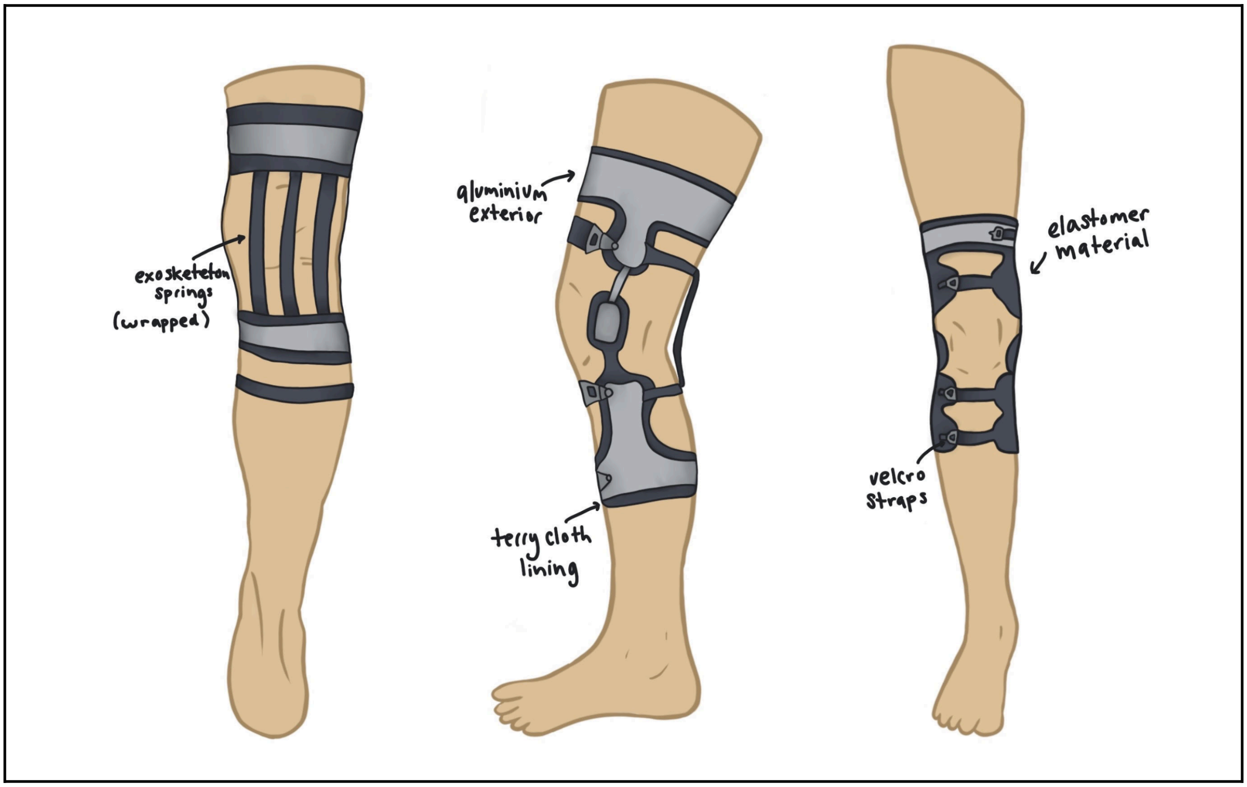



**Figure 3.12** K.N.E.E. final concept image.

The final design, the K.N.E.E. (Kinetic kNee Everyday Exoskeleton), is an innovative fusion of concepts from hard knee braces and passive knee exoskeletons, strategically tailored to address the needs of individuals suffering from patellofemoral pain syndrome. It is a wearable sports device that will align the kneecap and mitigate the forces experienced by the knee joint, especially during dynamic movements, such as the squat jump.

Aluminum is used for the K.N.E.E. 's structural framework, providing durability and lightweight. A terry-cloth lining is integrated for its comfort and moisture-wicking properties, which is optimal during physical exercise. The use of velcro straps and elastomers provides a secure and adjustable fit.

The exoskeleton component of the K.N.E.E., positioned at the back of the brace, comprises three fluoroelastomer springs, enveloped in cloth for comfort. The springs play a crucial role in generating tension, ultimately assisting the user in achieving a greater jump height. By leveraging the benefits of both hard knee braces and passive knee exoskeletons, the K.N.E.E. serves as a supportive performing-enhancing solution for individuals managing patellofemoral knee syndrome during squat jumps.

