Electronic Knee Wrap for Injury Prediction

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ABSTRACT

This research focuses on creating an electronic knee wrap for athletes to wear in order to monitor the motion of their knees to reduce the risk of suffering an Anterior Cruciate Ligament (ACL) injury or reinjury. While significant research has been conducted for identifying the factors responsible for an ACL injury, there is a need to quantitatively determine an athlete's risk of suffering the injury in order to determine if an athlete is fit to return to sports. To this end, this reserach explores the opportunity to mount a high performance, small area circuit on a knee wrap. A set of factors that are important to the calculation of an athelete's risk of a future knee injury, such as knee acceleration, knee orientation and valgus forces, is collected from the knee wrap in real time. In addition, this knee wrap will also be multi-purpose, allowing both doctors to monitor an athelete's recovery remotely and coaches to observe an athelete's performance on the field.

The design incorporates microcontrollers, inertial measurement units and wireless module mounted on the knee wrap. In order for the therapists and physicians to interact with the data, a server and a front-end web interface is implemented to display the data.

1. INTRODUCTION

ACL ruptures are one of the most common injuries in sport and very expensive to treat. There are approximately 175, 000 primary ACL reconstruction surgeries performed annually in the USA with an estimated cost of over $2 billion US [22]. This is followed by a lengthy rehabilitation period. Even then, over a quarter of patients reinjure their ACL [21]. These injuries also cause early-onset of osteoarthritis for numerous people between the ages of 30 and 50, and related injuries such as ACL tear in the other leg. [11]

An ACL injury can have an immense impact on an athelete's career and quality of life. Because of this, monitoring and reducing the risk of ACL injuries is exceptionally valuable and important. This research proposes the use of an electronic knee wrap (eKwip), to predict and prevent ACL injuries in both healthy athletes and injured patients. By monitoring the angles, orientation and movements of the knee of the wearer, eKwip is able to capture the important factors that are responsible for an ACL injury and allows doctors to observe the movements of the athelete and give recommendations to correct his running or landing posture to reduce the risk of future injuries. To encourage adoption of such a knee wrap, eKwip is designed to be unobtrusive and flexible, unlike the current mechanical braces on the market.

eKwip is designed to be mobile and allows the wearer to monitor his or her knee performance throughout the day to decrease the chance of future injury. It also allows physical therapist to easily observe and assess the performance of injured patients remotely. With eKwip, the aim is to reduce the rate of ACL injuries in both healthy athletes and injured patients.

eKwip utilizes various factors that have been demonstrated to cause the injury such as accelerations and angles. eKwip currently only acts as a system that collects information from the knee of the wearer and transmits to the computer of the doctors in the clinic, or coaches on the field. Although the type of information collected is tailored towards understanding the risk of ACL injury, the benefits of monitoring the knee is not restricted to just that. Additional rehab applications of eKwip may include monitoring patients post operation, collecting information on Stiff Knee, and tracking total joint cycles on older patients. Given the collected information, the doctors can then interpret the performance and health of the patients and give corresponding recommendations.

eKwip consist of a microcontroller that receives knee acceleration and orientation angles from its sensors. Using a wireless module, this data is quickly transmitted to the server, which calibrates the angles and acceleration, and displays them on the website in a user friendly format.

Sec. 2 reviews knee anatomy, including the major causes of ACL injuries and the performance requirement of eKwip. Then, Sec. 3 discusses the prior work in ACL detection and the common rehabilitation procedures used in the industry for measuring the strength of the ACL. Sec. 4 illustrates the basic idea of eKwip with the model diagram. Sec. 5 describes the technical implementation of eKwip in detail. As real-time analysis is a necessary component, Sec. 6 describes the performance of the system with respect to requirements and how the system improved over time as well as the sample results collected from eKwip. Sec. 7 details the future work that can be done to improve eKwip and

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Sec. 8 contains a brief discussion of potential ethical issues of the wrap. Throughout the paper, we focus on latency and unobtrusiveness of the wrap.

