The Influence of the Shape of the Cam Pulley on Leg Extension Machines

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Abstract

The optimal design of leg extension exercise machines is crucial in effectively targeting and activating the quadricep muscles during exercise. This research paper investigates the shape effectiveness of the cam pulley on leg extension machines on the tension in the user's quadriceps. This study surveyed three subjects for anatomical measurements, collected data using two different selectorized leg extension machines, and calculated the force and torque. The results provide insights into the function of the non-circular shape of the cam pulley in designing leg extension machines. This keeps the force on the shin pad consistent by applying more force during certain periods throughout the course of leg extension. With this insight, a design of a leg extension machine accounting for the differences in each individual's leg weight is proposed.

I. Introduction

Training quadriceps with a leg extension (LE) machine is important because quadricep muscles are critical for daily movement by helping to extend the leg at the knee joint and stabilize the knee by holding the patella (kneecap). A study by Scarborough (1999) shows the importance of quadricep strength in elderly patients. The patients with the greatest quadriceps strength were more stable when conducting chair rise exercises. In fact, the authors concluded that quadriceps strength had a significant correlation with maximum upper body vertical linear momentum as well as maximum upper body anteroposterior (A/P) linear momentum (Scarborough 1999). This demonstrates the strength of the quadricep muscle increases the subjects' speed in performance. Thus, the quadriceps are significant for conducting athletic movements, such as jumping, running, and kicking, as well as basic mobility movements such as walking, sitting up from a chair, and climbing stairs.

Moreover, a study by Jonsson and Alfredson (2005) revealed that eccentric quadriceps training can relieve knee pain. In this study, the authors used 15 subjects who suffered from chronic pain from the proximal patellar tendon. These subjects were asked to train their quadriceps on a decline board every day for 12 weeks. The results showed reduced tendon pain during activity and improved function. This suggests that not only does quadriceps training increase efficiency when performing basic mobility such as walking, running, and standing up, but it also can help relieve knee pain. Therefore, quadriceps are significant for rehabilitation as well.

Many selectorized leg extension machines (SLE) contain cam pulleys (Fig. 1). On an SLE, the cam pulley is usually located next to the seat. With the upward thrusting motion of the leg on the shin pad (SP), the cam pulley (CP) pushes down on the cable that is connected to the weights. This enables the person to load weights on their legs to effectively train their lower body. Unlike conventional pulleys that are circular, these cam pulleys are often non-circular, such as being triangular with round edges or oval (Fig. 2).

While several studies have investigated the design of LE machines, none have specifically shown how the shape of the CP on the LE machines affects the tension in the quadriceps. This study will explore the function and shape of the cam pulley and test how the tension in the quadriceps changes over the course of LE.

