463 DESIGN PROJECT - ANALYSIS OF A SQUAT

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INTRODUCTION

The squat is a fundamental compound movement crucial in all physical activity. It utilizes multiple muscle groups to perform and is great in strengthening ligaments, tendons, and bones as well as the muscles. A squatting movement is used for many daily life tasks such as picking something off the ground and sitting in a chair. Due to this, having the strength and mobility to perform a squat correctly will aid everyone in better physical activity.

In this report, the typical back squat is the movement to be analyzed. While there are many other squatting positions that may be safer or harder for some, a typical back squat is one of the most fundamental movements in exercise and will give a solid platform for the rest of the movements. Ultimately, performing the full range of motion in any exercise is important in reducing exercise induced injuries as well as flexibility, however, some professionals believe that the squat may be an expectation to that rule due to the extreme forces applied at the knee joints [1]. There are many biomechanical factors that may hinder individuals performing the exercise, leading to joint injuries. This report will factor in form, joint stability, muscle tightness and weakness when analyzing possible injuries that may occur due to forces. Next, the process of obtaining the biomechanical equations of motion will be explained and how they were used in determining the forces in the joints.

METHODS

To better analyze the squat motion we developed a free body diagram (figure 1). To begin constructing these diagrams, they were split into the back (figure 2), tibia (figure 3), and femur (figure 4) to model the forces and moments. Each segment was analyzed with consideration of the moment and focus at the joints as well as the accelerations that occurred at the center of mass of each segment. Throughout perfecting these diagrams, they were then used to determine the equations of motion in variable form. This included the acceleration and moments at first to then be allowed for the use of static analysis to solve for all of the moments and forces in the joints for both the hip and knee.