## 4.0 Discussion

### 4.1 Summary

Before we began to quantitively measure the squat jump, all of our group members performed them, and observed mild discomfort in our knees, despite our relatively young age. The quantitive measurements in OpenPose/MatLab provided insights into joint moments during the squat jump movement. The highest joint moments were consistently observed in the hip, reaching up to 0.6003M N*m, while the ankle exhibited the lowest moments. This aligns with the belief that the hip joint can endure greater forces compared to the hip and knee joints. The knee ranked second, peaking at 0.30015M N*m. We recognized that the knee joint is inherently unstable and undergoes lots of stress during the squat jump movement. Since the knee is frequently susceptible to injuries, we decided to focus on athletes experiencing patellofemoral pain syndrome when designing our device, specifically focusing on reducing joint forces and helping to align the knee.

### 4.2 Limitations

The project, while successful in many aspects, did have certain limitations. One of the constraints was the method of video recording. The movement of the camera was not always consistent, which could have affected the quality and clarity of the videos. This could be improved in future iterations by using a more stable and controlled method of recording, such as a tripod. Another limitation was the lack of weight variation in our design. While the hard knee brace design was effective for its intended purpose, it might not accommodate users of different weights and sizes. More weight variation might be needed to ensure that the product is versatile and can be used by a wider range of individuals. In terms of design, we chose a hard knee brace design over the other two designs we initially created. However, in retrospect, we could have combined some features of the other designs into our final chosen design to create a more comprehensive solution. This is a shortcoming that we could address in future design iterations. Lastly, our focus was mainly on the knee problem, targeting athletes as our primary users. However, we overlooked the fact that athletes often also suffer from hip and ankle issues. We could have considered these aspects and added more features to our product to provide a more holistic solution. This is a significant area for improvement in future iterations of the product. Despite these limitations, the project provided valuable insights and learnings that can guide future design and development efforts.

### 4.3 Future Work

To advance the design process, the next steps involve material testing for prototyping, with options ranging from 3D printing to digital or handmade models. Following this, the prototypes will undergo evaluation through methods such as user testing, expert reviews, and comparative analyses against similar products. Qualitative and quantitative metrics will be employed to assess user satisfaction and performance. The testing procedures will be meticulously defined, outlining the aspects of the design to be tested, the methodology for conducting tests, and a structured approach to record and analyze results. Concurrently, a critical review of the design process will be undertaken to identify any overlooked needs or requirements, addressed through revisiting user research, stakeholder consultation, or additional brainstorming sessions. Looking ahead, future iterations will focus on enhancing aspects that meet requirements while addressing identified shortcomings, forming a systematic plan for continual improvement in subsequent design iterations.

**5.0 Appendix**
**5.1 Citations**


*Differences and approximate derivatives - MATLAB diff*. (n.d.). Www.mathworks.com. https://www.mathworks.com/help/matlab/ref/diff.html

Balster, Wendy & Lim, Cheryl & Kong, Pui. (2016). Effects of a Deeper Countermovement on Vertical Jump Biomechanics after Three Weeks of Familiarisation - Preliminary Findings. International Journal of Human Movement and Sports Sciences. 4. 51-60. 10.13189/saj.2016.040401. (FBD photo reference)

McDevitt, S., Hernandez, H., Hicks, J., Lowell, R., Bentahaikt, H., Burch, R., Ball, J., Chander, H., Freeman, C., Taylor, C., & Anderson, B. (2022). Wearables for Biomechanical Performance Optimization and Risk Assessment in Industrial and Sports Applications. *Bioengineering*, *9*(1), 33. https://doi.org/10.3390/bioengineering9010033

Cleveland Clinic. (2018). *Patellofemoral Pain Syndrome (PFPS) | Cleveland Clinic*. Cleveland Clinic. https://my.clevelandclinic.org/health/diseases/17914-patellofemoral-pain-syndrome-pfps

*The Best Patellofemoral Knee Brace*. (2021, May 29). Spring Loaded Technology. https://springloadedtechnology.com/2021/05/the-best-patellofemoral-knee-brace-available/

*Clinical Biomechanics of Patellofemoral Pain Syndrome*. (n.d.). Physiopedia. https://www.physio-pedia.com/Clinical_Biomechanics_of_Patellofemoral_Pain_Syndrome

Hidayah, R., Sui, D., Wade, K. A., Chang, B.-C., & Agrawal, S. (2021). Passive knee exoskeletons in functional tasks: Biomechanical effects of a SpringExo coil-spring on squats. *Wearable Technologies*, *2*. https://doi.org/10.1017/wtc.2021.6

