System Design of a Biofeedback Active Sensor System (BASS) to Mitigate the Probability of ACL Injuries

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Abstract **- The anterior cruciate ligament is a main stabilizer between the tibia and femur. Tearing it causes loss of mobility and need for surgery. There is a 13% chance for a National Collegiate Athletic Association athlete to tear their anterior cruciate ligament each year. The recovery process can take up to 9 months, about a quarter of a collegiate athlete's career and 44% of those who complete rehabilitation return to athletic participation. Seventy percent (70%) of anterior cruciate ligament injuries occur from non-contact mechanisms. These decompose into 5 types of failure mechanisms. An analysis was performed on flexion/extension (37%) failure mechanisms. Examinations of the equations of motion of the knee shows the ground reaction and muscle force have the highest contributing weight when compared to the four (4) main contributing factors. The proposed solution includes a biofeedback sleeve that stores inputs and converts it to a tibial shear force approximator. From there, the sleeve warns the athlete if they are approaching a dangerous tibial shear force level. The proposed plan for preventing anterior cruciate ligament will produce $593,400,000, with $483,341 startup costs. The breakeven point occurs at 3 months, with a NPV of $15,968,608 and a return on investment of 18,284.59% after 5 years.**

Index Terms – Anterior cruciate ligament, Biofeedback, Prevention, Tear

INTRODUCTION

I. Context

The knee contains five major sets of components, bones, muscles, cartilage, tendons, and ligaments. The bones include the femur (1), patella (2), tibia (3), and fibia (4). The femur is the thigh bone. The fibia and tibia make up the shank, (the lower part of the leg) and the patella is also known as the knee cap. The next section are the muscles, these include the quadriceps (8), hamstrings (9), and gastrocnemius (calf) (10). After that, there is the meniscus (11) which acts as a cushion to absorb shock in dynamic movement. The tendons in the knee system are the hamstring tendons (7) (on the back of the knee), and patellar (6) and quadriceps tendons (5) that connect the quadriceps to the quadriceps to the patella to the tibia. Finally, there are

the ligaments, posterior cruciate ligament (PCL) (12), medial collateral ligament (MCL) (13), lateral collateral ligament (LCL) (14), and anterior cruciate ligament (ACL) (15). These all play a major role in the stability of the knee, specifically the ACL.
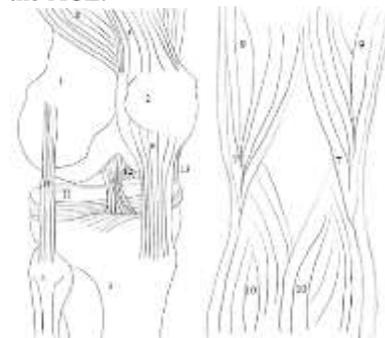

FIGURE I
KNEE

The Anterior Cruciate Ligament (ACL) is the primary stabilizing knee ligament preventing the anterior translation of the tibia. [1]

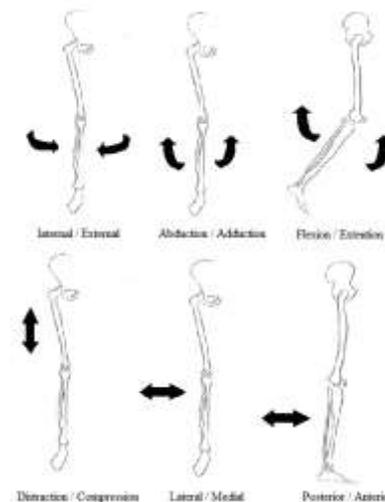ACL tears can be broken down into two categories, contact, and noncontact

FIGURE II
ACL TEAR MECHANISMS

These make up 30 % and 70 % of ACL injuries. Noncontact injuries can be broken down even further into

three categories, flexion/extension, internal/external rotation, and abduction/adduction, with two sub categories, flexion/extension with rotation and abduction/adduction with rotation. [2] For the purpose of this paper, flexion/extension injuries will be the focus at 37% of noncontact injuries which is 77,700 ACL injuries per year out of the total 300,000 ACL injuries per year. [1]

The ACL tears at 2100 N. The tears associated with flexion injuries are due to a phenomena known as Tibial Shear Force (TSF). When the leg is fully extended, there is a high amount of strain on the ACL from the tibia. The PCL, on the other hand, is relaxed. When the knee is flexed, the properties of the ACL and PCL switch.