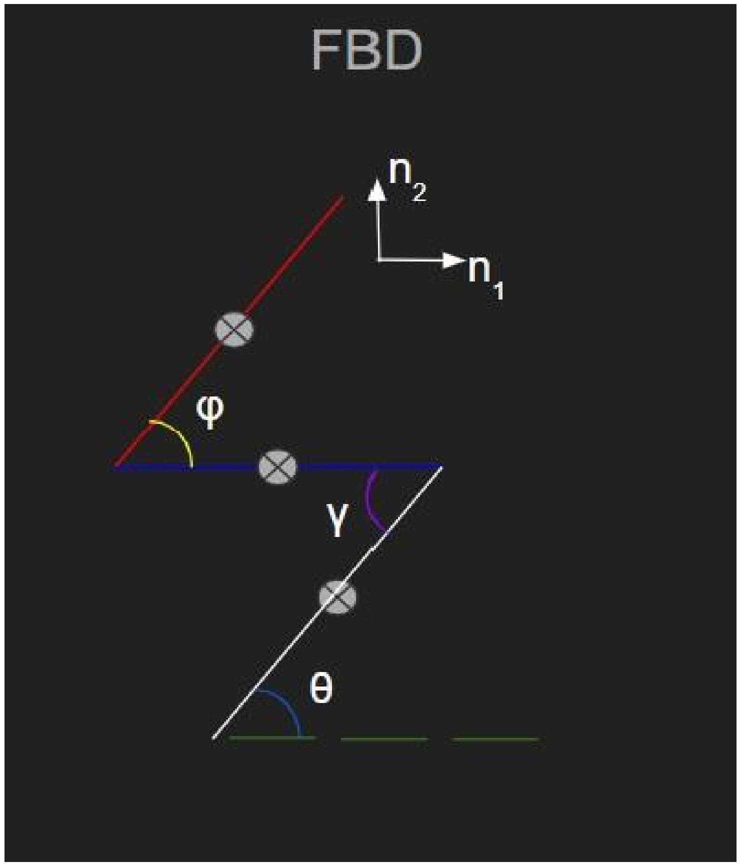

Figure 1: FBD

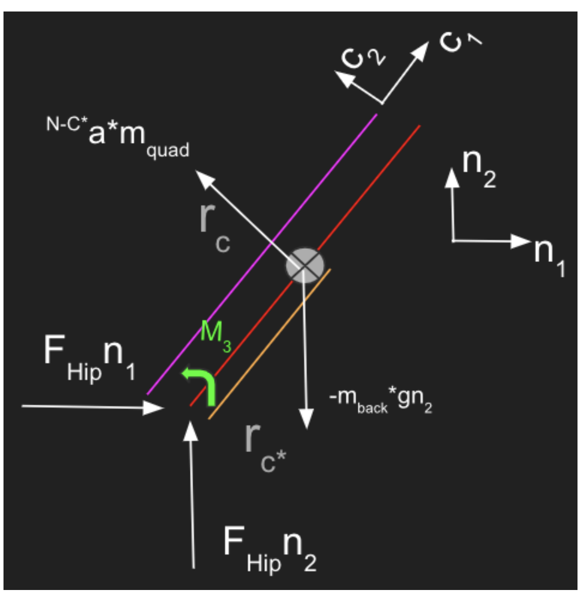

Figure 2: FBD of the back

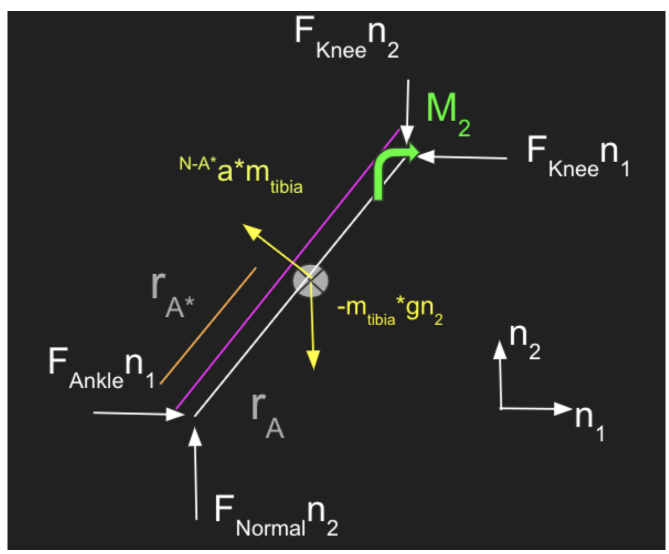

Figure 3: FBD of the tibia

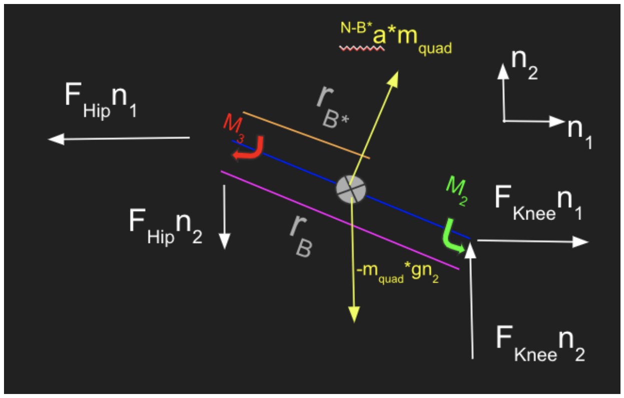

Figure 4: FBD of the femur

To begin solving for these equations of motion, the relative acceleration equations were derived for each segment. As the problem moved from the head of the body to the feet, the equations grew due to their reliance on each other as the whole body moved in a unit. Determining the moment equation is always the first step as it eliminates forces moving through the same point to aid in solving for the rest of the segment. With these steps in mind, the equation of the moment of the back was determined.

$$\sum M_3 = I_C\ddot{\varphi}\widehat{n_3} = M_3\widehat{n_3} - r_{c*} * m_{back} * g * C_2\widehat{n_3} + r_{c*} * m_{back}[r_B(S_2C_1\dot{\theta}^2 + S_2S_1\ddot{\theta} + C_2C_1\ddot{\theta} - C_2S_1\dot{\theta}^2) + r_{c*}(S_2C_2\dot{\psi}^2 + S_2^2\ddot{\psi} + C_2^2\ddot{\psi} - C_2S_2\dot{\psi}^2)]\widehat{n_3}$$

Equation 1: Moment of the back

After evaluating this, it was a simple static procedure to determine the forces in the hips

$$F_{Hip}\widehat{n_1} = -m_{back}[r_B(C_1\dot{\theta}^2 + S_1\ddot{\theta}) + r_{c*}(C_2\dot{\varphi}^2 + S_2\ddot{\varphi})]\widehat{n_1}$$