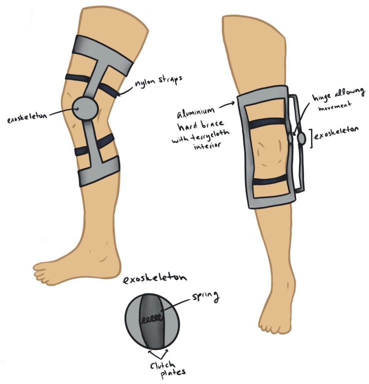
Moon, D.-H., Kim, D., & Hong, Y.-D. (2019). Development of a Single Leg Knee Exoskeleton and Sensing Knee Center of Rotation Change for Intention Detection. *Sensors*, *19*(18), 3960. https://doi.org/10.3390/s19183960

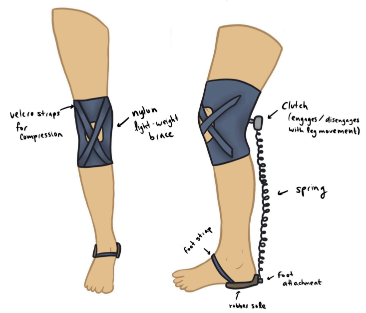
Ben-David, C., Ostraich, B., & Riemer, R. (2022). Passive Knee Exoskeleton Increases Vertical Jump Height. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, *30*, 1796–1805. https://doi.org/10.1109/tnsre.2022.3187056

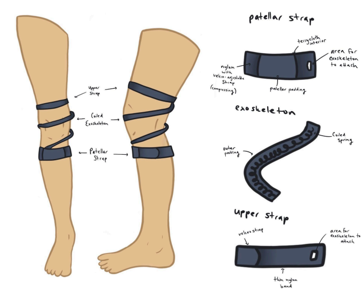
Lorenzen, K. (2018). *A Comparison of Biomechanical Outcomes in Single Leg Squat and Vertical Drop Jump in Youth and Young Adults with and without a Previous Youth Sport-Related Knee Joint Injury*. https://doi.org/10.11575/prism/31877

Zhao, M., & Zhang, J. (2022). Analysis and Comparison of Motion Biomechanics Characteristics of Squat Jump and Half-Squat Jump. *Mobile Information Systems*, *2022*, 1–7. https://doi.org/10.1155/2022/4304216

**Figure 2.1** Preliminary Sketches for each design (Design Concept Generation)




**Sketch 1** (Hard Knee Brace):

- Focuses on aligning knee
- Hard aluminum knee brace with a terry cloth interior and velcro straps to connect to knee
- Hinge on side for movement
- Exoskeleton part: basically a spring

**Sketch 2** (Soft Knee Brace):

- Soft knee brace made of nylon
- Velcro straps for compression to help align joints + adjustable
- Rubber sole and foot strap
- Exoskeleton part: clutch and foot attachment (basically a big spring)

**Sketch 3** (Patellar Strap):

- Patellar strap with a terry cloth interior with velcro straps
- Puts pressure on patella tendon
- Preventative rather than active fixing of issue
- Upper velcro strap to attach exoskeleton too
- Exoskeleton is a coiled spring with outer padding
- Made of three pieces for easy put on and take off

**Table 2.2** Ranking of conceptualized ideas

| Criteria | Hard Knee Brace | Soft Knee Brace | Patellar Strap |
|---|---|---|---|
| Cost (Availability) | 3 | 2 | 1 |
| Comfort | 2 | 1 | 3 |
| Practicality (Easy to take on/off) | 2 | 3 | 1 |
| Reducing joint forces and alignments | 1 | 2 | 3 |
| Total Results | 8 | 8 | 8 |

**Table 2.3** Weighted decision matrix

| Criteria | Weight | Hard Knee Brace | | Soft Knee Brace | | Patellar Strap | |
|---|---|---|---|---|---|---|---|
| | | Score | Weighted Score | Score | Weighted Score | Score | Weighted Score |
| Cost (Availability) | 10% | 1 | 0.2 | 2 | 0.2 | 3 | 0.3 |
| Comfort | 25% | 2 | 0.5 | 3 | 0.75 | 1 | 0.25 |
| Practicality (Easy to take on/off) | 25% | 2 | 0.5 | 1 | 0.25 | 3 | 0.75 |
| Reducing joint forces and alignments | 40% | 3 | 1.2 | 2 | 0.8 | 1 | 0.4 |
| Total Score | 100% | | 2.3 | | 2 | | 1.7 |

**Figure 2.5.** Segment analysis equations used in the calculations of the motions squat phase and take off phase, including how distances were found for each phase.