FIGURE III
SAGITTAL VIEW OF THE KNEE

Once, the ACL tears, an event known as anterior tibial translation occurs. When the ACL tears, the tibia is released and moves forward.
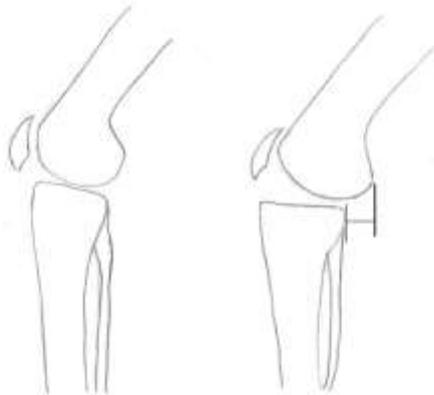

FIGURE IV
ANTERIOR TIBIAL TRANSLATION

II. Gap Analysis

There are ACL injury repression programs in place like the Santa Monica Sports Medicine Research Foundation's Prevent Injury and Enhance Performance (PEP) program. These exercise programs have been proven effective [3]. They focus on building muscle memory of good form and developing the muscles that support knee ligaments in an attempt to lower the probability of injury. The limitations on these programs occur in their implementation however. Only about 30% of coaches implement these programs correctly. [4][5][6]

That could be from limitation on how well a coach or trainer can observe the prevention exercises as well. The head weight training and fitness coach at George Mason University, John C Delgado, highlighted it was hard to observe an entire team and therefore it was probable that some participants form was not corrected. The method of observing an athlete's form was based on theories of kinesiology and experience of being a coach. These methods are subjective to what he knows as good form and also to what he can see when observing athletes. There was not any quantitative method to determine good form and the resultant ACL strain.

III. Problem Statement

There is no quantifiable method to determine ACL strain. There is currently no system that accurately quantifies ACL strain for a person at any given time.

METHOD OF ANALYSIS

The physics of the knee flexion tear need to be understood for a system to be put into place to mitigate it. The knee flexion tear is caused by Tibial Shear Force (TSF). TSF needs to be able to be quantified. To do so, all relative forces to the knee need to have a relative reference frame. This is done by using the shank angle, or the angle of the tibial head to the earths X-axis.

FIGURE V
TSF

This reference frame is important because the x-axis of this reference frame is line of action of the ACL ligament. Therefore any forces on the Shank reference frame in the X can be quantified as approximate ACL strain. [7]

Tibial Shear Force results from inputs from the force supplied by the momentum of the Shank (tibia and fibula), the momentum of the foot, the earth's ground reaction forces, and the relative contributions of the Gastrocnemius muscle, the quadriceps muscle, and the hamstring muscle.

$$TSF = F_{Shank} + F_{Foot} + F_{GroundReaction} + F_{Muscles} \quad (1)$$

$$TSF = m_s[a_{sx}\cos(\theta_s) - (a_{sy} + g)\sin(\theta_s)] + m_f[a_{fx}\cos(\theta_s) - (a_{fy} + g)\sin(\theta_s)] - F_{grx}\cos(\theta_s) + F_{gry}\cos(\theta_s) - \Sigma F_{GastroX} - \Sigma F_{QuadX} - \Sigma F_{HamX} \quad (2)$$

The foot contributes to TSF through its transferal of the earth's ground reaction forces and the resultant translation and moment forces at the ankle.
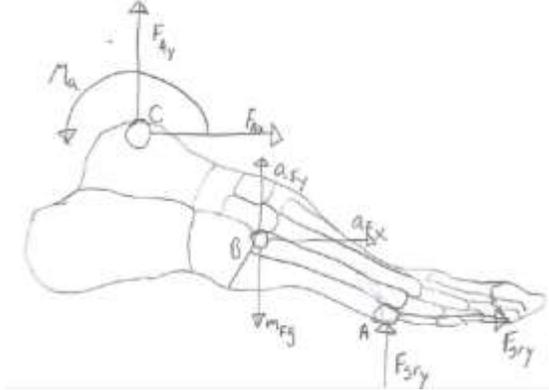

FIGURE VI
FOOT FREE BODY DIAGRAM

The shank, which is the tibia and the fibula together, contributes to TSF through its force it generates due to its force from motion and the force at the ankle do to the foot.
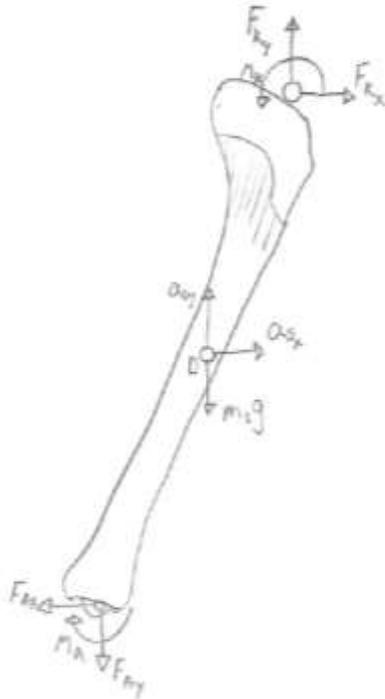