2. BACKGROUND

As the paper includes interdisciplinary content, it is necessary to first provide information in this section about the mechanical properties of the knee used throughout the paper.

2.1 Knee Joint and ACL

The knee joint is the largest joint in the human body that connects the femur and tibia. ACL is one of the four major ligaments in the knee. It originates from deep within the lower extremity of the femur and attaches in front of the spine of tibia. The Figure 1 below is representative of the knee anatomy and the location of ACL.

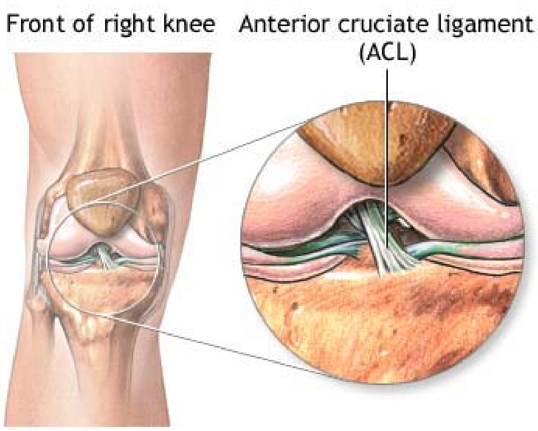

Figure 1: Knee anatomy and location of ACL

2.2 Knee Flexion Angles

ACL is responsible for resisting anterior translation and medial rotation of the tibia, in relation to the femur. This resistance is crucial for controlling the forward movement and twisting of the knee. Major cause of ACL injury is small knee flexion angle along with medial rotation. The knee flexion angle is the angle between the femur and the tibia. The medial rotation is the internal rotation of the knee towards the midline axis of the human body. As a result, these angles are an important indicator for the injury.

2.3 Asymmetric distributed forces

Another common reason for the ACL injury is due to asymmetric distributed forces acting on the joint. As these forces are not equally distributed, the resultant force direction does not pass through the vertical axis at the center of the leg. This resultant force causes anterior translation and medial rotation. Once the forces exceed the resistance offered by the ACL, the ACL ruptures due to excessive strain [6]. Now, these forces are caused due to sudden movements such as changing directions or landing from a jump, which are most common in sports [6]. These decelerations generally happen as fast as $50\mu s$ [19], and therefore, ekwip needs to be able to measure the deceleration as fast as 10s of milliseconds. The decelerations can then be related to the forces to provide a more complete analysis for risk calculations.

3. RELATED WORK

Related work for this project is divided among three fields: algorithms for ACL injury detection (Section 2.1), knee brace effectiveness/performance hindrance (Section 2.2), and Knee Mechanical Properties (Section 2.3).

3.1 ACL Injury Detection

This section covers research in minimizing the testing required to detect whether an athlete is at risk of suffering an ACL injury. Prior research in ACL Injury Detection has shown that techniques exist that accurately capture and analyze various measures relating to the knee to determine the probability of ACL injuries [17]. Using such metrics as knee flexion angles, medial rotation, and body mass, researchers were able to come up with a way to determine knee abduction moments (KAM), which are used to identify whether or not an athlete is at high risk for an ACL injury, with a sensitivity of 77% and specificity of 71% [17] [2].

3.2 Knee Brace Effectiveness/ Performance Hindrance

This section deals mainly with studies of the extent to which a Functional Knee Brace and a Prophylactic Knee Brace interacts with an athlete's ability to perform on the field. Prior research in using Functional or Prophylactic knee braces out in the field has shown that it potentially hinders an athlete's movement by restricting the anterior translation. In addition, the studies on the usefulness of these kinds of braces in preventing the injury are inconclusive [14]. Knee braces, especially Functional Knee Braces (FKB), which are more mechanical in nature and thus more obtrusive, are shown to provide 20-30% greater knee ligament protection. This suggests that while FKBs have an impact in reducing the severity of knee injuries, there is an opportunity to create a new brace to evaluate the risk index and thereby provide proof for the capability of existing braces. Another important factor of the effectiveness of knee braces is in rehabilitation, where a combination of exercises and brace use can speed up recovery [8]. eKwip can also provide evidence for establishing the usefulness of these exercises.