Foot

Squat

assumptions:
mass, segment lengths + masses constant
assuming $\alpha$, $I$, and mass for calculations
angles based off openpose data

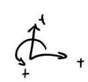
$\Sigma F_x = ma_x$

$F_{x\,ankle} - F_{ground\ rxn\ force} = ma_x$

$\Sigma F_y = ma_y$

$F_{y\,ankle} - F_{y\,ground\ rxn\ force} + F_{y\,gravity} = ma_y$
↳ (mass × 9.81)

$\Sigma M_{ankle} = I_{ankle}\alpha_{ankle}$ at com



$\{-F_{y\,ankle} \times$ horizontal distance from com $- F_{x\,ankle} \times$ vertical dis from com$\}$
moment at ankle joint

$+\{F_{y\,ground\ rxn\ force} \times$ horizontal dis. from com $+ F_{g_x} \times$ vertical dis from com$\}$
Moment of ground rxn force

$+ F_{gravity} \times$ dis from com$\}$
↳ moment due to gravity depending if $f_g$ is not acting at com

Shank
* ankle joint moments and forces from before with opposite signs

$\Sigma F_x = ma_x$

$F_{j\,knee\,x} + -(F_{j\,ankle\,x}) = ma$

$\Sigma F_{y\,shank} = ma_y$

$F_{j\,knee\,y} + -(F_{j\,ankle\,y}) - F_{g\,shank} = ma_y$

$\Sigma M_{shank} = I\alpha$ about shank com

$-(m_{ankle}) + \{F_{j\,knee\,y} \times$ hori. dist from vertical $+ F_{j\,knee\,x} \times$ vert. dis from com$\}$
↳ moment from knee joint forces

$+ F_{g\,shank} \times$ dis com $= I\alpha$
↳ if not acting at com

Thigh

$\Sigma F_x = m_{thigh}a_x$

**Figure 2.6.** Segment analysis calculations of the squat phase and take off phase continued.

$F_{jhipx} + -(F_{jkneex}) = ma$

$\Sigma F_y = m_{hip} a_y$

$F_{jhipy} + -(F_{jkneey}) + F_{g\,thigh} = ma_y$

$\Sigma M = I\alpha$

$(-M_{knee}) + \{-F_{jhipy} \times \text{hori. dis from com} + F_{jhipx} \times \text{vert dis from com}\} = I\alpha$

distances

ankle joint from com

horizontal distance = foot com to end of foot × cos θ

Vertical distance = foot com to end of foot × sin θ

Shank distances

horizontal dis. from knee joint to com = shank length from knee joint to com × cos Φ

vertical dis. from knee joint to com = shank length from knee to com × sin Φ

hip distances

horizontal distance from hip joint to thigh com = thigh length from hip to com × cos β

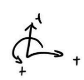
Vertical distance from hip joint to thigh com = thigh length from hip to com × sin β

Take off

The same equations can be used for take off phase with the angles provided from this time.

**Figure 2.7.** Segment analysis equations used in the calculations of the motions of the in air phase.

foot In air



$\Sigma F_x = ma_x$

$\Sigma F_x = F_{anklex} = 0$

$\Sigma F_y = ma_y$

$F_{yankle} - F_{g\,gravity} = ma_y$

$\Sigma M_{ankle} = I_{ankle}\alpha_{ankle}$ at com

$\{-F_{yankle} \times \text{horizontal distance from com}\} = I\alpha_{foot}$

moment at ankle joint

Shank

*ankle joint moments and forces from before with opposite signs

$\Sigma F_x = ma_x$

$F_{jkneex} + -(F_{janklex}) = ma$

$\Sigma F_{yshank} = ma_y$

$F_{jkneey} + -(F_{jankley}) - F_{g\,shank} = ma_y$

$\Sigma M_{shank} = I\alpha$ about shank com

$-(m_{ankle}) + \{F_{jkneey} \times \text{hori. dist from vertical} + F_{jkneex} \times \text{vert. dis from com}\} = I\alpha$

moment from knee joint forces

Thigh

$\Sigma F_x = m_{thigh} a_x$

$F_{jhipx} + -(F_{jkneex}) = ma$

$\Sigma F_y = m_{hip} a_y$

$F_{jhipy} + -(F_{jkneey}) + F_{g\,thigh} = ma_y$

$\Sigma M = I\alpha$

$(-M_{knee}) + \{-F_{jhipy} \times \text{hori. dis from com} + F_{jhipx} \times \text{vert dis from com}\} = I\alpha$

**Table 3.2** Ankle - Knee segment joint angle, angular velocity, and angular acceleration versus time graphs for participant 1 for each different weighted condition.