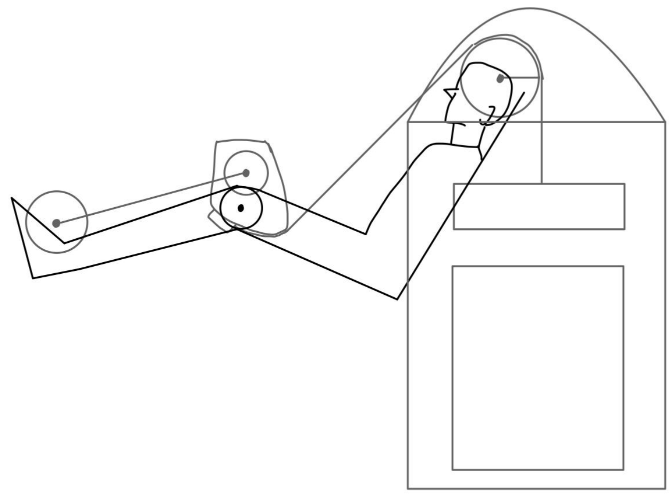

Figure 1: Selectorized leg extension machine that contains a cam pulley

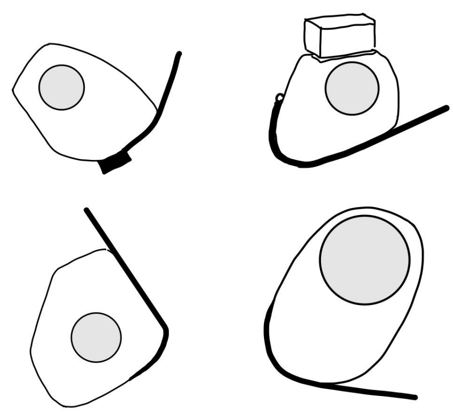

Figure 2: Unlike conventional pulleys that are circular, the cam pulleys on many selectorized leg extension machines are not circular. They are often irregularly shaped: triangular with round edges or oval-shaped.

II. Methods and Materials

Subjects

For morphometric data collection, three participants (two females and one male) served as subjects. Through a series of surveys, each subject's weight, distance from the foot to the patella, and distance from the patella to the knee joint were measured (Tab. 3). The participants were not required to have been trained on how to use the LE machine because only their bodily measurements were used for data analysis.

Data Collection

This experiment used two types of SLE machines, A and B SLE machines with varying shapes of CPs (Fig.3). First, the force of the shin pad (SP) on a leg (F_{SL}) without any weight added was measured using an electronic luggage scale (ELS). The ELS was tied around the SP and was elevated, allowing the ELS to scale the F_{SL} at three angles: 30°, 60°, and 90°, which is the angle of the tibia rotation from the starting position. The rope of the ELS (rELS) was held at 90º relative to the SP to measure the maximum normal force exerted by the SP. Next, the average of the measured F_{SL} values in three trials at each angle was calculated. Additional data for the calculation was collected from a human cadaver study (Clauser et al. 1969). According to the result of that study, the approximate mass of a human calf and foot combined is 3.805 ± 0.12 kg, and the approximate length from the knee joint to the center of mass (CM) of a human tibiale is 21.67 ± 0.3 cm. A value of 9.8 m/s^2 was used for the gravitational acceleration constant.

Figure 3: Selectorized leg extension machines with varying shapes of cam pulleys

Rigid Bodies	ABB	Forces & Torques
Shin pad+Cam pulley	S	$\Sigma F = F_{LS} + F_{GS} + F_{CS} + F_{MS} = 0$ $\Sigma \tau = \tau_{LS} + \tau_{GS} + \tau_{CS} = 0$
Leg+Foot	L	$\Sigma F = F_{SL} + F_{LS} = 0$ $\Sigma \tau = \tau_{LS} + \tau_{GL} + \tau_{LP} = 0$
Tension-only bodies		
Quadriceps	Q	$\Sigma F = F_{FQ} + F_{PQ} = 0$
Patellar tendon/ligament	P	$\Sigma F = F_{LP} + F_{QP} = 0$
Cable	C	$\Sigma F = F_{SC} + F_{WC} = 0$
Other bodies		
Machine+Torso+Femur	R	Fixed reference
Weight	W	$\Sigma F = F_{CW} + F_{GW} = 0$
Circular pulley	U	$\Sigma F = F_{CU} + F_{GU} + F_{MU} = 0$
Not bodies		
Gravity	G	

Table 1: Force body table showing forces present in the course of LE in static equilibrium

Center of Mass of Tibial	T
Knee Joint	K
Foot	F
Distance from center of mass of tibial to knee joint	D_{TK}
Distance from patella to knee joint	D_{PK}
Distance from foot to patella	D_{FP}