Equation 2: Force in the hip in n1 direction

$$F_{Hip}\widehat{n_2} = m_{back} * g\widehat{n_2} + m_{back}[r_B(C_1\ddot{\theta} - S_1\dot{\theta}^2) + r_{c*}(C_2\ddot{\varphi} + S_2\dot{\varphi}^2)]\widehat{n_2}$$

Equation 3: Force in the hip in n2 direction

After determining these equations for the first segment, the femur and the tibia were calculated simultaneously. Our team realized that each segment had to be equal and opposite in all respects. Knowing this, determining the other moments and force equations become simpler. applying the found moments and forces in the hip to the femur segment led to a simple calculation of the moment and forces in the knee. To do this, static summation equations were solved and provided the next set of motion equations.

$$\sum M_2 = I_A\ddot{\gamma} = M_2 - r_A * m_{tibia} g C_1 - r_a^* m_{tibia}\left[-r_A^*\left(C_1^2\ddot{\theta} - S_1C_1\dot{\theta}^2\right)\right] - r_a^* m_{tibia}[r_A^*\left(C_1S_1\dot{\theta}^2 + S_1^2\ddot{\theta}\right)]$$

Equation 4: Moment equation about the knee

$$F_{Knee}\hat{n}_1 = -m_{back}\left[r_B(C_1\dot{\gamma}^2 + S_1\ddot{\gamma}) + r_c^*\left(C_2\emptyset^2 + s_2\ddot{\emptyset}\right)\right] - m_{quad}[(r_A^*\left(C_1\dot{\theta}^2 + S_1\ddot{\theta}\right) - r_B^*(C_2\dot{\gamma}^2 + S_2\ddot{\gamma}^2)]$$

Equation 5: Force in the knee in the n1 direction

$$F_{Knee}\widehat{n_2} = -(m_{back} * g\widehat{n_2} + m_{back}\left[r_B\left(C_1\ddot{\gamma} - S_1\dot{\gamma}^2\right) + r_{c*}(C_2\ddot{\varphi} + S_2\dot{\varphi}^2)\right]\widehat{n_2} - m_{femur}(-r_{A*}\left(C_1\ddot{\theta} - S_1\dot{\theta}^2\right) + r_{B*}\left(C_2\ddot{\gamma} - S_1\dot{\gamma}^2\right) + m_{femur} * g)$$

Equation 6: Force in the knee in the n2 direction

Lastly, the forces in the ankle must be calculated as it is absorbing the shock of the movement and weight just as much. Already having the equations for the forces in the knee, they were applied to the free body diagram and once again a set of summation equations was formed. After solving, all of the necessary equations were determined.

$$F_{ankle}\widehat{n_1} = m_{tibia}\left[r_A^*\left(C_1\dot{\theta}^2 + S_1\dot{\theta}\right)\right] - m_{back}\left[r_B\left(C_1\dot{\theta}^2\dot{\gamma}^2 + S_1\ddot{\gamma}\right) + r_c^*\left(C_2\dot{\emptyset}^2 + S_2\ddot{\emptyset}\right)\right] - m_{quad}[r_A^*\left(C_1\theta^2 + S_1\ddot{\theta}\right) - r_B^*(C_2\dot{\gamma}^2 + S_2\ddot{\gamma})]$$

Equation 7: Force in the ankle in the n1 direction

$$F_{Ankle}\widehat{n_2} = F_{Knee}\widehat{n_2} + m_{tibia} * g - m_{tibia}(-r_{A*}\left(C_1\ddot{\theta} - S_1\dot{\theta}^2\right)\widehat{n_2}$$

Equation 8: Force in the ankle in the n2 direction

The moment about the ankle could have been calculated, however, it was determined to be negligible as it would be quite small and not a point of interest. Overall these equations gave us an idea of the motion, but nothing specific was derived. As our goal of this analysis was to determine the forces in the knees to ideally determine a cause of common injury, specific values of the forces applied would be more beneficial. Due to this, an excel analysis in the next step will estimate these values. As for test angles to consider, we believe our range of angles for the knees is from 90-120 degrees since this is what is considered the range of the latter squat of a full squat [2]. We believe the back angle should be limited to 45-90 degrees since at 90 degrees that is where the back is completely straight. Also any angle that is below 45 degrees would result in insufficient lifting and most likely will cause injuries.