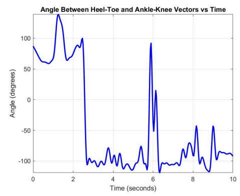
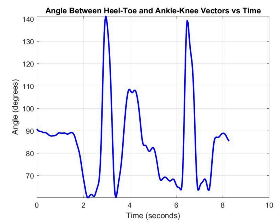
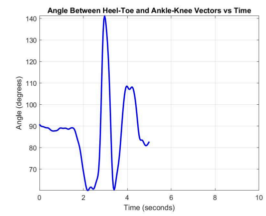
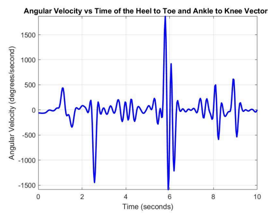
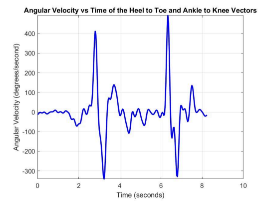
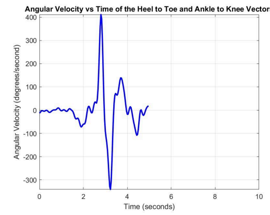
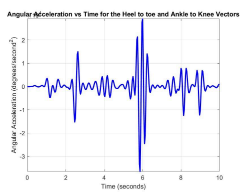
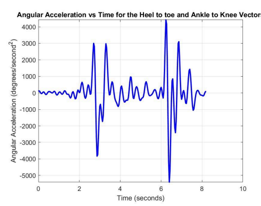
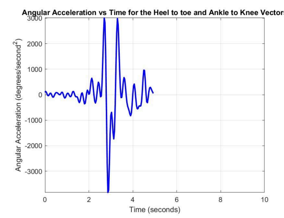
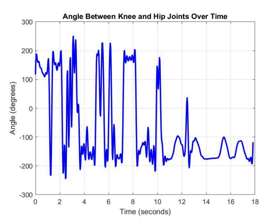
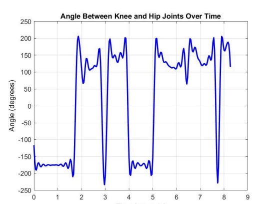
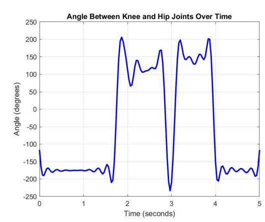
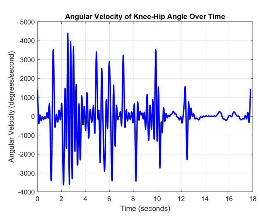
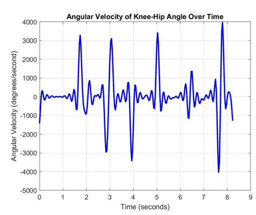
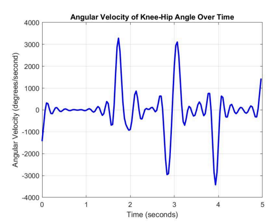
| | No Weight | 6 Pound Weight | 10 Pound Weight |
|---|---|---|---|
| **Joint angle versus Time** |  |  |  |
| **Angular Velocity versus Time** |  |  |  |
| **Angular Acceleration versus Time** |  |  |  |

**Table 3.3** Knee - Hip segment joint angle, angular velocity, and angular acceleration versus time graphs for participant 1 for each different weighted condition.

| | No Weight | 6 Pound Weight | 10 Pound Weight |
|---|---|---|---|
| **Joint angle versus Time** |  |  |  |
| **Angular Velocity versus Time** |  |  |  |

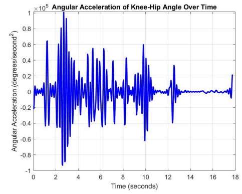
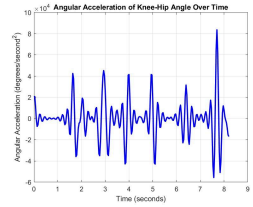
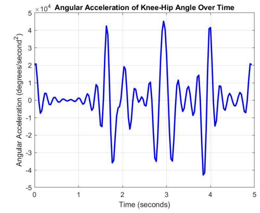
| | | | |
|---|---|---|---|
| **Angular Acceleration versus Time** |   |   |   |

**Table 3.4** Ankle - Knee segment joint angle, angular velocity, and angular acceleration versus time graphs for participant 2 for each different weighted condition.