Table 2: Subscript definitions

Calculation

With the average F_{SL} values at each angle, measurements were collected from each participant, using the approximate mass of a calf and foot of 3.805 ± 0.12 kg, and the approximate length from the knee joint to the center of mass (CM) of the tibia 21.67 ± 0.3 cm, the tension in the quadriceps was calculated. The force of the SP on F_{SL} without any weight added was substituted into a derived equation using the fundamental physics principles of force and torque to find the tension in the quadriceps. At each angle, three trials of measurements were made for accuracy, and there were a total of three measured values for each angle. To calculate the tension in the quadriceps, the average of these three values was calculated (Tab. 4.1, 5.1). Next, the average values were plugged into the derived equation. The equation was derived under the consideration that the system is at static equilibrium (Equation 1) where T_{LF} is the tension in the leg+foot system or the quadriceps, F_{LS} is the force of the leg+foot system on the shin pad, D_{FP} is the distance from foot to the patella, F_{GL} is the force of gravity of the leg+foot system, D_{TK} is distance from center of mass of tibial to knee joint, and D_{PK} is the distance from patella to knee joint.

$$T_{LF} = \frac{\sin\theta\left(F_{LS} \cdot D_{FP} + F_{GL} \cdot D_{TK}\right)}{D_{PK}}$$

Equation 1: The derived equation for the tension in the quadriceps equation during the course of LE

At static equilibrium, the sum of the forces in a system equals 0 N and the same is true for the sum of the torques. The same calculation was made for each angle and each SLE machine. As a result, there were a total of three values, which represented tension in the quadriceps for each SLE machine. The same process was repeated for each participant (Tab. 4.2, 5.2).

III. Results

			Distance from the patella to the knee joint	Distance from foot to patella
Participant	Age (year)	Weight (kg)	D_PK (cm)	D_FP (cm)
1	48	54	6.5	50.5
3	18	50	5.5	45.8
2	39	75	7.2	44.5

Table 3: Measurements from subjects included age, weight, distance from the patella to the knee joint, and distance from the foot to the patella

SLE Machine A:

Angles (Degrees)	Average F_SL (N)
30	82
60	74
90	75

Table 4.1. F_{SL} of SLE Machine A

SLE Machine A	30º (N)	60º (N)	90º (N)
Participant #1	380.7973562	604.172581	706.77502
Participant #2	309.597891	492.1773479	575.5857819
Participant #3	414.9857664	659.4102959	771.2142964

Table 4.2. Tension in quadriceps when using SLE Machine A

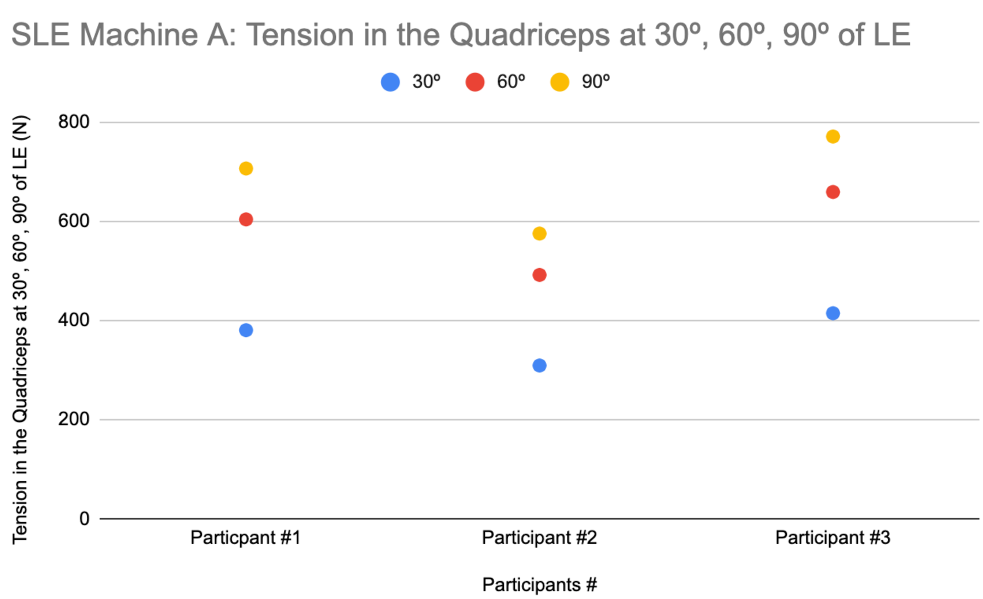

Figure 4: Graph of SLE Machine A: Tension in the Quadriceps at 30º, 60º, 90º of LE