3.3 Knee Mechanical Properties

Research has proved that the relative angle and forces between the femur and tibia are a major risk indicator to ACL injury. The paper *Shin, et al. 2006* provides the numerical data, which we will use to calculate the risk index for the athlete. [19] The authors of the paper created a model to track the knee flexion angle and the forces over time and found correlation with the experimental model of the injury.

4. SYSTEM MODEL

The technology behind eKwip is able to capture the movements of the knee and allow athletes and their physicians to monitor the motion of the leg. The system consists of several sub-components, each of which performs an important function as part of the system as a whole. The sub-components include a spandex wrap, a microcontroller, sensors, a wireless module, and a webserver.

Figure 2 shows a block diagram modelling the eKwip system.

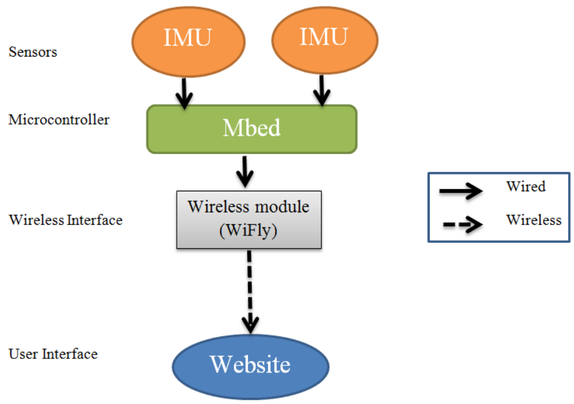

Figure 2: Block diagram of eKwip system

4.1 Wrap

In order to measure the movements of the leg and knee, a wrap is required to wrap around the leg and position the sensors appropriately. Since it is required to have a sensor on the upper leg and a sensor on the lower leg, so the relative position and movement can be measured, a wrap allows the correct placement of the sensors and keeps the sensors stationary.

4.2 Microcontroller

A microcontroller is required for eKwip so that the data collected is processed and transmitted elsewhere for further analysis. The microcontroller receives input from the sensors while simultaneously sending data out through its serial lines to the wireless module.

4.3 Sensors

eKwip requires two sensors in order to successfully model the position and movement of the leg and knee, because the relative motion of the upper and lower leg must be measured. The sensors are required to be able to measure acceleration, absolute orientation, and rate of change of the absolute orientation.

4.4 Wireless Module

After collecting the data, it needs to be transmitted elsewhere for further processing and analysis. A wireless module allows the microcontroller to stream data in real time over the internet to the server. Because of this, eKwip is able to display the motion of the leg and all pertinent data to the user in real time.

4.5 Server

For data visualization and extraction, a server is used. The server collects the data that is transmitted from the wireless module, processes it, and displays the motion of the leg to the user. Additionally, the server allows for the storage and retrieval of the raw data so it can be analyzed.

5. SYSTEM IMPLEMENTATION

eKwip consists of several components that all work together to collect data about the position and motion of the knee and leg, send the data over a wireless network link to a server, and analyze the data in order to display an image of the knee and collect comprehensive data regarding the motion of the knee.

The process begins in the IMU sensors, which use accelerometers and gyroscopes to measure the absolute orientation, acceleration, and rate of change of acceleration. This data is passed to the microcontroller, which packetizes the data and sends it to the wireless module. The Wifly then transmits the data packets over the wireless network to the server.

The server receives the data packets and parses the data. It then computes the position and movement of the knee in order to display the image of the leg in the graphical user interface and record the position and motion data in a file on the server, which can be used for graphing and further analysis.

5.1 Spandex Wrap

eKwip is a spandex wrap that fits around the leg, above and below the knee. A wrap of this type was chosen because it's relatively small, unobtrusive, and stays close to the skin, which is important for correctly measuring the movement of the knee itself, instead of the movement of the wrap. The wrap was designed to be unobtrusive in order to encourage athletes to wear it more often. Unlike current mechanical braces on the market, eKwip does not hinder the movement of the knee, which makes eKwip much more attractive to athletes.