RESULTS

The forces in the hip and knees were calculated to be the greatest, as assumed. As the original assumption states, the forces in the hip and knees increase as angle and angle derivatives increase with time. The greatest magnitude of force is at the lowest point of the squat, where the knee angle makes a full 90 degree angle with the ground. From rest, or at 0 degrees, the forces start to increase as time goes on. Using the equations above, the maximum force was found to be about 380 N at the bottom of the squat motion before returning to the initial position.

These results are shown below in Figure 5, where the forces in the hip are compared to time and angle increase. At the peak of the plot is where the hip makes a full bend at the bottom of the squat motion. As time continues, the force in the knee decreases as the angle goes back to 0 degrees. The oscillation of forces is likely due to the forces in the hip as the squat motion comes to a complete repetition.

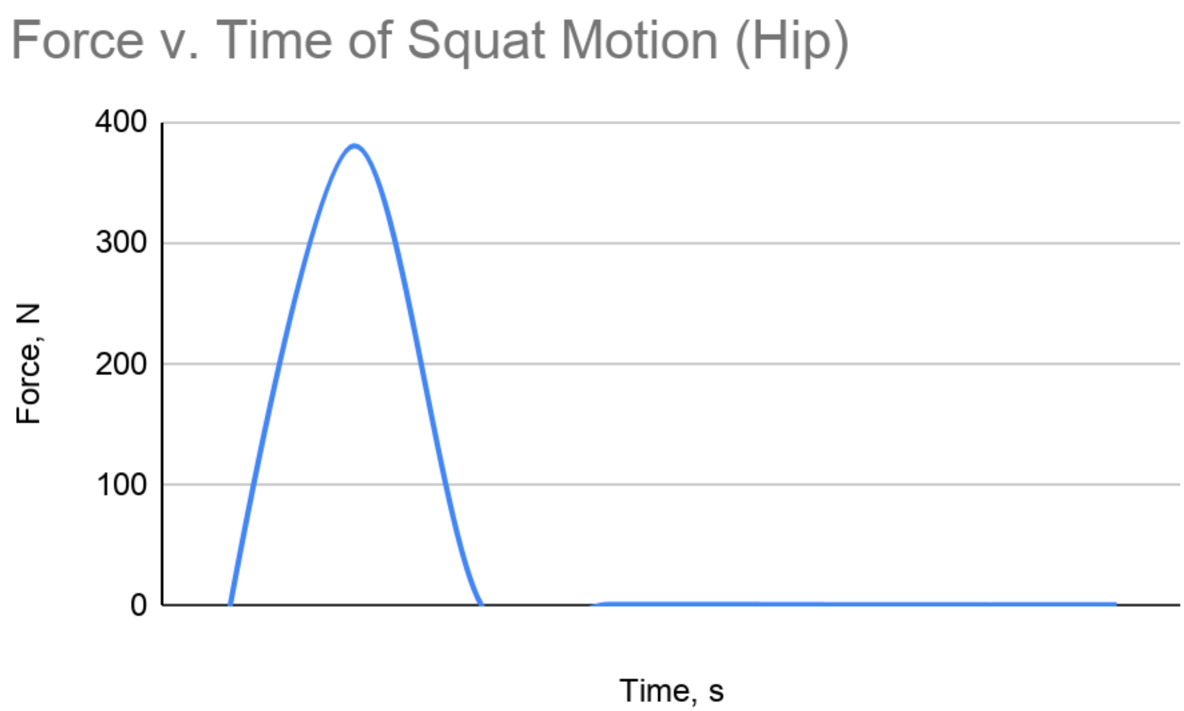

Figure 5: Force v. Time plot, Hip

The results within the knee component of the squat movement are represented in the Figure 6 plot. The plot follows the same trend as the hip did, where the peak is the point of maximum force in the knee. In this case, the maximum force at the peak is about 480 N. These results are valid due to the amount of stress in the knees during a squat. The intense force going into the knees during just one repetition is likely what causes knee problems over time as people continue to perform back squats. It is important to keep the knees bent at all times during the squat motion, to prevent injury. This is shown at the end of the parabola, where the force does not go directly back to zero. When the motion is complete, the knees are still slightly bent, which causes a constant force within the knees throughout the entire movement until the workout set is done.