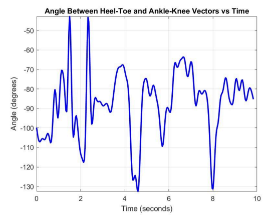
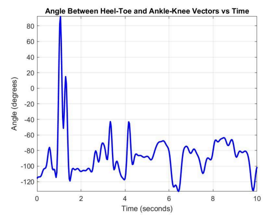
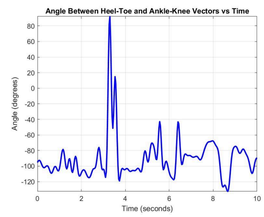
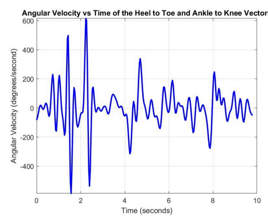
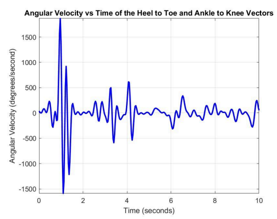
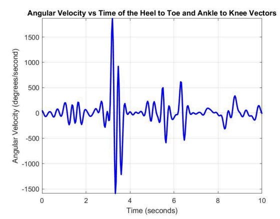
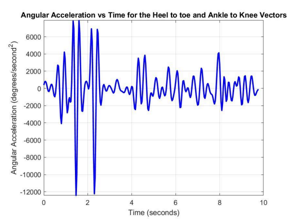
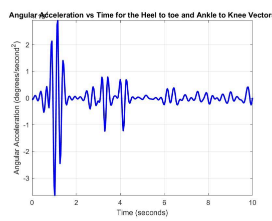
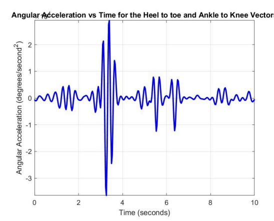
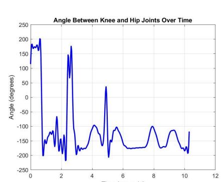
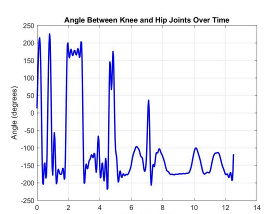
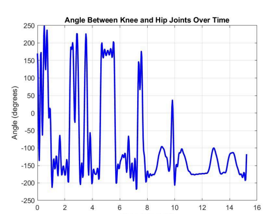
| | No Weight | 6 Pound Weight | 10 Pound Weight |
|---|---|---|---|
| **Joint angle versus Time** |   |   |   |
| **Angular Velocity versus Time** |   |   |   |
| **Angular Acceleration versus Time** |   |   |   |

**Table 3.5** Knee - Hip segment joint angle, angular velocity, and angular acceleration versus time graphs for participant 2 for each different weighted condition.

| | No Weight | 6 Pound Weight | 10 Pound Weight |
|---|---|---|---|
| **Joint angle versus Time** |   |   |   |

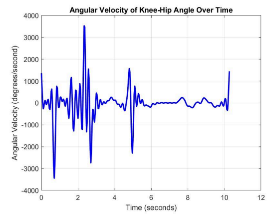
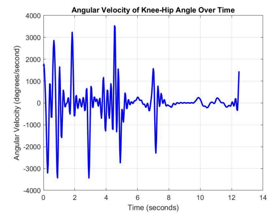
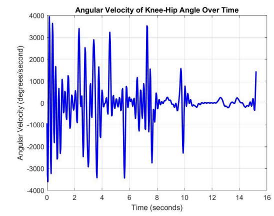
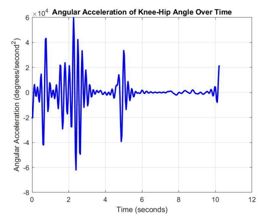
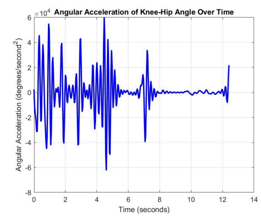
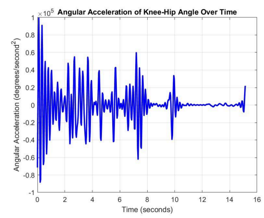
| | | | |
|---|---|---|---|
| **Angular Velocity versus Time** |   |   |   |
| **Angular Acceleration versus Time** |   |   |   |

**Table 3.6** Ankle - Knee segment joint angle, angular velocity, and angular acceleration versus time graphs for participant 3 for each different weighted condition.