5.2 mBed Microcontroller

The microcontroller is responsible for reading data from the sensors and sending the data over the network link. A microcontroller was chosen based on storage capacity, clock speed, ease of use, and the ability to multitask. These are important because a fast processor will allow the reading of data at a high frequency, a decent amount of storage will facilitate the storage of the code libraries in use and to give some initial storage for the data, and the ability to multitask will enable the reading of data and send it over a network link simultaneously. Given all these considerations, the mBed LPC1768 [12] was selected as an ideal microcontroller for this project.

The mBed is ideal for this project because of its small size and impressive performance. Perhaps most importantly, the mBed has the ability to interface with many different modules at the same time, as it includes three UART serial ports, two SPI ports, two I2C ports, a USB port, a CAN port, and an ethernet port, among other GPIO pins. The mBed contains a powerful 96 MHz ARM Cortex-M3 processor. These features come together to allow several sensors and communication devices to be connected to the mBed at one time.

5.3 UM6-LT Sensors

In addition to the microcontroller, eKwip also requires sensors to collect information from the wearer's knee. A set of two inertial measurement units, or IMUs, were selected for this purpose. Two IMUs are required, one on the upper leg and one on the lower leg, so the relative angles of the knee can be measured in order to give an accurate model of the leg. A small IMU that is able to send data very quickly and communicates via UART serial is utilized by eKwip. This allows easy mounting of the IMUs, fast data reading, and easy interface with the mBed. In accordance with all of these considerations, the Pololu UM6-LT [18] was chosen as the best IMU for this application. The UM6-LT is approximately the size of a quarter, and can measure absolute angles, rate of change of the angles, and acceleration.

An mBed library for the sensors was initially used in order to set up the IMUs and get initial data readings. However, once performance became a concern, it was clear that the library would not give the speed required for the prediction of ACL injuries. The UM6-LT offers two operating modes, broadcast and query. The library used query mode, which involves sending a query to the IMU and waiting for a response. This was the limitation in the speed, so a new library was implemented, which utilizes the UM6-LT's broadcast mode. This allows much faster reading, on the order of 3ms per data point, as opposed to the previous read time of 30ms.

5.4 Wifly Wireless Module

In order to allow coaches to monitor the performance of athletes on the field and doctors to monitor the recovery of injured patients, a wireless interface that allows eKwip measurements to be displayed in real time was implemented. In order to achieve wireless communication, a Wifly module [13] was integrated into the system. The Wifly is a small Wifi board that communicates via UART serial. Having a wireless connection is useful because data can be streamed in real time to the server that is running in order to provide an intuitive visualization to users and/or their doctors. The only constraint with this is that the user must be in range of a wireless network.

The Wifly is configured to send a packet each time a data point is received. This, along with an increased baud rate on the serial line between the mBed and the Wifly module, allowed for a wifi sampling rate of up to 100 Hz.

5.5 Node.js Server

The server is implemented with Node.js [15] and communicates with the eKwip wrap via websockets [5]. Websockets were chosen in order to provide a stream of information from the wrap to the server. The server collects the data streamed from the wrap and in turns communicates to the front-end interface. Some simple logic is implemented on the server to normalize and calibrate the data sent from the wrap, as well as filter out possible measurement errors. The front-end currently displays a 3D model of the knee given the data from eKwip with WebGL [7]. However, in the future, the front-end will also allow multiple users to log in to view indivisualized reports and statistics, and share this information with their physician. This can allow patients and doctors to monitor the performance of the knee as well as observe the recovery of a patient over time.

6. RESULTS

This section provides some useful benchmarking of the final eKwip prototype to ensure the accuracy and precision of the collected measurements are comparable to industry standards. The performance of the wrap is then assessed against the accuracy and precision required to determine the risk of ACL injuries. Finally, some sample data collected by eKwip on healthy and injured patients is shown at the end of the section.