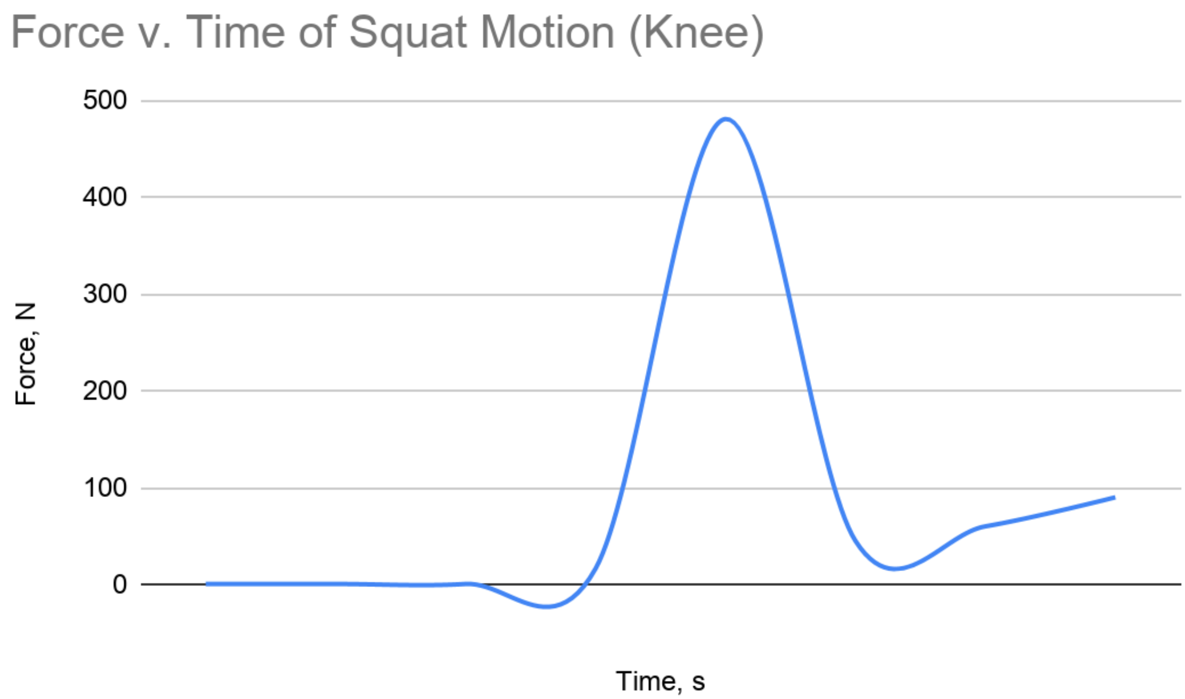

Figure 6: Force v. Time plot, Knee

The forces found within the ankle saw much more dynamic change than the other joints, but at a much lower magnitude. The team believes this to be caused by the shift in forces in the hip and knee joints. The ankle is there for stability, so when the force shifts higher up in the body, the ankle must compensate. Because it is only there to balance out the forces, it feels a much lower force as seen in figure 7, with a max of 30 newtons. The team would expect to see higher forces on the ankle if the person performing the squat was off balance, due to there needing to be more compensation and correction of the forces above.