SLE Machine B:

Angles (Degrees)	Average F_SL (N)
30	130
60	120
90	112

Table 5.1: F_{SL} of SLE Machine B

SLE Machine B	30º	60º	90º
Participant #1	568.4786638	918.6960869	992.2942508
Participant #2	458.9015715	742.38616	802.7211986
Participant #3	616.1476936	996.525139	1077.241569

Table 5.2: Tension in quadriceps when using SLE Machine B

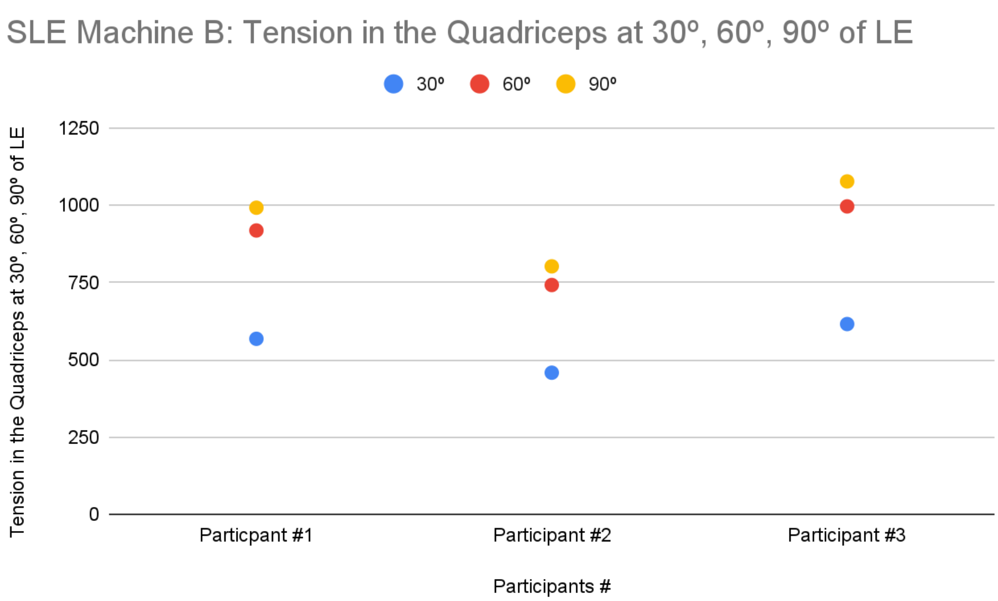

Figure 4: Graph of SLE Machine B: Tension in the Quadriceps at 30º, 60º, 90º of LE

Over the course of an LE, the angle of the moving arm and the F_{SL} and F_{GL} should change. For example, the torque from both F_{SL} and F_{GL} increases as the angle of extension (θ) increases. Torque is equivalent to the perpendicular force multiplied by the length of the moment arm. However, as the θ changes, both F_{SL} and F_{GL} no longer exert force perpendicularly to their moving arms. Thus, the torque changes by the factor of sin(θ). At 90º, the torque on the leg-foot system is the greatest, while at 30º, the torque on the leg-foot system is the smallest out of the range of data collected (Fig. 5).