FIGURE VII
FREE BODY DIAGRAM SHANK

The muscle force contributions to TSF have to be understood by the flexion angle. Flexion angle is the relative angle between the femur and the tibia.
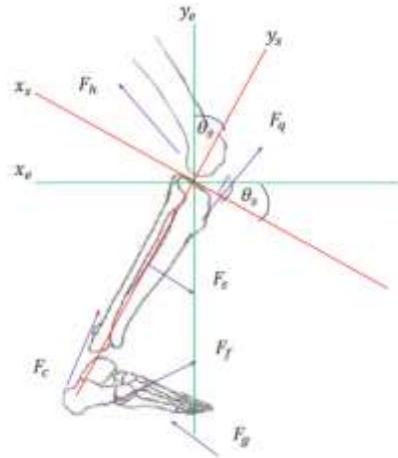

FIGURE VIII
SHANK REFERENCE FRAME

In the model uses flexion angle b. The quadriceps muscle connects to the patella (knee bone) by a tendon which then connects to the tibia via a tendon. [8]

The relative force on the tibia is therefore relative to the position of the patella. The patella position changes due to knee flexion. Therefore the relative contribution to TSF from the quadriceps is due to flexion angle.

$$\Sigma F_{QuadX} = F_{Quad}\sin((-.238)*(180 - \theta_{flexB}) + 22.2) \quad (3)$$

The hamstring muscle contributes to TSF by pulling on the tibia in the opposite way as the quadriceps. In this way the Hamstring is the largest muscular mitigator of TSF. The hamstring contribution is directly related to the flexion angle.

$$F_{HamX} = F_{Ham}*\cos(90 - \theta_{flexB}) \quad (4)$$

The gastrocnemius muscle (calf) contributes to TSF by connecting to the lower part of the femur. In this way it also creates a TSF force in the opposite direction of the quadriceps. It mitigates TSF but not in the magnitude of the hamstring muscles.

$$F_{gastroX} = F_{gastro}*\sin(\sin^{-1}((d*\sin(\theta_{flexB}))/(d^2 + tib_{length}^2 - 2*d*tib_{length}*\cos(\theta_{flexB}))^{-2})) \quad (5)$$

d in this model is the distance between the center of the knee to the connection point of the gastrocnemius to the femur, which is about 3 centimeters.

Ground Reaction Force contribution comes from the body's dissipation of the earth's forces due to Newton's laws. These forces have not been theoretically measured for this problem due to the complexity of the system. The Ground reaction forces would counteract the body's center of mass and momentum which is based on the athletes predetermined neuromuscular response to their landing goals. It can be thought of as a smart spring that an athlete's form would have to be analyzed to derive.

I. Sensitivity Analysis

A Sensitivity analysis was conducted on the model which was run through a simulator to determine the effects of the TSF contributors have to total TSF. The contributions of the muscles to TSF were analyzed first by varying the flexion angle. All other parameters were held at their average values to isolate the change. The contributions of the ground reaction forces were analyzed by keeping a constant shank angle and then computing the effects to TSF by varying their contributions in body weight.

II. CONOPS

The solution is a wearable device that uses a Biofeedback Active Sensor System (BASS) to actively quantify the ACL strain during flexion modes, and then warning the user when they reach a high reading. In this way, a user is given knowledge of their bad form and can actively change their form to mitigate their probability of tear.
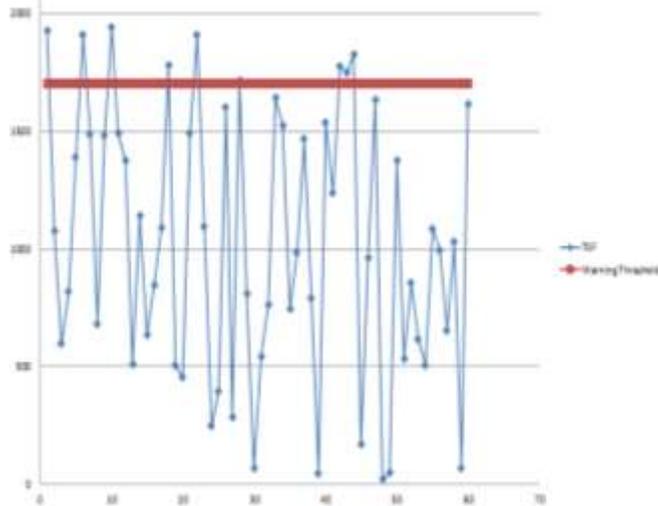

FIGURE IX
SAMPLE OUTPUT

FIGURE X
BASS

SYSTEM COMPONENTS

To actively monitor all the contributing factors to TSF, there are sensors for measuring all the factors, knee flexion, shank angle, acceleration of the shank, acceleration of the foot, and the earth's ground reaction forces.