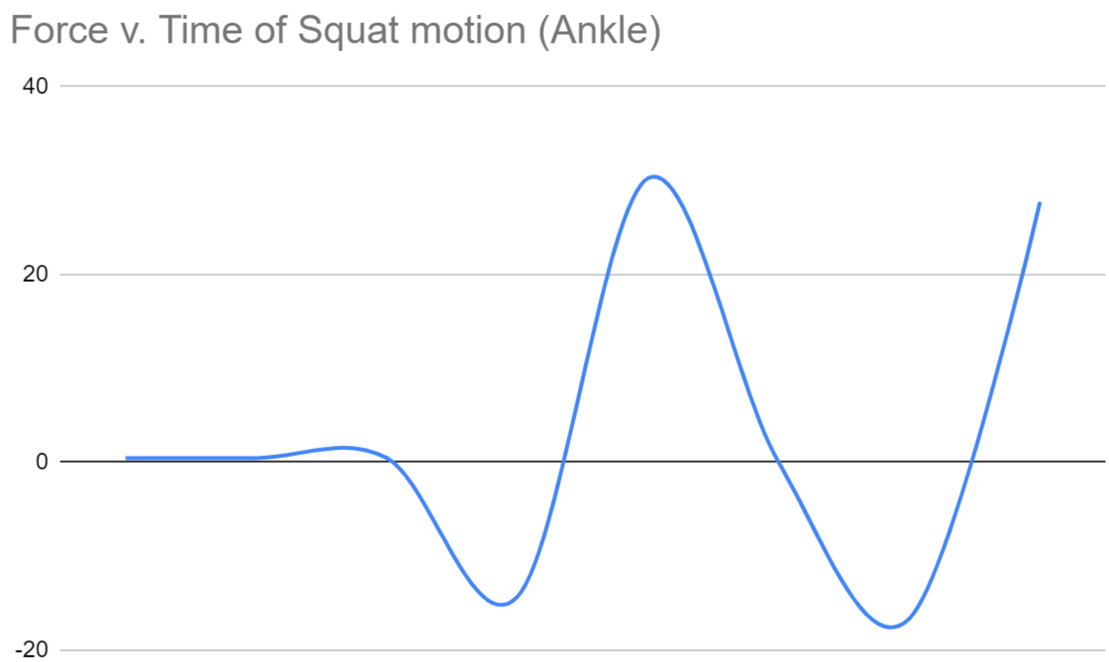

Figure 7: Force v. Time plot, Ankle

DISCUSSION

The team successfully modeled the dynamic squat motion, and the results are consistent with expected values. Experiment values were compared to other values found by other experiments. These figures can be found in the appendix. Both graphs show the proper loading motion that the hips and knees are subjected to. An important note is the maximum force that occurs when the knees are bent to a 90 degree angle. The large force found in the knee joint supports the countless claims of knee injuries and pain during squatting. The tail end of figure 6 also supports proper squatting technique, and shows the knees at a slightly bent angle to avoid locking them out.

Also from our graphs we can note that the proper technique to avoid excessive force in the knee and hips would be one that happens fairly quick. This means when someone is squatting it is best to do it at a quick pace rather than a slow pace. For example we had the time it took to go start to the end position to be around 1.5 s, if someone were to complete the motion at 2 or 3 seconds they experienced more of the force on their joints which leads to injury. Another thing we realized was that the force would be less as the angle changes. So having a consistent angle at which the knees are bent would lead to preventing injuries. However there is a limit to the angle because once the angle of the knees is below 90 degrees then the chance of injury is even higher due to losing leverage on the weight. Also not to mention that during squatting there is a point where the center of mass cannot pass otherwise the lifter would be unbalanced. This is another point the team wants to emphasise, the center of mass of the lifter. These calculations and numbers could drastically change if the performer of the squat is off balance, most notably in the back and hips. The hips would likely need to compensate for this off balance, putting even more of a torque on the hips and lower back, which would lead to increased chance of injury.

CONCLUSION

After analyzing the dynamic squat motion, it was revealed that the forces in the knees and hips work almost in sync. This meant as the force in the hip went up, it peaked then decreased, but the majority of that force went into the knee as shown in our graphs. Additionally, the knee force starts at zero then increases around the same time where the force in the hips went to zero. This coincides with the idea of conservation of energy. The movement transfers the energy from the hip to the knees, with very little loss to friction and heat dispersion. If any lifter, athlete or not, wanted to do squats they need to understand that their knees and hips will need to be strong to prevent injuries. Moreover, lifters need to understand their bodies to better know the limits of what they are capable of since squatting relies heavily on balance. While balance and strength are beneficial, having proper mechanics when performing the squat motion, prevents unexpected injuries. If someone is doing the squat incorrectly they could be applying these forces in the wrong locations of the joints leading to increased chances of injury.

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APPENDIX

Appendix A: Expected value: Forces when performing a squat.