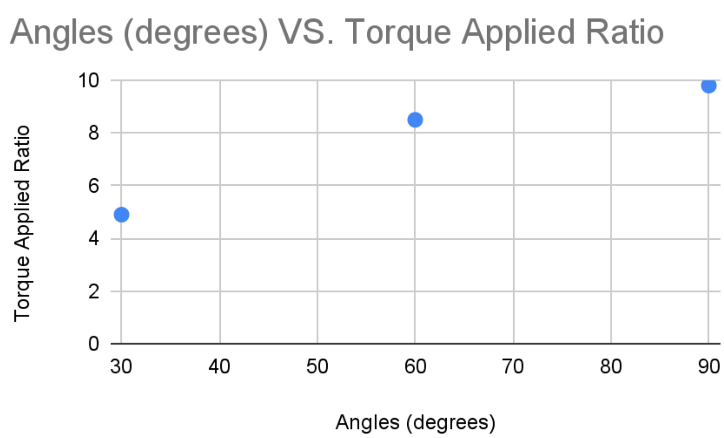

Figure 5. Graph showing the relationship between the angle of extension of the leg and the torque on the leg+foot system

The ratio of the torque on the leg-foot system should be 50% at 30º, 87% at 60º, and 100% at 90º (Fig. 5). Thus, the measured F_{SL} should also have values following this ratio over the course of using the LE. However, the measured F_{SL} values did not follow this ratio. For example, in SLE machine A, the F_{SL} values at 30º, 60º, and 90º, were 82 N, 74 N, and 75 N, respectively (Tab. 4.1). Instead, the F_{SL} values were similar at all three angles. Both measured F_{SL} values from SLE machines A and B were similar. The F_{SL} values at 30º, 60º, and 90º, in order, were 130 N, 120 N, and 112 N (Tab. 5.1).

The differences among the F_{SL} values across a range of LE angles from both SLE machines A and B suggest that an athlete performing on the LE machines would have similar tension in the quadriceps over the course of the workout. If the CP was circular, the measured F_{SL} values should vary by the ratio, 0.5:0.87:1. However, the actual values from both SLE machines A and B follow the approximate ratio of 1.0:0.9:0.9, varying only slightly from each of their mean values. In fact, it is the non-circular shape of the CPs of the SLE machines that prevents such significant variances in measured F_{SL} values. The shape of the cam pulley is designed to add extra force in the first 0º to 60º of LE to maintain similar force, and thus, torque, on the leg-foot system throughout the course of LE.

IV. Discussion

This study provides evidence that the shape of the CP modifies the force of the SP on the leg to maintain constant force throughout the course of an LE, although the findings are limited to measurements obtained from two SLE machines and calculations. Further studies should investigate several SLE machines, each with different CP shapes. By exploring the function of the non-circular CP in SLE machines, this study provides insight into potential cam shape designs that allow the force on the leg to be nearly constant throughout the LE. And also identifies a means to discover a design that not only maintains consistent force of the shin pad on the leg but also ensures a consistent tension in the quadriceps throughout the LE.

For future studies to ensure consistent tension in the quadriceps through LE, the machine should account for the change in torque on the leg due to gravity. Depending on the weight of the athlete's leg, the force of the SP will be felt differently due to gravity on a leg at any one angle. Thus, when athletes with different leg weights perform an LE, the athlete with greater leg weight would have more tension in their quadriceps even though the same amount of weight is added by the machine.

Furthermore, to maintain a set tension in the quadriceps of athletes with all leg weights, the CP should keep its shape and include rubber or memory foam padding around its rim. Depending on the weight of the leg or the force of the leg on the SP, the rubber or foam padding will prevent force on the athlete's leg by lessening the momentum in the SP by the applied force. The rubber or foam padding will work for most athletes with different leg weights because the padding adjusts the force of the SP on a leg with its property of dampening the force exerted without having the individual to adjust the LE machine.

An advantage of having such a design of an LE machine is establishing consistent force of the SP for all athletes. Such design of LE machines with this CP makes them more accessible, regardless of the experience of the athlete with the machine use. Such CP designs will prevent the need for individual adjustment of the machine while maintaining consistent tension in the quads for most users. Free-weight quadricep exercises require trial and error depending on the athlete's proficiency level because they require mindful adjustment in form, weight, and power distribution. Compared to free weights, this design of the LE machine will be more efficient and easy to use for beginners.

Works cited

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