The system will route the sensor readings to a microprocessor that will actively run the data against a TSF algorithm. When the sensor reading reach above a threshold, then the processor will then cause a beeper and light to go off which will actively alert the user to their bad form.
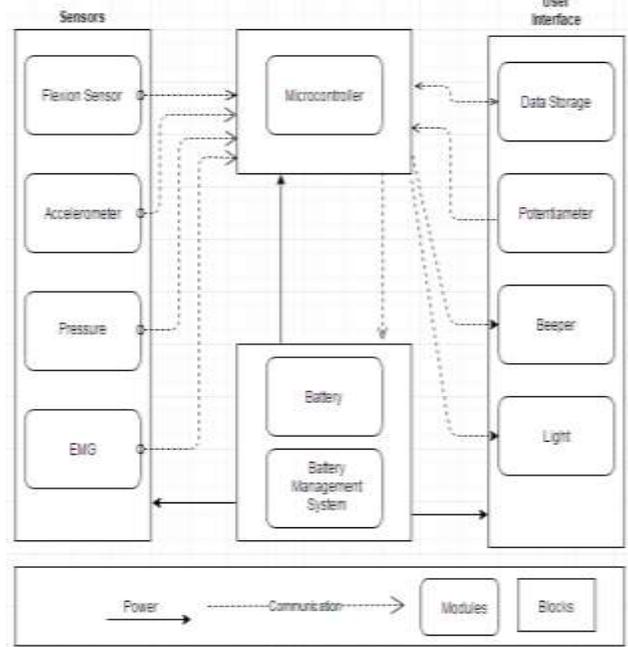

FIGURE XI
COMPONENTS DIAGRAM

I. Design Alternatives

The components used were the flex sensor for the flexion and shank angle detection, MyoWare Muscle Sensor for muscle activation, Force Sensors for ground reaction force, 3-axis accelerometer for acceleration, and the wearable microcontroller for the processor.
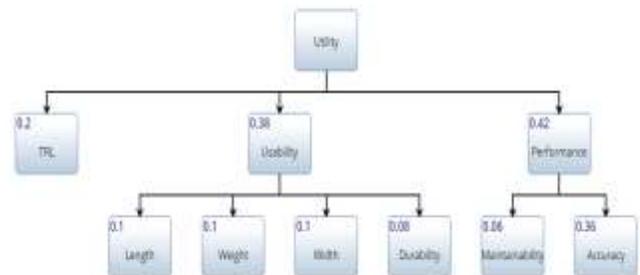
II. Value Hierarchy

FIGURE XII
VALUE HIERARCHY

III. Utility VS Cost

A utility vs cost analysis was performed on each set of components using the value hierarchy to rate their utility. The most usable and cost effective alternative was selected for each necessary component.

TABLE I
SYSTEM COMPONENTS

Variable	Unit	Cost
Flexion & Shank	Flex Sensor	$12.95
Muscle Activation	MyoWare Muscle Sensor	$37.95
Ground Reaction Force	Force Sensor	$8.50
Acceleration	3-axis Accelerometer	$7.95
Processor	Wearable Microcontroller Board	$19.95

BUSINESS PLAN

There is a potential market size of just under $600 M. This includes a market of ACLI sufferers (300,000 per year), NCAA athletes (420,000 per year), and professional athletes (18,000 per year). With a selling price of $300 per sleeve, this equates to a total market value of $593 M.

TABLE II
BUSINESS SCENARIOS

Scenarios	Expected	Pessimistic	Optimistic
Market Share	25%	10%	50%
Penetration Rate	5%	2%	10%
Market Share Value	$148,350,000	$59,340,000	$296,700,000

The initial costs consist of startup and investment, $92 K and $391 K respectively

TABLE III
STARTUP COSTS

Costs	Amount per unit	Description
Market Research (non-recurring cost)	3331	20 test product * cost of producing 1 unit
Overhead	63,200	Rent, Utilities, Health Ins
Rent + Utilities	54,000	$30/square feet* 1800 square feet
Utilities	6000	500/month*12 months
Health Insurance	3200	4 employees * cost of insurance/year
Marketing	20,000	
Website Development (non-recurring cost)	5640	visual design, programming, content support, client training
Signing for webhost	59.4	$4.95/month*12 month
Total Startup Cost	**92,230**	