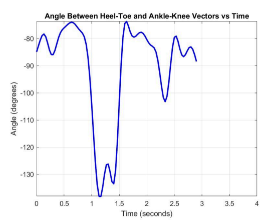
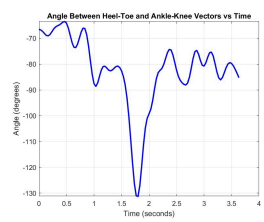
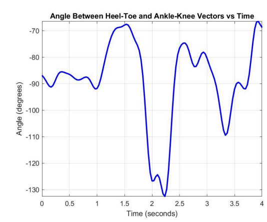
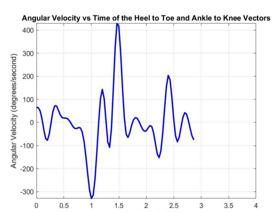
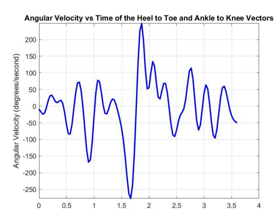
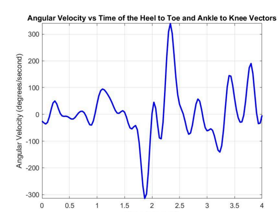
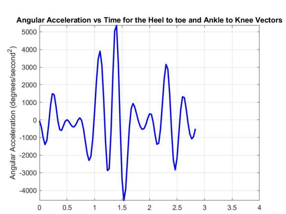
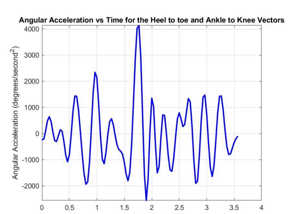
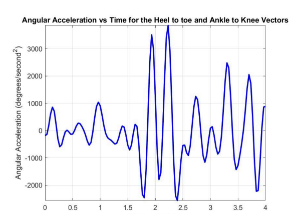
| | **No Weight** | **6 Pound Weight** | **10 Pound Weight** |
|---|---|---|---|
| **Joint angle versus Time** |   |   |   |
| **Angular Velocity versus Time** |   |   |   |
| **Angular Acceleration versus Time** |   |   |   |

**Table 3.7** Knee - Hip segment joint angle, angular velocity, and angular acceleration versus time graphs for participant 3 for each different weighted condition.