6.1 Performance

In order to correctly predict ACL injuries in real time, data must be collected at a certain frequency so that subtle movements and accelerations are captured in the data. Data transfer speeds were a major concern throughout work on the project. Problems with the library used in data transfer were identified and rectified, allowing eKwip to trasmit the movements and acceleration data at useful speeds.

Another issue with performance resulted from the WiFi module buffering data until the data packet was large enough to send. Configuring the WiFi module to send data after receipt of each data packet as well as shortening the data string used to communicate each data point further increased transmission speed. These changes sped up the data presented on the server by about 14.5%, a major increase and critical for the different use cases of eKwip.

The improvements in data sampling and network transmission rates can be seen in Figure 3.

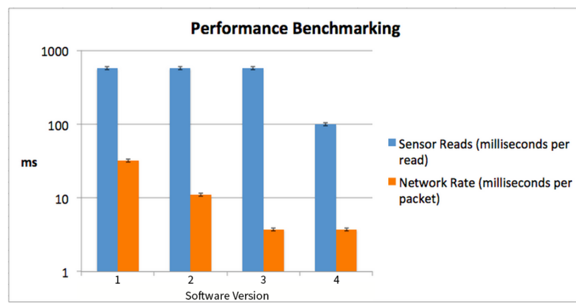

Figure 3: Network and sensor performance of eKwip in various versions

The accuracy of eKwip is determined by measuring the actual angle of the knee and comparing it to the angle given by the sensors. The final prototype scored an error of 5.00% with a standard deviation of 3.39%.

Proximity of the sensors to the leg is also important in producing an accurate measurement of the movements of the wearer. The proximity is measured from various knee positions of the wearer to the skin of the upper and lower leg. The average distance from the sensors are found to be 0.22cm with a standard deviation of 0.08cm.

The precision of eKwip is determined by repeated measurements of the same position of the knee, confirmed by a protractor. The average standard deviation of eKwip is found to be 1.05%.

6.2 Testing eKwip

Two subjects were used in testing out eKwip's accuracy and measuring capabilities, one who suffered no knee injury and one who had recently recovered from an ACL injury. The wrap was not tested on both knees of the injured subject due to the possibility that the healthy knee of the subject may compensate for the injured knee, skewing any data collected. Both subjects wore the wrap on the right knee (which was the injured knee for our injured subject) and walked on a treadmill for 10 seconds.

The data collected and saved on our server was used to calculate the knee flexion angles of both subjects "!!!! WE MAY NEED TO DISCUSS HOW WE CAME UP WITH THE ANGLES". As seen in Figure 4, there is

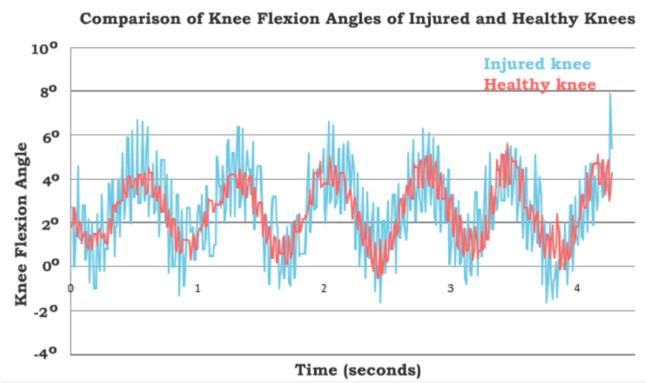

Figure 4: Block diagram of eKwip system

7. FUTURE WORK

At its current point, eKwip is in the prototype stage. While the current implementation is able to collect data on the wearer's knee movements as well as transmit that data to the server, there is no conclusive metric being calculated for the prototype nor is there a way for the information to be displayed.