TABLE IV
OPERATIONAL COSTS

Component Acquisition Costs	Amount	Description
Potentiometer X2	0.34	Measures threshold
Knee Sleeves X2	4	Wearable component
Pressure Sensors X16	127.2	Measures Ground Reaction Force
Speakers X2	0.94	Beeps When 1900 N is reached
Accelerometers X2	1.02	Measures Acceleration
Processor	19.95	Process input and make calculations
Flexion Sensor X4	51.8	Measures Knee Flexion
Parts Cost	204	
Labor	20	hourly rate
Total Variable Costs	307851.2	ProductionFor4Employees*cost of components + labor cost * 4
Fixed costs	83,259	
Overhead	63,200	Rent, Utilities, etc.
Marketing	20,000	
Webhost	59.4	
Total Operational Costs	**391,111**	

RESULTS

The results of the muscle force contributions, varied by flexion angle, show that at approximately 160 degrees, the quadriceps muscle force dominates the hamstring and gastrocnemius muscle in the TSF reference and therefore contributes more overall force to TSF. This verifies the concept of "Quad-Dominance" which refers to the tendency to absorb ground reaction forces with flexion angles lower than 20 degrees. [9]
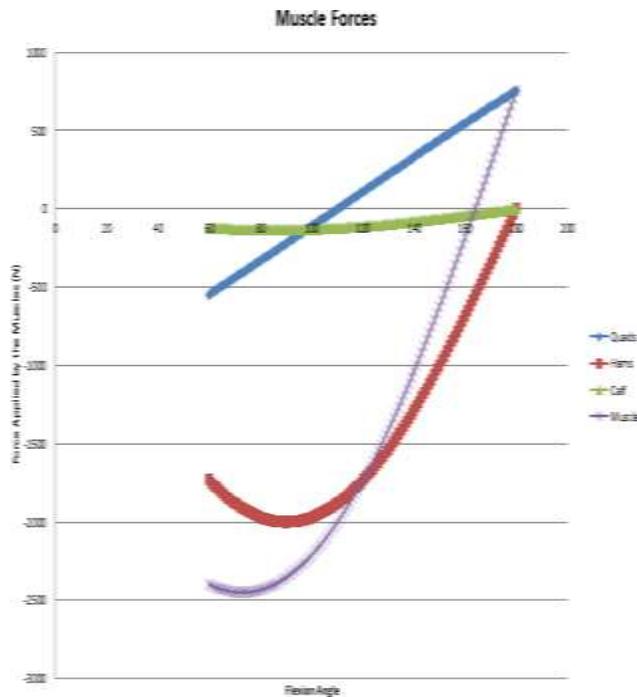
FIGURE XIII
MUSCLE FORCES VS TSF

The last analysis shows the contributions of ground reaction forces to TSF by varying the magnitude of the ground reaction forces by body weights. The X axis ground reaction force actually dissipates overall TSF while the Y axis forces contribute linearly to a maximum of 700 Newtons.
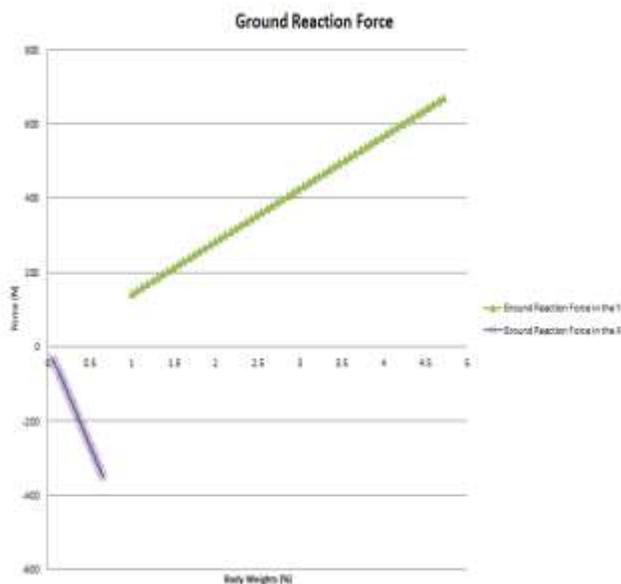

FIGURE XIV
GROUND REACTION FORCES VS TSF

RECOMMENDATIONS

Since the proposed system and analysis focused on one mechanism of injury, it is suggested that a thorough analysis on the rotation and abduction injury be made. In this way the overall causes of ACL injury can be understood and mitigated which would more fully contribute to decreasing the number of tears.

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