| | **No Weight** | **6 Pound Weight** | **10 Pound Weight** |
|---|---|---|---|

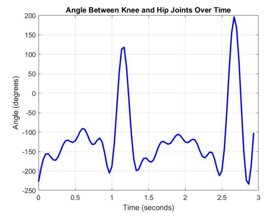
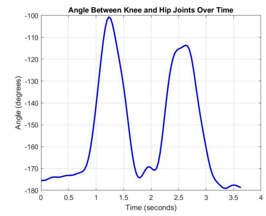
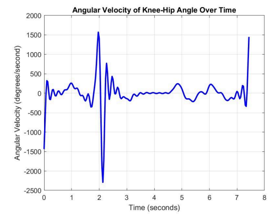
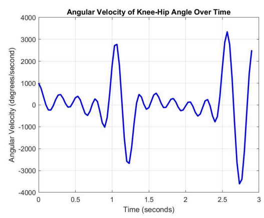
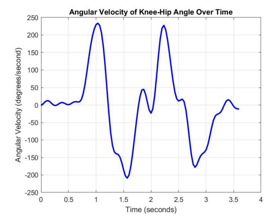
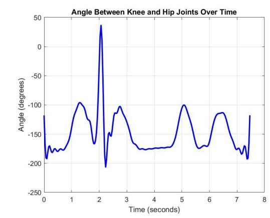
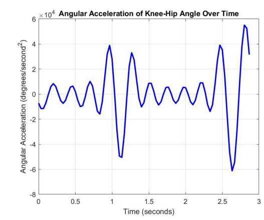
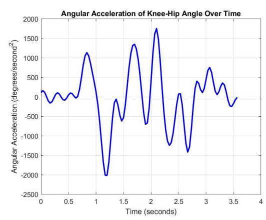
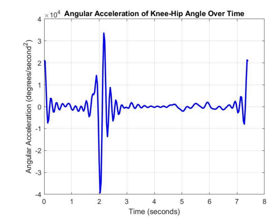
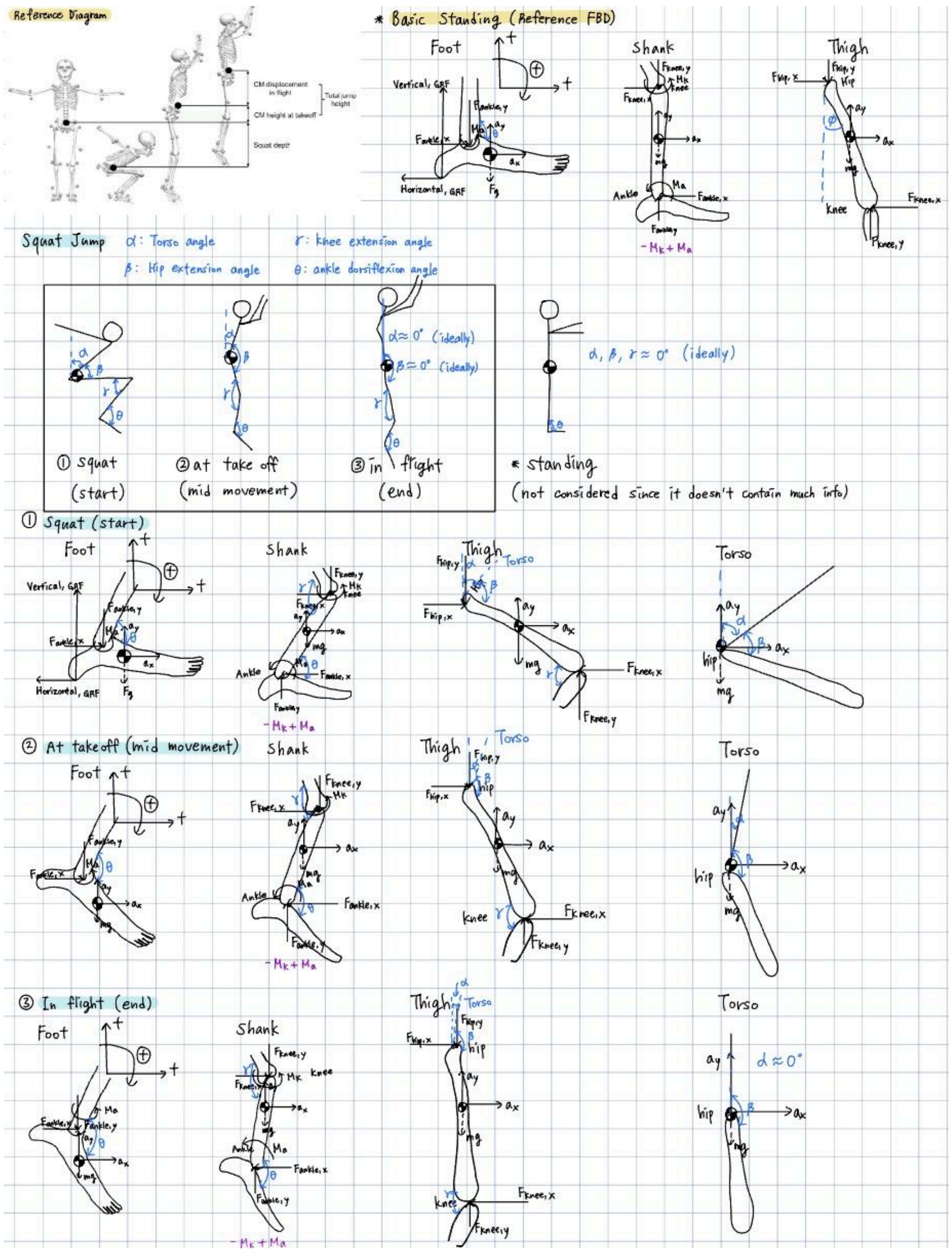
| | | | |
|---|---|---|---|
| **Joint angle versus Time** |   |   |   |
| **Angular Velocity versus Time** |   |   |   |
| **Angular Acceleration versus Time** |   |   |   |

**Figure 3.10** Free Body Diagram of the squat jump motion. Including the squat, take off, and in flight phase of the motion. (Phase 5)




### 5.2 Group Contributions

| | Final Report | Project Brochure | Presentation |
|---|---|---|---|
| Elin Lee | Overall write-ups for Methods (Approach and Device Concept Selection) and Results (FBD), and Discussion (Limitations and Future Work), Phase 5 analysis | Design Details, Materials and their effects on joint forces, commercial phrase idea | Information collection and FBD's |

| | | | |
|---|---|---|---|
| Ellie Smith | Overall data collection process behind the report; Data Analysis (OpenPose and MATLAB) in Methods and Results (Calculations and Figures), Phase 5 analysis | Intended Uses and How our design aims to mitigate these risks/ Solve the issue, overall aesthetics | MatLab analysis and images |
| Stacey Sholter | Literature research for Introduction, Results (Design Conceptualization and Final Design), and Discussion (Summary) | Final Design Drawings (with different views) | Designing of the presentation, script writing |