7.1 Knee Injury Risk Index

The first step moving forward is to come up with an algorithm to calculate the Knee Injury Risk Index (KIRI). In order to do this, certain factors, such as the calculated Q-angle or knee adduction moment during movement, after being calculated, will be given certain weights and a final KIRI value will be returned for the wearer "!!! HOW". The Q-angle is formed from a line drawn from the Anteriro Superior Iliac Spine (the front of the pelvic bone at the hip level) to the center of the kneecap, and from the center of the kneecap to the Tibial Tubercle (a bump about 5 centimeter below the kneecap on the front of the Tibia "!!! conley2007female MISSING CITATION". The knee adduction moment determines how force is distributed at the knees "!!! noyes2010knee MISSING CITATION". A higher Q-angle means that the wearer has an increased risk of ACL injuries, while the knee adduction moment of a person in movement will affect how certain loads are applies to their knees and ACL.

7.2 Machine Learning

Another important issue that needs to be addressed is the variability of gaits, resting positions, and Q-angles from person-to-person. Designing a wrap that fits everyone will not generate accurate results as various athletes wear the wrap. The proposed solution to this issue is to produce a basic machine learning algorithm that will cause eKwip to adapt to wearer. The algorithm will likely collect data on the wearer initially. Then, using this information, eKwip will adjust its collection formulas to fit with how the wearer normally rests or moves. This aspect of the project will likely be the most difficult; therefore, a major portion of the remaing time will be spent on creating and validation the implementation. "!!! EXPLAIN HOW WE ARE GETTING DATA"

7.3 Graphical User Interface

Presenting the data and information collected by eKwip will be useful for physical therapists or coaches. For situations when an atheletes starts to complain about either soreness and recieve a high KIRI score, physical therapists or coaches should be able to go to the site and see a timeline or graph of the wearer's various data points over time. This will give the physical therapist or coach a better idea of how their athlete is moving about and should give a notion of what needs to be fixed. In addition, as the server currently shows how the athlete's knee is moving about in real-time, a future implementation of this feature could include a replay of the movements about five or ten minutes prior.

7.4 Testing & Validation

Testing and validation of all data collection and the system itself will be carried out along with the implementation of the previously mentioned features. Validation is critical for the system and will determine whether or eKwip is actually useful as an aid for physical therapists or coaches. Fortunately, access to equipment at the Penn Sports Medicine Center will allow us to test eKwip against what is currently being used. Because of the nature and focus of the project, certain data will be very risky or even dangerous to collect on an actual person. Fortunately, knee models at the Penn Sports Medicine Center will allow us to collect this information as well as give us methods to gather data on the knee in various positions or stances. Moving forward, testing and validation will be continually done, with majors tests performed when major milestones are completed on the project.

7.5 Reach Goals

Based on how fast these features can be implemented and how much time remains, the reach goal set for the project may be pursued: to implement a prevention measure for eKwip that will be an extension of the prediction. However, this largely depends on how fast reads and calculations on the system itself can be performed as well as how quickly accuracy of the values can be achieved. Prevention also requires major research into potential materials to use, as eKwip would need a method to brace the sudden movement of the wearer to lessen or prevent the injury. In addition, a Prevention implementation will modify the rate and method of data collection and calculation.

8. ETHICS

The rapid increase in the acceptance of wearable technology will create numerous problems. In the current form of the wrap can cause physical discomfort for the user. For instance, the microcontroller, soldered on the PCB board, has pins sticking out. Those pins can cause friction during use and leave the user with scratches and injuries on his femur and tibia. To solve this problem, the wrap can have a custom-made PCB board that can mount the microcontrollers, IMUs and the wifly module without the pins coming in any contact with the skin.

In addition to physical injuries, it is possible that the wrap can create financial problems for the athletes. If all the athletes are mandated to use the wrap, the manufacturer can put a ridiculous price tag that will economically burden the athletes. Medical devices are highly regulated by FDA. For approval, the company has to go through 7-10 years of extensive testing while spending millions of dollars. While this would justify the price tag, it would nevertheless reduce the accessibility of the wrap for everyone other than athletes. One way to reduce the price tag would be to cover the cost of the wrap under insurance. This strategy would raise the insurance prices but they wonâĂŹt increase significantly enough than standalone purchase as the cost is distributed by the insurance companies among lot of people.

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